

Environmental Implications of Clear Aligner Therapy: A Review of Plastic Waste, Microplastic Release, and Sustainability Challenges

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Abstract:

Background: Clear aligner therapy (CAT) has expanded rapidly worldwide, yet the environmental consequences of producing and discarding large numbers of single-use thermoplastic aligners remain insufficiently examined. This narrative review critically synthesizes literature published between 2021 and 2025 on environmental hazards associated with CAT, including plastic waste generation, microplastic release, chemical leaching, disposal practices, and mitigation strategies.

Materials and Methods: PubMed/MEDLINE and Google Scholar were searched in January 2026, and 47 sources (laboratory, analytical chemistry, life-cycle, survey-based, and review articles, plus commentaries) were included.

Results: Aligners are predominantly made of non-biodegradable thermoplastics such as polyethylene terephthalate glycol (PETG) and thermoplastic polyurethane (TPU); an illustrative calculation based on assumed parameters suggests that aligner mass alone could amount to roughly 1,500-4,500 metric tons annually. Laboratory and simulated-wear studies report microplastic release, with particle sizes in the low-micrometer range, and evidence for nanoplastic release is limited. Leaching of bisphenol A and other compounds is generally reported at low concentrations, but heterogeneous methods and material variability preclude definitive risk characterization. Recycling uptake is low because of contamination barriers and limited infrastructure, and awareness among clinicians and patients appears limited. Current evidence establishes hazard (potential for release) more firmly than exposure or harm, and most data derive from laboratory or modeling studies.

Conclusion: Material innovation, waste-management systems, regulatory oversight, professional education, and well-designed exposure and life-cycle studies are needed to reduce environmental impact while preserving clinical effectiveness.

Key Word: clear aligners; orthodontics; microplastics; bisphenol A; plastic waste; recycling; sustainability; life-cycle assessment

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I. INTRODUCTION

Clear aligner therapy (CAT) has become a widely used, esthetic, and removable alternative to conventional fixed orthodontic appliances, with millions of patients treated worldwide¹⁻³. Its growth reflects patient preference, digital treatment workflows, and reported clinical effectiveness for selected malocclusions³. Unlike fixed appliances, which generate mainly metal, ceramic, and small elastomeric waste, clear aligners are single-use thermoplastic devices fabricated from petroleum-based polymers. A treatment course involves a series of aligner sets, each worn for one to two weeks and then discarded^{2,4,5}. At population scale, this pattern generates large volumes of non-biodegradable plastic waste.

Emerging research has described several hazard pathways (Figure no 1), including (1) microplastic and nanoplastic release during intraoral use; (2) chemical leaching of potentially harmful compounds such as bisphenol A (BPA); (3) accumulation of non-biodegradable waste in landfills and possible environmental contamination; and (4) greenhouse gas emissions from manufacturing, transport, and disposal. Importantly, most available evidence establishes hazard, that is, the potential for release, rather than demonstrated human or ecological exposure or harm. Surveys suggest limited awareness of these issues among clinicians and patients^{6,7}, and recycling options remain scarce and technically challenging^{8,9}. Despite broader attention to sustainability in dentistry¹⁰, systematic consideration of these issues within orthodontics remains limited^{5,11,12}.

This narrative review synthesizes current evidence on material composition and waste generation, microplastic release, chemical safety, disposal and recycling, clinician and patient awareness, and mitigation

strategies, and it identifies knowledge gaps to inform approaches that reduce the environmental footprint of orthodontic care.

II. REVIEW METHODOLOGY

This study was designed as a structured narrative review and was reported with reference to the Scale for the Assessment of Narrative Review Articles (SANRA)¹³. No protocol was registered, and PRISMA reporting was not formally applied. PubMed/MEDLINE and Google Scholar were searched in January 2026 for records published in English between 2021 and 2025, using Boolean combinations of terms related to clear aligners, thermoplastic orthodontic appliances, plastic waste, microplastics, bisphenol A, chemical leaching, recycling, sustainability, and life-cycle assessment.

