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ORTHODONTIC CLEAR ALIGNERS AS A POTENTIAL SOURCE OF MICROPLASTIC EXPOSURE: IMPLICATIONS FOR HUMAN HEALTH AND ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

The widespread adoption of clear aligners has transformed contemporary orthodontic practice by providing an aesthetic and comfortable alternative to conventional fixed appliances. These appliances are primarily manufactured from thermoplastic polymers such as polyethylene terephthalate glycol (PETG), polyurethane, and polycarbonate. Although aligner therapy offers numerous clinical advantages, increasing attention has been directed toward the potential release of microplastics resulting from the mechanical and chemical degradation of these materials in the oral environment. Microplastics, defined as plastic particles smaller than 5 mm, have recently been detected in various human tissues and environmental systems, raising concerns regarding their potential biological and ecological impact.

This narrative review aims to summarize current scientific evidence regarding microplastic release from orthodontic clear aligners and to discuss its potential implications for human health and environmental sustainability. A literature search was conducted using the PubMed database to identify English-language publications published between 2020 and 2026. Studies addressing aligner materials, polymer degradation mechanisms, experimental evidence of microplastic release, and the biological or environmental effects of microplastic exposure were included.

Available studies indicate that orthodontic aligners may release micro- and nanoplastic particles due to mechanical wear, cyclic loading, and chemical interactions with saliva. Additionally, the increasing global use and disposal of thermoplastic aligners may contribute to environmental plastic pollution. Further interdisciplinary research is required to clarify the clinical significance of these findings and to support the development of safer and more sustainable orthodontic materials.

KEYWORDS

Clear Aligners; Microplastics; Orthodontic Materials; Polymer Degradation; Oral Health; Environmental Sustainability

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Introduction

Clear aligner therapy has become an increasingly important component of contemporary orthodontic treatment. Over the last two decades, clear aligners have gained popularity among both clinicians and patients because they offer an aesthetic, removable, and relatively comfortable alternative to conventional fixed appliances (Panayi et al., 2024; De Stefano et al., 2025; Eliades & Eliades, 2024). Their widespread adoption has been further supported by advances in digital orthodontics, including three-dimensional scanning, virtual treatment planning, and computer-aided design and manufacturing technologies (Panayi et al., 2024; Eliades & Eliades, 2024). As a result, clear aligners are now used in an expanding range of clinical situations, from mild tooth movement to more complex orthodontic corrections, and their use continues to grow globally (De Stefano et al., 2025; Delgado et al., 2025).

The clinical attractiveness of clear aligners is closely related to the properties of the materials from which they are produced. Most aligners are manufactured from transparent thermoplastic polymers, including polyethylene terephthalate glycol (PETG), polyurethane (PU), polycarbonate, or multilayer combinations of these materials (Daniele et al., 2021; Delgado et al., 2025; Eliades & Eliades, 2024). These polymers are expected to combine transparency, flexibility, dimensional stability, and mechanical resistance while maintaining biocompatibility during prolonged contact with the oral environment (Delgado et al., 2025; Pozzan et al., 2025). However, the performance of these materials is not static. Their mechanical, optical, and surface properties may change during clinical use as a result of thermal fluctuations, salivary exposure, masticatory stress, repeated insertion and removal, and cleaning procedures (Lombardo et al., 2017b; Daniele et al., 2021; Delgado et al., 2025; Pozzan et al., 2025). From a materials science perspective, clear aligners therefore represent not only orthodontic devices but also polymer-based systems subjected to continuous physical and chemical challenges intraorally (Eliades & Eliades, 2024; Delgado et al., 2025).

Interest in the behavior of thermoplastic orthodontic materials has grown substantially in recent years. Previous studies have examined stress relaxation, force decay, surface roughness, optical stability, structural aging, and other physicochemical characteristics of aligner materials, demonstrating that intraoral service conditions can affect their integrity and performance (Lombardo et al., 2017b; Daniele et al., 2021; Pozzan et al., 2025). These changes are clinically relevant because the efficacy of aligner therapy depends on predictable force delivery and material stability (Lombardo et al., 2017b; Pozzan et al., 2025). In addition, retrospective clinical data suggest that the predictability of tooth movement with aligners is not uniform across movement types, further underscoring the importance of appliance design and material performance in clinical outcomes (Lombardo et al., 2017a). At the same time, material degradation may also raise broader biological and environmental concerns. In particular, increasing attention has been directed toward the possibility that degradation of aligner polymers may lead to the release of microplastic and nanoplastic particles (Quinzi et al., 2023; Panayi et al., 2024; De Stefano et al., 2025).

