Content available at: https://www.ipinnovative.com/open-access-journals

Journal of Advances in Oral Health

Journal homepage: https://jaoh.in/

Review Article

Sustainable orthodontics: Aligners, environmental contamination and the green responsibility ahead

Yenika Manchanda[1*], Litesh Singla[1], Divya Singla[1], Harvinder Singh[1], Amanjot Kaur[1]

[1]Dept. of Orthodontic and Dentofacial Orthopedics, National Dental College and Hospital, Derabassi, Punjab, India

Abstract

The rapid evolution of clear aligner therapy has transformed orthodontic practice, offering patients an esthetic, comfortable and digitally driven alternative to traditional fixed appliances. However, this innovation has also introduced significant environmental and bioethical challenges. This review explores the composition of aligner materials, their environmental footprint, chemical toxicity and challenges associated with biomedical waste disposal. It further discusses emerging strategies to mitigate environmental contamination through sustainable materials, recycling initiatives and responsible clinical practices. The article emphasizes the crucial role of orthodontists in promoting eco-conscious treatment systems and calls for collaborative action between researchers, clinicians and manufacturers toward a greener orthodontic future.

Keywords: Aligners, Orthodontics, Environmental sustainability, Thermoplastic polymers, Recycling, BPA, Biodegradable materials.

Received: 09-04-2026 **Accepted:** 07-05-2026 **Available Online:** 23-05-2026

1. Introduction

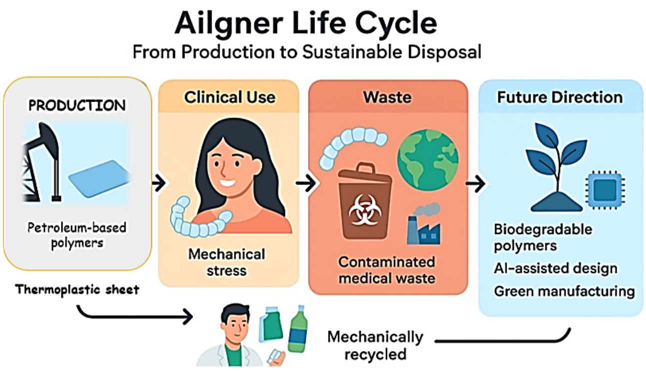

Figure 1. *Aligner life cycle from production to sustainable disposal*

Orthodontics has witnessed a profound transformation over the past two decades, largely driven by the introduction and rapid advancement of clear aligner therapy. Unlike traditional fixed appliances, which rely on brackets and archwires, aligners provide a removable, nearly invisible alternative that appeals particularly to adult patients seeking esthetic and convenient treatment options. The integration of digital technologies, including three-dimensional (3D) intraoral scanning, computer-aided design and manufacturing (CAD/CAM), and artificial intelligence-based treatment planning, has further revolutionized the field by enhancing precision, predictability, and patient-specific customization.[1]

Initially, orthodontic esthetics were improved through the use of ceramic and polycarbonate brackets; however, the advent of transparent thermoplastic aligners marked a paradigm shift in clinical practice. These aligners are fabricated using advanced polymeric materials that combine transparency, flexibility, and strength, enabling controlled tooth movement through sequential staging. As a result, aligner therapy has become one of the fastest-growing segments in orthodontics worldwide.

Despite these clinical advantages, the increasing reliance on disposable thermoplastic materials has raised critical environmental concerns. Each patient undergoing aligner therapy typically uses multiple sets of plastic trays over the course of treatment, contributing significantly to biomedical plastic waste. These materials are predominantly petroleum-based and non-biodegradable, leading to long-term environmental persistence and ecological harm. Furthermore, the production and disposal processes associated with aligners contribute to carbon emissions, microplastic generation, and potential release of toxic by-products.

In addition to environmental considerations, there is growing concern regarding the biocompatibility and chemical safety of aligner materials. The potential leaching of substances such as bisphenol A (BPA) under intraoral conditions has prompted investigations into their toxicological effects, including endocrine disruption and metabolic disorders. Consequently, the concept of sustainability in orthodontics has emerged as a critical area of research and clinical responsibility.