Sources were included if they addressed clear aligners or thermoplastic orthodontic appliances, or closely related dental materials and clinical practice with direct environmental relevance (for example, dental-sector sustainability and microplastics in dentistry), and if they were experimental, analytical, survey-based, life-cycle, review, or commentary articles. Case reports and sources without environmental relevance were excluded. In total, 47 sources were included and are cited throughout. Two additional background references (a regulatory opinion on bisphenol A and the SANRA scale) were cited for context only. Because the available evidence is heterogeneous, no formal risk-of-bias assessment was undertaken; instead, the type of evidence supporting each statement (laboratory or simulated wear, modeling, survey, or review) is indicated in the text.

III. REVIEW

Material composition and waste generation

Clear aligners are most commonly manufactured from thermoplastic polymers, principally polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), and related copolyester or multilayer systems^{3,14,15}. These materials are selected for transparency, flexibility, biocompatibility, and the ability to deliver controlled orthodontic forces^{3,15,16}. PETG-based products generally offer high clarity and stiffness, whereas TPU-based products provide greater elasticity^{3,15}. Direct-printed aligners made from photopolymer resins and shape-memory polymers are emerging alternatives that may change the waste, particle-release, and leaching profile of the appliance¹⁷⁻¹⁹, although their environmental performance has been little studied.

PETG and TPU are petroleum-derived synthetic polymers that are not biodegradable under ambient environmental conditions. Discarded aligners are therefore expected to persist for long periods in landfills and natural environments, as is characteristic of conventional plastics^{11,20,21}, although studies that directly follow the degradation of used aligners in soil, water, or under ultraviolet exposure are scarce.

Manufacturing involves thermoforming polymer sheets over three-dimensional (3D) printed or milled dental models, followed by trimming and finishing. This generates additional plastic waste in the form of excess sheet material, discarded models, and by-products^{4,8}. Life-cycle assessments of aligner systems and related appliances indicate that production contributes appreciably to the overall footprint through energy use, raw-material supply, and transport^{4,8,22}.

Published estimates of aligner waste are preliminary and rely on market data and treatment averages^{2,5,8,11}. To illustrate the potential scale, a simple calculation was performed using assumed parameters: 30-40 aligner sets per patient, two arches, and 5-8 g per aligner, which gives approximately 300-640 g of plastic per patient. With an assumed 5-7 million new patients per year, aligner mass alone would amount to approximately 1,500-4,500 metric tons annually. These parameters are assumptions rather than measured values, and the result is highly sensitive to aligner mass, number of sets, and patient volume; it should be read as an order-of-magnitude illustration, not an empirical estimate. The calculation also excludes retainers, packaging, shipping materials, attachment templates, auxiliary devices, and 3D-printed models, which may add materially to the total^{4,8}.

Comparisons with fixed appliances reveal trade-offs. Fixed appliances generate less plastic by mass but involve metal extraction and processing, disposable components such as elastics and ligatures, and, in some treatment models, a different pattern of clinical visits and associated travel^{8,22}. The balance depends strongly on assumptions and system boundaries, which is why standardized life-cycle assessments are needed^{8,22,23}.

Microplastic and nanoplastic release

The oral environment exposes aligners to mastication forces, thermal cycling, chemical challenge from saliva, food, and beverages, and biofilm formation²⁴⁻²⁷. Laboratory studies using scanning electron microscopy (SEM), atomic force microscopy (AFM), and spectroscopic methods have documented progressive surface changes, including cracks, pitting, and material loss, after simulated or real wear periods of days to weeks²⁴⁻²⁸. Spectroscopic and cyclic-loading experiments have detected secondary microplastic detachment after exposure to artificial saliva or mechanical loading^{24,25,29}. Reported particle sizes are generally in the low-micrometer range (approximately 5-20 μm in some reports), with limited evidence of nanoplastic-sized fragments^{24,25,29,30}. Release appears to depend on aligner material, wear duration, thermal and chemical conditions (for example, hot or

acidic beverages), and mechanical loading such as parafunctional habits^{25,27}. Most of this evidence derives from in vitro or simulated-wear experiments, and direct measurements in patients remain limited^{30,31}.

Particles released in the mouth are likely to be swallowed and to pass through the gastrointestinal tract, where they may be excreted or, for the smallest sizes, potentially absorbed^{32,33}. Animal and in vitro studies of micro- and nanoplastics generally suggest that the smallest particles can cross epithelial barriers and accumulate in tissues, but the significance of exposure from aligners specifically remains unclear³¹⁻³³. In vitro work also reports inflammatory responses, oxidative stress, and cytotoxicity for plastic particles in cell cultures; its relevance to real-world exposure is uncertain³¹⁻³³.