Microplastics are commonly defined as plastic particles smaller than 5 mm, while nanoplastics are generally described as particles in the nanometer range produced either through primary manufacturing processes or through the degradation of larger plastic items (Campanale et al., 2020; Galloway, 2015; Yong et al., 2020). In recent years, microplastics have emerged as a major topic in environmental and biomedical research because they have been documented in environmental compartments relevant to human exposure, including freshwaters, drinking water, food-related pathways, and human tissues and fluids (Prata et al., 2020; Koelmans et al., 2019; Feng et al., 2023). Human exposure may occur through ingestion, inhalation, and dermal contact, and there is growing concern regarding the potential toxicological effects of these particles, including oxidative stress, inflammatory responses, altered barrier integrity, cellular uptake, and tissue accumulation (Campanale et al., 2020; Yong et al., 2020; Wright & Kelly, 2017; Feng et al., 2023). Evidence of plastic particles in human placenta, blood, and lung tissue has further intensified concern about the long-term implications of chronic microplastic exposure (Ragusa et al., 2021; Leslie et al., 2022; Jenner et al., 2022).

Although microplastics have been studied extensively in environmental science, their relevance to dentistry and orthodontics has only recently begun to attract focused attention. Dental practice involves the widespread use of synthetic polymers in restorative materials, impression materials, resin-based appliances, and orthodontic devices. Consequently, dentistry may represent both a source of plastic waste and a setting in which patients are repeatedly exposed to polymer-based materials (Šimunović et al., 2025; Shariff et al., 2025; Shinkai et al., 2025). Recent reviews have highlighted that micro- and nanoplastics in dentistry remain insufficiently investigated and that obtaining high-quality evidence in this field is challenging due to methodological heterogeneity and the novelty of the subject (Šimunović et al., 2025; Shariff et al., 2025). Nevertheless, the issue is increasingly recognized as important not only from a materials and toxicological perspective, but also from the standpoint of environmental sustainability in oral healthcare (Šimunović et al., 2025; Shinkai et al., 2025).

Within orthodontics, clear aligners are particularly relevant to this discussion because they are replaced frequently throughout treatment, sometimes on a weekly or biweekly basis, generating repeated cycles of material use and disposal (Panayi et al., 2024; De Stefano et al., 2025). From a clinical viewpoint, these devices remain in prolonged contact with saliva, dental biofilm, beverages, and mechanical forces in the oral cavity (Daniele et al., 2021; Pozzan et al., 2025). From an environmental viewpoint, their large-scale manufacture and disposal contribute to the broader burden of plastic consumption associated with healthcare and dentistry (Panayi et al., 2024; Shinkai et al., 2025). This dual relevance makes aligners a useful model for considering both patient-related and ecological consequences of polymer degradation in dental medicine.

The first direct evidence suggesting that orthodontic aligners may release microplastic particles under simulated oral conditions was provided by Quinzi et al. (2023), who reported secondary microplastic detachment after seven days of exposure to artificial saliva. More recently, Barile et al. (2025) demonstrated structural damage and microplastic release during cyclic loading of clear aligners, reinforcing concerns that routine clinical use may promote particle generation. In addition, emerging biological evidence suggests that orthodontic-derived microplastics may not be biologically inert. Warunek et al. (2026) reported that such particles can affect macrophage differentiation and homeostasis, pointing to a possible inflammatory or immunological relevance. At the same time, broader review articles in orthodontics have emphasized that the modernization of treatment through polymer-based appliances may carry unintended consequences related to microplastic exposure and environmental waste (Panayi et al., 2024; De Stefano et al., 2025; Shariff et al., 2025).

Despite the growing relevance of this topic, the available literature remains fragmented. Some studies focus on the physicochemical properties of aligner materials, others examine mechanical degradation, and only a small number directly assess microplastic release or biological effects (Quinzi et al., 2023; Barile et al., 2025; Warunek et al., 2026). Moreover, the clinical significance of aligner-derived microplastics has not yet been clearly established (De Stefano et al., 2025; Shariff et al., 2025). It remains uncertain how much particle release occurs in vivo, what proportion of particles may be ingested or retained, whether these particles exert measurable local or systemic effects, and how aligner-related waste should be considered within the broader discussion of sustainable dentistry (Panayi et al., 2024; De Stefano et al., 2025; Shinkai et al., 2025). These unresolved questions highlight an important gap between rapidly expanding clinical use of aligners and the still limited evidence regarding their long-term biological and environmental footprint.