This review aims to provide a comprehensive analysis of aligner materials, their environmental and biological implications, and the strategies available to mitigate their ecological impact. By integrating material science,

*Corresponding author: Yenika Manchanda
Email: yenikamanchanda14@gmail.com

https://doi.org/10.18231/j.jaoh.16796.1778144741

environmental awareness, and clinical practice, the article highlights the need for a paradigm shift toward sustainable orthodontics.[2]

2. Review Methodology

This systematic review was conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to evaluate the environmental impact, material composition, and biocompatibility of clear aligner therapy.

2.1. Search strategy

A comprehensive literature search was performed across electronic databases including PubMed, Scopus, and Web of Science for studies published between January 2000 and December 2024. The search strategy incorporated combinations of the following keywords:

"clear aligners," "thermoplastic polymers," "polyurethane," "PET-G," "biodegradable materials," "bisphenol A," "microplastics," and "dental waste management."

Boolean operators (AND, OR) were used to refine the search.

2.2. Study selection

A total of 85 records were identified through database searching. After removal of 15 duplicates, 70 articles were screened based on titles and abstracts.

Of these, 40 studies were excluded due to lack of relevance.

The remaining 30 full-text articles were assessed for eligibility. After full-text review, 15 articles were excluded for the following reasons:

Irrelevant to aligner materials or sustainability (n = 3)

Insufficient or unclear data (n = 6)

1. Non-English publications (n = 3)
2. Conference abstracts or incomplete reports (n = 3)
3. Finally, 15 studies were included in the qualitative synthesis.

2.3. Inclusion criteria

1. Studies evaluating clear aligner materials or polymers
2. Articles addressing environmental impact or sustainability
3. Studies investigating BPA release or biocompatibility
4. Peer-reviewed publications in English

2.3. Exclusion criteria

1. Studies unrelated to orthodontic aligners
2. Editorials, opinion articles without supporting data
3. Conference abstracts or unpublished data
4. Non-English articles

2.4. Data extraction and analysis

Relevant data from selected studies were extracted and categorized into key themes:

1. Material composition and mechanical properties
2. Environmental impact and waste generation
3. Chemical toxicity (e.g., BPA release)
4. Recycling and sustainability strategies

A qualitative synthesis was performed to identify trends, gaps, and future research directions in sustainable orthodontics.[3–4]

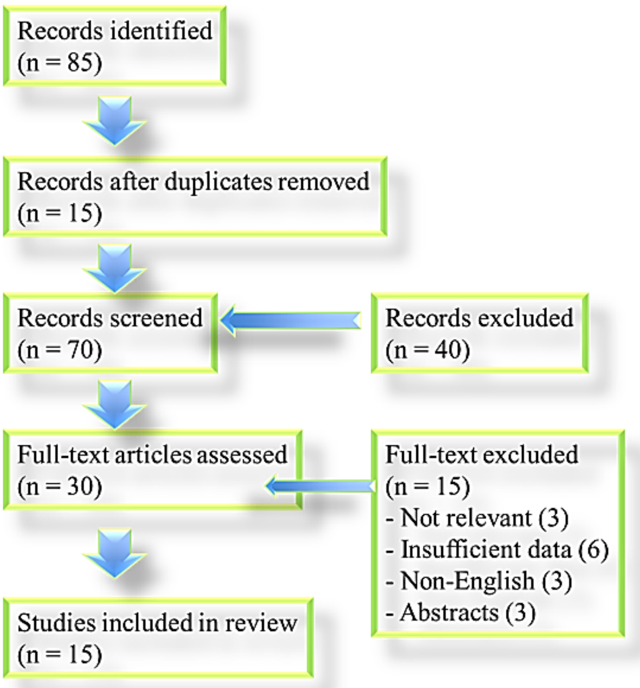

Figure 2. *PRISMA flow diagram illustrating the systematic process of literature identification, screening, eligibility assessment, and inclusion. A total of 85 records were identified through database searching, of which 15 duplicates were removed. After screening 70 records, 40 were excluded based on titles and abstracts. Thirty full-text articles were assessed for eligibility, and 15 were excluded due to irrelevance, insufficient data, non-English language, or being conference abstracts. Finally, 15 studies were included in the qualitative synthesis.*