Particles expelled or rinsed from aligners during cleaning would enter wastewater. Conventional wastewater treatment has been described as retaining a large fraction of microplastics while still allowing some release, particularly for the smallest particles, with retained particles concentrating in sludge^{33,34}. Microplastics have been reported in dental healthcare settings³⁴, and dentistry has been proposed as a contributor to the environmental microplastic burden^{31,33,35,36}. Direct attribution of environmental particles to aligners, however, has not been demonstrated, and monitoring and source-apportionment studies are required^{31,33,34}. Microplastic pollution in general is a recognized ecological concern, with reported effects on aquatic organisms^{32,33,35}.

Chemical leaching and safety

Bisphenol A (BPA), a known endocrine-disrupting compound, has been investigated in orthodontic and dental materials because of possible hormonal effects at low exposure levels^{14,28,37-41}. PETG and TPU are not synthesized from BPA; where BPA has been detected, possible origins include additives, manufacturing residues, contamination, or other oral materials such as composite resins and attachments, and this attribution remains unresolved^{28,40,42}. Analytical studies using chromatographic and mass-spectrometric techniques have generally reported BPA and other eluted compounds at low concentrations, with considerable variation across brands, materials, and test conditions^{37,39,40}. Comparisons with older exposure limits should be interpreted cautiously, because regulatory benchmarks have been tightened; for example, the European Food Safety Authority's 2023 re-evaluation lowered the tolerable daily intake for BPA to 0.2 ng/kg body weight per day⁴³.

Leaching depends on material composition, manufacturing, thermal exposure, mechanical stress, and aging, and some studies report increased release after thermal cycling or prolonged intraoral aging^{14,26,28,37,38,41}. Other compounds discussed in the literature include plasticizers such as phthalates, residual monomers, and polymer degradation products^{14,39,41,42}. Chemical characterization has identified a range of organic compounds eluting from aligners, but the toxicological significance of most is unknown^{9,14,39}.

Clear aligners are regulated as medical devices in most jurisdictions and typically undergo biocompatibility testing in accordance with ISO 10993 standards^{14,16,19}. Such tests address cytotoxicity, sensitization, and irritation but do not comprehensively address long-term low-dose exposure or environmental impact^{14,16,26,39}. Systematic and umbrella reviews suggest that aligners are generally biocompatible for short-term intraoral use^{16,19,40}. However, existing protocols may not capture chronic microplastic exposure, low-dose endocrine-active compounds, or cumulative exposures^{14,28,37,41,42}.

From an environmental perspective, discarded aligners could release additives in landfills or aquatic settings, but direct measurements for aligners are lacking^{9,42}. By analogy with other plastics the pathway is plausible, while its magnitude relative to other plastic sources remains unquantified^{39,42}.

Disposal practices and recycling barriers

Surveys of clinicians and patients indicate that used aligners are most commonly discarded with household or general waste, and only a minority are recycled or returned^{6,7}. This pattern reflects limited awareness, a lack of convenient recycling options, and uncertainty over whether aligners are medical waste or recyclable plastic^{6,7,20}. Several of these surveys come from single countries or regions, so their findings may not generalize^{6,7}.

Incineration of plastics can release hazardous compounds depending on polymer chemistry and combustion conditions. Nitrogen-containing polymers such as TPU can yield nitrogenous combustion products, whereas incomplete combustion of aromatic polyesters such as PETG can produce aromatic hydrocarbons. Modern waste-to-energy facilities apply emission controls, whereas incomplete or uncontrolled burning can release toxic compounds^{9,36}. Chemical analyses of aligner disposal have been used to examine such emissions⁹.

The main barrier to recycling is contamination with saliva, biofilm, and food residues, since municipal programs generally do not accept items contaminated with body fluids^{20,44}. Manufacturer take-back programs and specialized recycling pathways require cleaning or disinfection followed by mechanical or chemical reprocessing^{8,21,44}. Recent work has investigated alkaline hydrolysis as a chemical recycling route for aligners⁴⁴ and microbial degradation of polyethylene terephthalate as an experimental approach²¹. Participation in take-back remains low, which has been attributed to limited awareness, inconvenience, and a lack of incentives^{6,7,20}. Further technical challenges include polymer degradation during use, additives and colorants, and the economics of collecting small, contaminated volumes^{8,44}. Life-cycle assessments suggest that recycling reduces impacts relative to landfill or incineration only when collection rates are high and reprocessing is energy-efficient^{8,22,23}.