For these reasons, a focused narrative review is justified. The present review aims to summarize current evidence concerning microplastic release from orthodontic clear aligners, with particular attention to material composition, degradation mechanisms, and available experimental data. In addition, it seeks to discuss the possible implications of aligner-derived microplastics for human health and environmental sustainability. By integrating evidence from orthodontics, dental materials science, toxicology, and environmental research, this review aims to provide a clinically relevant overview of an emerging issue that is likely to become increasingly important in future orthodontic practice.

Methodology

This study was designed as a narrative review aimed at summarizing current evidence on microplastic release from orthodontic clear aligners and its possible implications for human health and the environment. The review focused primarily on publications related to clear aligners and thermoplastic orthodontic materials, while also including selected studies on the broader biological and environmental effects of microplastics in order to provide an appropriate scientific context for discussion.

A structured literature search was conducted using the PubMed database as the primary source of scientific literature. The search was limited to English-language publications published between 2020 and 2026 and available in full-text open-access form whenever possible. In addition, a limited number of pre-2020 background studies were included when considered essential for conceptual, methodological, or contextual support. Additional hand-searching of reference lists from relevant articles was performed to identify further studies of direct relevance to the topic. This approach was chosen because the field of microplastic release from orthodontic aligners is relatively new and still limited in the number of directly focused studies.

The search strategy combined terms related to orthodontic aligners, thermoplastic materials, microplastics, nanoplastics, polymer degradation, oral exposure, human health, and environmental impact. The main keywords and combinations included "clear aligner," "orthodontic aligner," "thermoplastic aligner," "microplastic," "nanoplastic," "polymer degradation," "orthodontic materials," "oral health," and "environmental sustainability."

The inclusion criteria comprised original research articles, experimental laboratory studies, review articles, and selected broader publications relevant to the toxicological and environmental aspects of microplastics. Studies were included if they addressed at least one of the following areas: (1) material composition and physicochemical properties of clear aligners, (2) degradation or aging of thermoplastic orthodontic materials, (3) direct or indirect evidence of microplastic or nanoplastic release from aligners or related dental materials, (4) biological effects of microplastic exposure relevant to oral or systemic health, and (5) environmental consequences associated with plastic waste generated by dental or medical materials. Because the number of publications dealing specifically with aligner-derived microplastics remains limited, selected high-quality contextual studies on general microplastic exposure in humans and ecosystems were also included to support the interpretation of the findings.

The exclusion criteria included studies not published in English, articles outside the selected publication period unless considered exceptionally relevant as background literature, conference abstracts without sufficient methodological detail, duplicate publications, and studies unrelated to orthodontic aligners, dental polymers, or the health and environmental implications of microplastic exposure. Publications focused exclusively on unrelated dental specialties or on materials without relevance to polymer-based orthodontic appliances were also excluded.

The selection process involved an initial screening of titles and abstracts, followed by full-text assessment of studies considered potentially relevant. Particular attention was given to the extent to which each article contributed meaningful evidence to the central research question of this review, namely whether clear aligners may represent a source of microplastic exposure and how such exposure may be interpreted from clinical and environmental perspectives. After thematic screening and qualitative evaluation, the selected body of literature was established as the core evidence base for the present review.

Organized search strategy and transparent selection criteria were applied in order to ensure scientific relevance, thematic consistency, and practical usefulness of the reviewed literature.

Results

3.1. Clear aligner materials and their physicochemical properties

The selected body of literature indicates that contemporary clear aligners are predominantly manufactured from transparent thermoplastic polymers, most commonly polyethylene terephthalate glycol (PETG), polyurethane (PU), and multilayer polymer systems designed to optimize mechanical performance, transparency, and patient comfort (Daniele et al., 2021; Delgado et al., 2025; Eliades & Eliades, 2024). These materials are expected to provide sufficient elasticity, dimensional stability, optical clarity, and biocompatibility while maintaining orthodontically effective force delivery over the prescribed period of use (Delgado et al., 2025; Pozzan et al., 2025). However, the reviewed studies consistently show that these properties are dynamic rather than static and may be altered during intraoral service (Lombardo et al., 2017b; Daniele et al., 2021; Pozzan et al., 2025).