3. Discussion

3.1. Composition and mechanical properties of clear aligners

The development of modern orthodontic aligners relies heavily on advancements in polymer science. Polymers are macromolecules composed of repeating monomeric units linked through covalent bonds, forming long chains with unique structural and functional properties. Their versatility, cost-effectiveness, and adaptability make them ideal for a wide range of biomedical applications, including orthodontic appliances.[5]

Clear aligners are primarily fabricated from thermoplastic polymers such as polyethylene terephthalate glycol (PET-G), thermoplastic polyurethane (TPU), and multilayered copolymers. These materials are selected based on their ability to provide a balance between flexibility and stiffness, which is essential for delivering controlled orthodontic forces while allowing easy insertion and removal.

Within the oral environment, aligner materials are exposed to a complex and dynamic milieu characterized by saliva, enzymes, fluctuating pH levels, and temperature variations. These factors can influence the physical and chemical stability of the polymers, leading to degradation and potential alteration of mechanical properties. For instance, exposure to acidic or alkaline conditions may accelerate hydrolytic degradation, while temperature fluctuations can induce thermal expansion and contraction, affecting the fit and performance of the aligner.

Mechanical properties such as elastic modulus, stress relaxation, and creep behavior play a crucial role in determining the effectiveness of tooth movement. Aligners must maintain consistent force delivery over time; however, viscoelastic relaxation can result in a gradual decrease in force, potentially compromising treatment outcomes. Additionally, repeated occlusal loading during mastication may lead to deformation or fracture of the material.[6]

Thermal behavior is another critical consideration. Polymers do not exhibit a sharp melting point but instead undergo a gradual transition from a glassy to a rubbery state at the glass transition temperature (Tg). For aligner materials, the Tg must remain well above intraoral temperatures to ensure dimensional stability and mechanical integrity. Techniques such as differential scanning calorimetry (DSC) are used to evaluate these thermal properties.

Furthermore, polymer aging—both physical and chemical—can affect aligner performance. Physical aging involves structural relaxation and increased brittleness, while chemical aging includes oxidation and hydrolysis leading to chain scission. These processes may compromise transparency, strength, and biocompatibility, highlighting the need for continuous material innovation.

3.2. Polymer structure and thermal behavior

Polymers are macromolecules composed of repeating structural units connected through covalent bonds (Figure 3). The molecular architecture and weight distribution of these chains determine the material's thermal and mechanical characteristics. Unlike small molecules with well-defined melting points, polymers exhibit complex phase transitions due to the entanglement of their long chains and the coexistence of amorphous and crystalline regions.

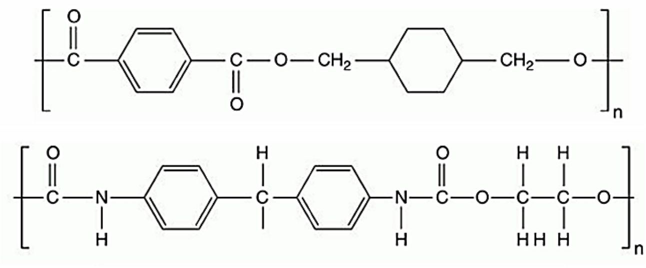

Figure 3. *a: chemical structure of polyethylene tetraphthalate glycol material (PET-G), 3b: chemical structure of polyurethane material (PU)*

Clear aligners are fabricated from thermoplastic polymers—materials that soften upon heating and solidify upon cooling without undergoing chemical change. Two widely utilized thermoplastic polymers in aligner fabrication are polyethylene terephthalate glycol (PETG) and thermoplastic polyurethane (TPU). PETG, a copolymer of polyethylene terephthalate and glycol, exhibits enhanced flexibility and reduced brittleness compared to PET due to glycol's ability to inhibit crystallization. TPU, on the other hand, is a versatile elastomer that can be chemically tailored for specific hardness and elasticity, offering superior impact resistance, flexibility and chemical stability in moist environments.