Promising approaches include closed-loop manufacturer take-back systems, mono-material designs that simplify reprocessing, and chemical recycling methods that tolerate contaminated feedstock^{5,20,44}. Reuse of recovered material in non-medical products would need regulatory and safety evaluation^{5,44}.

Clinician and patient awareness

Surveys of orthodontists and general dentists report limited awareness of the environmental impact of aligners, and many respondents in some surveys had not considered it^{6,7}. Clinicians frequently report a lack of sustainability training and uncertainty about advising patients, and some perceive environmental considerations as secondary to clinical efficacy^{12,45}. A growing subset is nevertheless willing to adopt more sustainable approaches when guidance is available^{12,36,45-47}. Reported barriers include the lack of guidelines, limited alternatives, cost and performance concerns, and limited support from professional organizations^{12,45,47}.

Patient awareness is similarly limited. Surveys indicate that many patients are unaware that aligners are non-biodegradable or that disposal method matters, and patients report receiving little disposal advice from their clinicians^{6,7}. Patients appear willing to recycle when it is convenient^{7,20}, and addressing practical barriers is likely to matter as much as information^{20,44}. Patient education and stewardship statements at the consent stage are plausible levers^{12,45}, but controlled evidence that educational interventions change actual disposal behavior is currently lacking.

Mitigation strategies and sustainable innovations

Material innovation. Bio-based polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), modified natural polymers, and hybrid materials are under investigation as alternatives to petroleum-derived thermoplastics^{17,18,23}. PLA is compostable under industrial conditions, but its suitability for intraoral use, including moisture and thermal sensitivity and retention of mechanical properties, has not been established, and primary data on PLA aligners are limited²³. Biodegradable does not mean benign: life-cycle assessments must account for agricultural inputs, land use, composting infrastructure, and particle release during degradation^{22,23}. Incremental improvements, such as BPA-free formulations, reduced additive content, and surface treatments, may reduce chemical release while retaining current materials^{14,28,37,39,42}.

Waste management and recycling. Priorities include expanding take-back and recycling systems^{8,21,44}, simplifying participation for patients and clinics^{6,7}, standardizing disposal protocols^{12,36,45,47}, and developing safe reuse applications for recovered material⁴⁴.

Clinical waste reduction. Optimized digital treatment planning that limits refinement sets, and the reuse or redesign of auxiliary items, may reduce waste, and clinical innovations aimed at waste reduction have been reported⁴⁸. Protocols that reduce the number of aligners used per patient have been proposed, but their clinical effectiveness and trade-offs require evaluation².

Education and policy. Sustainability content could be integrated into orthodontic curricula and continuing education^{12,45,46}, supported by professional guidelines^{2,12,36} and accessible patient resources^{6,7,20}. Collaboration among manufacturers, clinicians, regulators, and waste-management providers would be needed to align material design, labeling, and disposal systems^{2,10,12}.

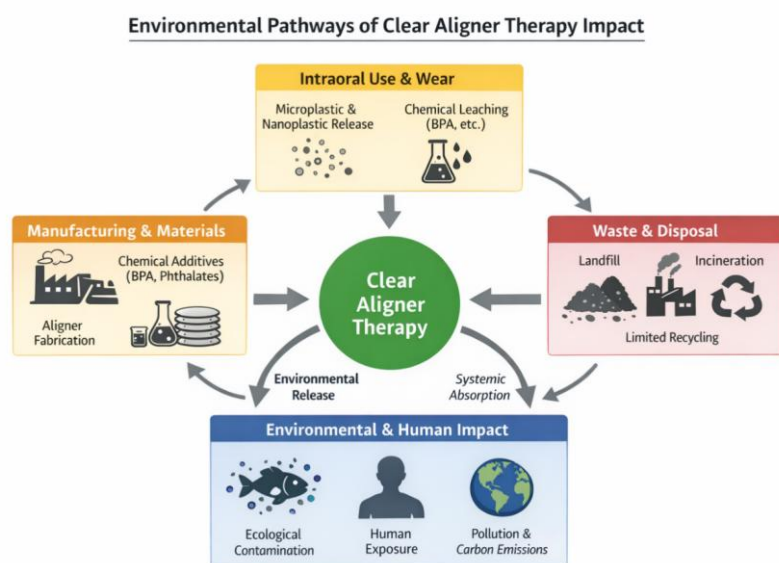


Figure no 1: Conceptual framework of environmental pathways associated with clear aligner therapy.