Earlier work on aligner materials demonstrated that thermoplastic polymers exhibit time-dependent mechanical behavior, including stress relaxation and force decay, which may affect force delivery during aligner use (Lombardo et al., 2017b). More recent investigations have expanded this perspective by emphasizing that the physicochemical characteristics of aligner materials are closely linked to their clinical durability and susceptibility to degradation (Delgado et al., 2025; Eliades & Eliades, 2024). Reviews of thermoplastics used in clear aligner therapy have highlighted the diversity of materials currently employed and the lack of complete standardization across products, with important differences in thickness, polymer composition, multilayer structure, and manufacturing method (Delgado et al., 2025). Similarly, new three-dimensional experimental models have confirmed that different aligner materials exhibit distinct mechanical profiles, suggesting that polymer choice may directly influence resistance to deformation and surface damage during use (Pozzan et al., 2025).

Optical and surface-related characteristics also appear to be clinically relevant. Daniele et al. (2021) showed that commonly used PETG- and PU-based aligners differ in color stability as well as chemico-physical and optical properties. These findings are important because alterations in transparency, surface roughness, and structural integrity may reflect underlying material aging (Daniele et al., 2021; Eliades & Eliades, 2024). From a broader materials science perspective, current orthodontic polymers must therefore be viewed as multifunctional systems that operate under repeated thermal, chemical, and mechanical challenges in the oral cavity rather than as inert appliances (Eliades & Eliades, 2024; Delgado et al., 2025).

Taken together, the reviewed literature suggests that clear aligner materials are vulnerable to progressive changes during treatment (Lombardo et al., 2017b; Daniele et al., 2021; Pozzan et al., 2025). Although these changes are often discussed primarily in relation to force delivery or esthetics, they also form the basis for considering whether intraoral degradation may contribute to the generation of microplastic and nanoplastic particles (Quinzi et al., 2023; Panayi et al., 2024; De Stefano et al., 2025).

3.2. Mechanisms of material degradation and potential particle release

The reviewed studies indicate that degradation of clear aligner materials is likely to be multifactorial (Delgado et al., 2025; Eliades & Eliades, 2024). Several interacting conditions within the oral cavity may contribute to changes in polymer structure, including temperature fluctuations, salivary exposure, cyclic mechanical loading, repeated insertion and removal, biofilm accumulation, and cleaning procedures (Daniele et al., 2021; Delgado et al., 2025; Barile et al., 2025). These mechanisms may act independently or synergistically, progressively affecting the surface and internal structure of aligner polymers (Eliades & Eliades, 2024; Shariff et al., 2025).

Saliva represents one of the most relevant chemical factors, as aligners remain in prolonged contact with a humid environment containing electrolytes, proteins, enzymes, and microbial metabolites. Under these conditions, water absorption, hydrolytic changes, and polymer softening may occur, depending on the material composition (Quinzi et al., 2023; Delgado et al., 2025). Mechanical stress is also significant because aligners are subjected to repeated loading during mastication, speech, swallowing, and insertion-removal cycles. Over time, such repetitive forces may induce local deformation, surface abrasion, microcrack formation, and material fatigue (Lombardo et al., 2017b; Pozzan et al., 2025; Barile et al., 2025).

The literature further suggests that oral contamination and biofilm-related surface changes may be relevant to material aging processes in aligners. Because aligners are repeatedly exposed to oral microorganisms and saliva, their surfaces may undergo biological and physicochemical alterations at the material-environment interface. Although the currently available review literature does not provide direct evidence that biofilm alone drives microplastic release, it supports the broader interpretation that intraoral exposure conditions may contribute to cumulative surface changes over time (Shariff et al., 2025; De Stefano et al., 2025).

Cleaning regimens may represent an additional source of mechanical and chemical stress. Daily hygiene recommendations for aligners often involve brushing, rinsing, soaking in cleaning agents, or other routine maintenance procedures. Although these practices are intended to preserve appliance cleanliness and transparency, they may also affect surface stability depending on the chemical composition of the aligner and the type of cleanser used (Daniele et al., 2021; Delgado et al., 2025). Overall, the reviewed evidence supports the interpretation that clear aligner degradation is not attributable to a single factor, but rather to the cumulative effect of multiple oral and behavioral stressors acting on thermoplastic materials over time (Eliades & Eliades, 2024; Barile et al., 2025).