Both materials are transparent, biocompatible and suitable for thermoforming—a critical process in aligner fabrication. PETG and TPU are preferred not only for their clarity and strength but also for their recyclability and processability, aligning with current sustainability goals in dental material science.[7]

4. Glass Transition and Viscoelasticity

Unlike crystalline solids, polymers transition gradually from a rigid, glassy state to a more rubber-like state over a temperature range known as the glass transition temperature (Tg). Above Tg, the polymer chains gain sufficient mobility to deform under stress; below Tg, the material behaves as a hard, brittle solid. For aligner materials, the Tg must remain well above intraoral temperatures to ensure mechanical stability during use. Differential scanning calorimetry (DSC) is commonly employed to determine Tg, which for PETG is approximately 85°C. This thermal buffer ensures that aligners maintain their intended mechanical properties even under varying oral conditions (Figure 4).[7]

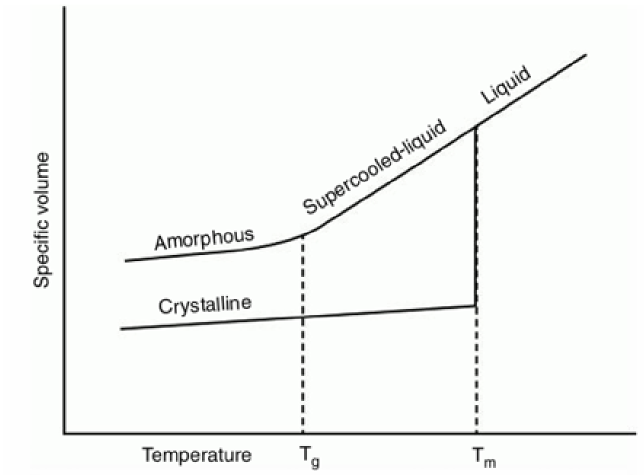

Figure 4. *Specific volume versus temperature. Tm represents melting temperature and Tg represents glass transition temperature*

5. Aging of Aligner Polymers

Polymeric materials used in aligners undergo physical and chemical aging during clinical use. Physical aging refers to the gradual relaxation of the polymer chains toward a lower energy state, leading to reduced free volume, increased stiffness and potential brittleness over time. Exposure to saliva and dietary components accelerates this process through molecular diffusion and plasticization where absorbed water or organic molecules increase chain mobility and reduce Tg, temporarily softening the material.[7]

Chemical aging, in contrast, involves irreversible reactions such as hydrolysis and oxidation, leading to chain scission, loss of strength and surface cracking. These processes compromise the aligner's mechanical performance, transparency and biostability. Therefore, modern aligner materials are designed to resist both forms of degradation, ensuring predictable force delivery and esthetics throughout the wear cycle.[7]

Manufacturers must also maintain transparency regarding material composition and production processes, as even minor changes can influence the aligner's performance and patient outcomes. Future research should focus on developing next-generation biopolymers that combine enhanced mechanical stability with improved biodegradability and environmental sustainability, paving the way for a more efficient and eco-conscious orthodontic future.

Clear aligners are fabricated from advanced thermoplastic polymers such as polyurethane (PU), polyethylene terephthalate glycol (PET-G) and multilayered copolymers designed for controlled elasticity. These materials must exhibit a balance between flexibility allowing for insertion and removal and stiffness to deliver adequate orthodontic forces. The aligner's biomechanical behavior depends on its elastic modulus, stress relaxation and deformation resistance under cyclic loading (Table 1).[8]

Table 1. *Comparison of common thermoplastic materials used in clear aligners*

Material	Base Composition	Mechanical Properties	Remarks
Polyurethane (PU)	Petroleumderived polymer	High flexibility, moderate stiffness	Common in pressure-formed aligners
PET-G	Polyethylene terephthalate glycol	Good clarity, high rigidity	Common in vacuum-formed systems
Polycarbonate	Bisphenol-based polymer	High strength, low flexibility	Limited due to BPA toxicity
Multilayer copolymers	PU + PET blends	Enhanced force retention	New-generation aligners