Research gaps and priorities

Key priorities include (1) tracking aligner waste and disposal at the population level^{5,8,11,20}; (2) quantifying exposure to microplastics under realistic intraoral conditions, including in patients^{24,25,29-31,35,49}; (3) harmonizing analytical methods for chemical leaching and extending safety assessment to long-term, low-dose exposure^{14,28,37-41}; (4) conducting standardized life-cycle assessments that compare aligners, fixed appliances, and retainers^{4,8,22,23}; (5) testing whether educational and incentive-based interventions change disposal behavior^{6,7,12,20}; and (6) evaluating alternative and bio-based materials for performance and environmental outcomes^{17,18,23}. Table no 1 summarizes the main evidence gaps and the corresponding research priorities.

Table no 1: Summary of current evidence gaps and research priorities

Domain	Current evidence status	Main gaps	Research priority
Waste generation	Modeled estimates and illustrative calculations	No measured, population-level data	Standardized waste tracking and reporting
Microplastic release	Mainly in vitro and simulated wear	Limited in vivo data; inconsistent methods	Patient-based and harmonized laboratory studies
Nanoplastic exposure and systemic absorption	Evidence from general micro- and nanoplastic literature	Little aligner-specific data	Toxicokinetic and exposure modeling
Chemical leaching	Generally low concentrations; variable methods	Long-term, low-dose and cumulative effects; origin of BPA	Standardized assays; source attribution
Environmental fate	Plausible pathways by analogy to other plastics	No direct tracing of discarded aligners; no landfill leachate data	Degradation, leachate, and wastewater studies
Life-cycle assessment	Few assessments, some focused on retainers	Inconsistent boundaries; limited comparisons	Standardized comparative assessments
Recycling	Experimental chemical and biological routes	Contamination; low uptake; infrastructure	Pilot take-back and recycling systems
Clinician and patient awareness	Surveys, often single-region	No data on behavior change after interventions	Intervention trials with outcome tracking
Alternative materials	Early-stage research	Limited intraoral performance and environmental data	Bio-based and printed-material evaluation

Abbreviations: BPA, bisphenol A. Gaps and priorities are the author's synthesis of the cited literature.

Limitations

This review has several limitations. First, it is a narrative review without a registered protocol; only two databases were searched, the search was conducted in January 2026 and does not capture later publications, and screening and extraction were performed by a single author without duplicate verification. Second, restricting the search to English-language articles from 2021 to 2025 may have excluded relevant earlier or non-English work, and general environmental literature (for example, on plastic persistence and wastewater treatment) was cited only to a limited extent. Third, many primary studies rely on in vitro simulation models rather than real-world exposure assessments, restricting extrapolation to clinical and environmental conditions. Fourth, methodological heterogeneity in microplastic detection and chemical analysis limits direct comparison across studies. Fifth, the waste estimate presented is an illustrative calculation based on assumed parameters, and several surveys derive from single regions. Finally, no formal risk-of-bias assessment was performed.

IV. CONCLUSIONS

Clear aligners offer clear clinical benefits, but their widespread use creates a growing stream of non-biodegradable plastic waste, with plausible pathways for microplastic release and chemical leaching. Current evidence establishes hazard more firmly than exposure or harm, and most data come from laboratory and modeling studies. Recycling uptake and awareness appear low, and direct environmental measurements are scarce. Addressing these gaps will require standardized life-cycle and exposure studies, validated alternative materials, practical recycling infrastructure, and the integration of sustainability into orthodontic education and practice. These steps warrant systematic attention if the environmental footprint of aligner therapy is to be reduced without compromising clinical outcomes.

DECLARATIONS

Author contributions: Mahesh Kumar: conceptualization, literature search, data synthesis, drafting, and critical revision of the manuscript. The author approved the final version and agrees to be accountable for all aspects of the work.

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Data availability: No new data were generated; all data are from the cited sources.

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