3.3. Direct evidence of microplastic release from clear aligners

Among the reviewed studies, the most direct evidence of microplastic release from clear aligners was provided by Quinzi et al. (2023), who reported secondary microplastic detachment after exposing orthodontic aligners to artificial saliva for seven days. This study is particularly important because it moved the discussion beyond theoretical concerns and provided experimental proof that aligner materials can release particles under simulated oral conditions (Quinzi et al., 2023). The findings suggest that even short-term exposure may be sufficient to induce measurable particle detachment, thereby supporting the hypothesis that aligners may act as a direct source of microplastic exposure (Quinzi et al., 2023; Panayi et al., 2024; De Stefano et al., 2025).

Further support for this concern was provided by Barile et al. (2025), who experimentally assessed material damage and microplastic release during cyclic loading of clear aligners. Their results showed that repeated mechanical stress can induce structural damage and promote particle release, reinforcing the notion that clinically relevant loading conditions may contribute to polymer fragmentation (Barile et al., 2025). Taken together, the findings of Quinzi et al. (2023) and Barile et al. (2025) form the strongest direct evidence currently available for aligner-derived microplastic generation.

In addition to these direct studies, indirect support comes from investigations of material aging, surface alterations, and mechanical deterioration in aligner polymers. Research on stress relaxation, physicochemical aging, and surface stability has consistently shown that aligner materials undergo measurable changes during service, even if microplastic particles were not the primary outcome in those studies (Lombardo et al., 2017b; Daniele et al., 2021; Pozzan et al., 2025). These observations strengthen the plausibility of particle generation because polymer degradation, crack formation, and surface wear are recognized pathways through which larger materials may produce smaller fragments (Delgado et al., 2025; Eliades & Eliades, 2024).

At the same time, the literature remains limited in several important respects. Only a small number of studies have directly measured particle release, and the reported evidence is largely based on in vitro or simulated conditions (Quinzi et al., 2023; Barile et al., 2025; De Stefano et al., 2025). There is still insufficient information regarding particle size distribution under real intraoral conditions, the total quantity of particles released during a complete course of treatment, inter-brand variability, and the possible generation of nanoplastics below the detection thresholds of some analytical methods (Panayi et al., 2024; De Stefano et al., 2025; Shariff et al., 2025). Therefore, while the currently available evidence supports the existence of aligner-derived particle release, the magnitude and clinical relevance of this phenomenon remain incompletely defined.

3.4. Biological relevance of aligner-derived microplastics

The selected literature suggests that the biological implications of microplastic exposure should not be dismissed as purely theoretical. Although evidence specifically addressing the in vivo effects of clear aligner-derived microplastics remains scarce, broader research on microplastics in mammalian systems indicates several mechanisms through which these particles may exert biological effects. These include oxidative stress, inflammatory signaling, cellular uptake, barrier penetration, and interactions with immune cells (Campanale et al., 2020; Yong et al., 2020; Wright & Kelly, 2017; Galloway, 2015).

One of the most relevant findings within the orthodontic field was reported by Warunek et al. (2026), who showed that orthodontic-derived microplastics can affect macrophage differentiation and homeostasis. This observation is significant because macrophages play a central role in inflammation, immune surveillance, and tissue response to foreign materials. The study suggests that aligner-derived particles may not be biologically inert and that they may have the capacity to modulate immune behavior under experimental conditions (Warunek et al., 2026). Although this evidence does not by itself establish a clinically significant health risk, it provides an important mechanistic signal warranting further investigation (De Stefano et al., 2025; Shariff et al., 2025).

The broader biomedical literature also reinforces concern about chronic microplastic exposure. Plastic particles have been identified in human placenta, blood, and lung tissue, demonstrating that environmental microplastics can enter the human body and may reach systemic compartments (Ragusa et al., 2021; Leslie et al., 2022; Jenner et al., 2022). These findings do not directly prove that orthodontic aligners contribute substantially to the total exposure burden, but they create a biologically plausible context in which even small additional sources of repeated exposure may deserve attention (Campanale et al., 2020; Yong et al., 2020; Galloway, 2015).