Table 2. *Environmental consequences of improper disposal of aligner plastics*

Disposal Method	By-products Released	Environmental Consequences
Landfill	Microplastics	Soil and groundwater contamination
Burning	Cyanides, phosgene	Air pollution, toxic gas emission
Ocean dumping	Microplastics	Marine life ingestion, ecological imbalance

Table 3. *Summary of key studies evaluating BPA presence in orthodontic aligners*

Author (Year)	Material Studied	BPA Detection	Clinical Implication
Iliadi et al., 2020	Various thermoplastics	Trace levels detected	Potential low-dose exposure risk
Schuster et al., 2018	Vacuum-formed PET-G	Minor BPA leaching	Recommend water pre-soak
Ryokawa et al., 2006	Thermoplastic aligners	Leaching reduced after 24h soak	Supports pre-treatment practice

Table 4. *Classification of plastic recycling methods*

Recycling Type	Process Description	Advantages / Limitations
Mechanical Recycling	Shredding and remolding of plastics	Simple but limited by contamination
Chemical Recycling	Depolymerization to monomers	High cost but retains material quality
Energy Recovery	Incineration for energy generation	Reduces waste but releases CO_2

5.1. Environmental impact of thermoplastic waste

The environmental implications of clear aligner therapy are becoming increasingly significant in the context of global plastic pollution. Thermoplastic polymers used in aligners are predominantly derived from non-renewable petroleum resources and are resistant to natural degradation processes. As a result, discarded aligners contribute to the accumulation of persistent plastic waste in landfills and aquatic ecosystems.

A typical aligner treatment may involve the use of 20 to 40 trays per patient, each worn for one to two weeks. Considering the growing number of patients undergoing aligner therapy worldwide, the cumulative volume of plastic waste generated is substantial. Unfortunately, only a small fraction of this waste is recycled, primarily due to contamination and lack of appropriate recycling infrastructure for biomedical plastics.

Improper disposal methods, such as incineration or open burning, can release hazardous substances including dioxins, furans, cyanides, and phosgene gas. These emissions contribute to air pollution and pose serious health risks to both humans and wildlife. Similarly, landfill disposal leads to the fragmentation of plastics into microplastics, which can infiltrate soil and groundwater systems, ultimately entering the food chain.

Marine pollution is another critical concern, as plastic waste often finds its way into oceans, where it is ingested by marine organisms. This not only affects biodiversity but also disrupts ecological balance and food safety. Microplastics derived from orthodontic materials may persist for decades, highlighting the urgent need for sustainable waste management solutions.

Thermoplastic aligners are predominantly petroleum-based and non-biodegradable. Once discarded, they contribute to long-term environmental pollution. Improper disposal or incineration releases harmful gases including cyanides, phosgene and dioxins. Globally, only about 9% of total plastic waste undergoes recycling, which highlights the scale of the orthodontic plastic challenge (Table 2).[1]

5.2. Chemical additives and bisphenol a (BPA) exposure

The incorporation of chemical additives is essential for enhancing the physical properties of thermoplastic materials.

Bisphenol A (BPA), commonly used in the production of polycarbonate plastics and epoxy resins, improves transparency, durability, and resistance to impact. However, BPA is a well-known endocrine-disrupting chemical with potential adverse effects on human health.

Although many aligner manufacturers claim to use BPA-free materials, studies have demonstrated the presence of trace amounts of BPA released under simulated intraoral conditions. Factors such as temperature, mechanical stress, and exposure to saliva can influence the extent of BPA leaching. While the levels detected are generally low, chronic exposure over extended periods may pose cumulative health risks.

BPA has been associated with a range of biological effects, including hormonal imbalance, reproductive disorders, metabolic diseases, and increased risk of certain cancers. Its ability to mimic estrogen and interfere with endocrine signaling pathways has raised concerns regarding its safety, particularly in long-term orthodontic treatments.

Clinical recommendations to minimize BPA exposure include pre-soaking aligners in water before use, avoiding exposure to high temperatures, and limiting the reuse of worn aligners. Continued research and regulatory oversight are necessary to ensure the safety and transparency of orthodontic materials.