From a dental perspective, the oral cavity represents a particularly relevant exposure route because aligners are worn for prolonged periods and remain in close contact with saliva, mucosa, and teeth (Daniele et al., 2021; Quinzi et al., 2023). Any particles released from the material may potentially be swallowed, retained transiently in the oral environment, or transported further into the gastrointestinal tract (Panayi et al., 2024; De Stefano et al., 2025). However, the current literature does not provide sufficient clinical evidence to determine actual exposure doses, accumulation patterns, or long-term health consequences associated specifically with aligner therapy. Thus, the results currently support caution and further research rather than definitive clinical conclusions (De Stefano et al., 2025; Shariff et al., 2025).

3.5. Microplastics in dentistry and the relevance of aligners

A recurring theme across the selected literature is that dentistry has only recently begun to address microplastics and nanoplastics as a meaningful scientific and clinical issue (Šimunović et al., 2025; Shariff et al., 2025). Reviews focused on dentistry have emphasized the methodological difficulty of studying these particles, including challenges related to contamination control, particle detection, polymer identification, and the heterogeneity of dental materials (Šimunović et al., 2025). At the same time, dentistry uses a wide range of synthetic polymers, suggesting that dental materials may represent an underrecognized source of both patient exposure and plastic waste (Shariff et al., 2025; Shinkai et al., 2025).

Within this context, clear aligners occupy a particularly important position. Unlike many other dental materials, they are used continuously for extended periods, replaced repeatedly during treatment, and discarded in high numbers (Panayi et al., 2024; De Stefano et al., 2025). Their removable nature also increases the frequency of handling, cleaning, and environmental exposure outside the oral cavity (Delgado et al., 2025; Shariff et al., 2025). This combination of prolonged wear, repeated replacement, and mass disposal distinguishes aligners from many conventional orthodontic materials and strengthens their relevance within the emerging discussion on microplastics in dentistry (Panayi et al., 2024; Šimunović et al., 2025; Shariff et al., 2025).

Recent orthodontic reviews have increasingly acknowledged this issue. Panayi et al. (2024) argued that the modernization of orthodontic treatment through polymer-based appliances may carry unintended consequences related to microplastic generation and chemical exposure. De Stefano et al. (2025) similarly concluded that the available evidence raises legitimate concern regarding microplastic release from clear aligners, while also noting that the present evidence base remains limited and heterogeneous. Overall, the selected body of literature suggests that clear aligners should now be considered not only as orthodontic devices but also as polymeric materials of toxicological and environmental relevance (Panayi et al., 2024; Shariff et al., 2025; De Stefano et al., 2025).

3.6. Environmental implications of clear aligner use

The reviewed literature indicates that the issue of clear aligners extends beyond potential patient exposure and also includes an environmental dimension. The global increase in plastic production and the insufficient capacity of current mitigation strategies have made plastic pollution a major public health and ecological concern (Borrelle et al., 2020; Koelmans et al., 2019). In this broader context, healthcare-related plastics are increasingly scrutinized, including those used in dentistry (Shinkai et al., 2025).

Although aligners represent only one component of healthcare plastic waste, their treatment model is inherently consumption-intensive. Multiple appliances are manufactured for each patient, often used for short intervals, and then discarded. This repeated replacement pattern creates cumulative waste over the course of treatment (Panayi et al., 2024; De Stefano et al., 2025). If discarded without appropriate waste management or recycling pathways, aligners may contribute to the overall burden of persistent polymer waste (Borrelle et al., 2020; Koelmans et al., 2019). Reviews on environmental sustainability in dentistry have emphasized the need to consider the life cycle of dental materials, including production, use, disposal, and the ecological consequences of polymer-based devices (Shinkai et al., 2025).

The environmental concern is therefore twofold. First, discarded aligners contribute directly to plastic waste. Second, material degradation during use may generate microplastic particles before disposal, raising the possibility of both clinical and ecological dissemination (Quinzi et al., 2023; Barile et al., 2025; Panayi et al., 2024). While the precise environmental footprint of clear aligner therapy has not yet been fully quantified, the selected studies support the conclusion that aligners should be included in broader discussions of sustainable dentistry, responsible material development, and environmentally conscious orthodontic practice (Shinkai et al., 2025; Shariff et al., 2025).