Bisphenol A (BPA) and other chemical additives improve the transparency and toughness of thermoplastics but pose toxicological concerns. While aligner manufacturers often claim BPA-free formulations, several independent studies have reported trace amounts of BPA release when aligners are exposed to heat, saliva and mechanical stress. Chronic exposure to BPA has been linked to endocrine disruption, infertility, metabolic disorders and carcinogenesis (Table 3).[3]

5.3. Recycling and waste management strategies

Effective waste management is a cornerstone of sustainable orthodontics. Recycling of thermoplastic materials presents a viable approach to reducing environmental impact; however, several challenges must be addressed. Since used aligners are considered biomedical waste, they require proper decontamination before recycling.

Mechanical recycling involves shredding and reprocessing plastics into secondary products, although this method may result in reduced material quality. Chemical recycling, on the other hand, breaks down polymers into their monomeric components, allowing for the production of high-quality materials but at a higher cost. Energy recovery through controlled incineration can reduce waste volume but contributes to carbon emissions.

Orthodontic clinics play a critical role in waste segregation and management. Implementing designated collection systems for used aligners, educating patients on proper disposal, and collaborating with recycling facilities can significantly improve sustainability outcomes. Additionally, manufacturers can adopt take-back programs and closed-loop recycling systems to minimize waste generation.

Mechanical recycling, which involves reprocessing plastics into granules for non-medical use, is a viable solution. However, because aligners are intraoral devices, they are classified as contaminated medical waste and require decontamination before recycling. Orthodontic clinics should collect used aligners in labeled biomedical waste containers, followed by sterilization and transfer to specialized recycling facilities (Table 4).[8–10]

6. Future Directions: Toward Green Orthodontics

The future of orthodontics lies in the integration of sustainability with technological innovation. Research is increasingly focused on the development of biodegradable and bio-based polymers such as polylactic acid (PLA) and cellulose derivatives. These materials offer the potential to reduce environmental persistence while maintaining the mechanical properties required for clinical performance.[11–12]

Advances in additive manufacturing and 3D printing have opened new avenues for aligner fabrication. By producing aligners directly from digital models, material wastage can be minimized, and production efficiency can be enhanced. Furthermore, the use of artificial intelligence in treatment planning can optimize aligner sequencing, reducing the total number of trays required per patient.

Sustainable packaging, reduced energy consumption during manufacturing, and the use of renewable resources are additional strategies that can contribute to a greener orthodontic ecosystem. Collaboration among researchers, clinicians, manufacturers, and policymakers is essential to drive innovation and establish standardized guidelines for environmentally responsible orthodontic care.

Emerging research focuses on the development of biodegradable or bio-based polymers such as polylactic acid (PLA) and cellulose acetate, which offer comparable transparency and elasticity to traditional plastics. The integration of 3D printing with recyclable resins could revolutionize aligner fabrication by minimizing material wastage. Artificial intelligence can further optimize treatment planning to reduce the number of aligners required per case, thereby lowering overall plastic consumption.[13–15]

7. Conclusion

Clear aligner therapy represents a significant advancement in modern orthodontics, combining esthetics, comfort, and technological precision. However, its environmental implications cannot be ignored. The widespread use of non-biodegradable thermoplastic materials has introduced new challenges related to plastic waste, chemical safety, and ecological sustainability.

Orthodontists have a crucial role in addressing these challenges by adopting responsible clinical practices, promoting patient awareness, and supporting sustainable innovations. The development of biodegradable materials, efficient recycling systems, and digital optimization techniques offers promising solutions for reducing the environmental footprint of orthodontic treatment.

Ultimately, the transition toward sustainable orthodontics requires a collective effort that balances clinical excellence with environmental responsibility. By embracing this paradigm shift, the orthodontic community can contribute to a healthier planet while continuing to deliver high-quality patient care.

Aligner therapy exemplifies the harmony between technological innovation and patient-centered care, yet it presents environmental challenges that cannot be overlooked. Orthodontists must advocate for sustainable practices, including the responsible disposal and recycling of aligners. Collaborative efforts among manufacturers, clinicians, and environmental agencies are essential to establish standardized protocols for eco-friendly orthodontic care. The discipline of orthodontics has both the opportunity and the responsibility to lead the dental profession toward sustainability.

8. Source of Funding

None.

9. Conflict of Interest

None.

References

1. Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Efficacy of clear aligners in controlling orthodontic tooth movement: a systematic review. *Angle Orthod.* 2015:881-9. https://doi.org/10.2319/061614-436.1
2. Eliades T, Adel SM, Akyalcin S. Environmental footprints in orthodontics: The World Federation of Orthodontists' white paper on sustainable practices, challenges and research imperatives. *J World Fed Orthod*. 2025;14:194-201. https://doi.org/10.1016/j.ejwf.2025.06.003
3. Iliadi A, Koletsi D, Papageorgiou SN, Eliades T: Safety Considerations for Thermoplastic-Type Appliances Used as Orthodontic Aligners or Retainers. A Systematic Review and Meta-Analysis of Clinical and In-Vitro Research. *Materials Basel*. 2020138, 1843-2020. https://doi.org/10.3390/ma13081843
4. Delgado JI, Kehyaian P, Fernández-Blázquez JP: Thermoplastics for Clear Aligners: A Review. *Polymers (Basel*. 2025, 17:1681. https://doi.org/10.3390/polym17121681
5. Ryokawa, Hiromi & Miyazaki, Yoshikazu & Fujishima, Akihiro & Miyazaki, Takashi & Maki, Koutaro. (2006: The mechanical properties of dental thermoplastic materials in a simulated intraoral environment. *Orthodontic Waves.* 65:64-72. https://doi.org/10.1016/j.odw.2006.03.003
6. Fang D, Zhang N, Chen H, Bai Y: Dynamic stress relaxation of orthodontic thermoplastic materials in a simulated oral environment. *Dent Mater J*. 2013;32:946-51. https://doi.org/10.4012/dmj.2013-131
7. Nanda R, Castroflorio T, Garino F, Ojima K, editors. Principles and Biomechanics of Aligner Treatment. 1st ed. St. Louis (MO): Elsevier; 2022.
8. Freitas MPM: Aligners, Environmental Contamination, and The Role of Orthodontics. *Angle Orthod*. 2022;1:148-9. . https://doi.org/10.2319/1945-7103-92.1.148
9. Ke Y, Zhu Y, Zhu M: A comparison of the mechanical properties of clear orthodontic aligners. *Angle Orthod*. 2019, 89:654–661. https://doi.org/10.2319/073018-553.1
10. Lombardo L, Arreghini A, Maccarrone R, et al.: Optical properties of orthodontic aligners—spectrophotometry analysis of three types before and after aging. *Prog Orthod*. 2015;16:41. https://doi.org/10.1186/s40510-015-0107-5
11. Ryu JH, Kwon JS, Jiang HB, Cha JY, Kim KM: Effects of thermoforming on the physical and mechanical properties of thermoplastic materials for clear aligners. *Korean J Orthod.* 2018, 48:316–25 https://doi.org/10.4041/kjod.2018.48.5.316
12. Hopewell J, Dvorak R, Kosior E: Plastics recycling: challenges and opportunities. *Philos Trans R Soc B Biol Sci.* 2009; 364:2115–26. https://doi.org/10.1098/rstb.2008.0311
13. Geyer R, Jambeck JR, Law KL: Production, use, and fate of all plastics ever made. *Sci Adv.* 2017;3:e1700782. https://doi.org/10.1126/sciadv.1700782
14. Rochester JR: Bisphenol A and human health: a review of the literature. *Reprod Toxicol*. 2013;42:132–55. https://doi.org/10.1016/j.reprotox.2013.08.008
15. European Commission: A European Strategy for Plastics in a Circular Economy. 2018. Available from: https://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf

Cite this article: Manchanda Y, Singla L, Singla D, Singh H, Kaur A. Sustainable orthodontics: Aligners, environmental contamination and the green responsibility ahead. *JAOH*. 2026;3(1):3-8.