3.7. Overall synthesis of the reviewed evidence

Overall, the selected literature shows a converging pattern rather than isolated observations. First, clear aligners are made of thermoplastic polymers that are susceptible to physicochemical and mechanical change during intraoral use (Lombardo et al., 2017b; Daniele et al., 2021; Delgado et al., 2025; Pozzan et al., 2025). Second, experimental evidence now indicates that these changes can be accompanied by direct release of microplastic particles under simulated oral and loading conditions (Quinzi et al., 2023; Barile et al., 2025). Third, broader toxicological research suggests that microplastics may exert biologically relevant effects, including inflammatory and immunological responses (Campanale et al., 2020; Yong et al., 2020; Wright & Kelly, 2017). Fourth, the repeated use and disposal of aligners introduce a meaningful environmental dimension to their clinical application (Panayi et al., 2024; Shinkai et al., 2025).

At the same time, the literature remains limited by the small number of directly focused studies, methodological heterogeneity, and insufficient in vivo data (De Stefano et al., 2025; Shariff et al., 2025). The results therefore support recognition of clear aligners as a plausible source of microplastic exposure and plastic waste, while also underscoring the need for further standardized experimental and clinical research.

Discussion

The findings reviewed in this paper suggest that orthodontic clear aligners should no longer be considered exclusively from a biomechanical and esthetic perspective. Instead, they should also be viewed as polymer-based medical devices with potential toxicological and environmental relevance. The currently available literature indicates that thermoplastic aligner materials undergo measurable physicochemical and mechanical changes during use and that, under simulated oral conditions, these changes may result in the release of microplastic particles (Quinzi et al., 2023; Barile et al., 2025). Although the available evidence is still limited, these observations are sufficient to justify closer scientific and clinical attention to the issue.

One of the main implications of the reviewed evidence is that the traditional perception of clear aligners as relatively inert appliances may be incomplete. Orthodontic treatment with aligners depends on continuous contact between thermoplastic materials and the oral environment, where they are exposed to saliva, temperature variation, biofilm accumulation, mechanical stress, and repeated cleaning procedures (Daniele et al., 2021; Delgado et al., 2025; Pozzan et al., 2025). From a materials science standpoint, such exposure makes some degree of surface aging or structural alteration unsurprising. What is more important, however, is that recent studies now suggest that these alterations may extend beyond clinically visible wear and may include the generation of microplastic particles (Quinzi et al., 2023; Barile et al., 2025). This shifts the discussion from material performance alone to the broader question of patient exposure.

At present, the direct clinical significance of aligner-derived microplastics remains uncertain. The available in vitro and simulated studies demonstrate the plausibility of particle release, but they do not yet define the actual burden of exposure in vivo. It remains unclear how many particles are released during routine treatment, whether release differs substantially between brands or material classes, what fraction of the released material is swallowed or retained in the oral cavity, and whether chronic low-level exposure during orthodontic treatment produces measurable biological effects. These questions are especially relevant because aligner therapy typically involves repeated replacement of appliances over many weeks or months, meaning that even a small amount of particle release per aligner could theoretically become cumulative over time (Panayi et al., 2024; De Stefano et al., 2025).

Importantly, concerns regarding aligner-derived microplastics should be interpreted against the background of a growing body of evidence showing that microplastics are biologically active and may be relevant to human disease. Microplastics are no longer regarded solely as environmental pollutants; they are now recognized as particles capable of entering human tissues and interacting with biological systems. Their presence has already been documented in human placenta, blood, and lung tissue (Ragusa et al., 2021; Leslie et al., 2022; Jenner et al., 2022), and broader review-level evidence indicates that micro- and nanoplastics are increasingly being identified in human tissues and fluids, while laboratory studies using animal models and human-derived cell systems consistently suggest adverse biological effects (Feng et al., 2023).

The health implications of this exposure are increasingly difficult to dismiss as hypothetical. A systematic review of preclinical evidence found that microplastics may act as triggers of intestinal dysbiosis, increase intestinal permeability, and enhance the expression of inflammatory mediators such as IL-1α, IL-1β, TNF-α, IFN-γ, and IL-6 (Souza-Silva et al., 2022). These findings are highly relevant in the context of clear aligners because any particles released intraorally are likely to be swallowed and enter the gastrointestinal tract. Additional review evidence suggests that nano- and microplastics may contribute to respiratory disorders, disturbances of gut microbiota, inflammatory bowel disease, apoptosis, and genotoxic or cytotoxic effects, depending on exposure conditions and particle characteristics (Winiarska et al., 2024).

A particularly important example of documented clinical relevance comes from the observational study by Marfella et al. (2024), in which micro- and nanoplastics were detected in carotid atheromatous plaques. Polyethylene was identified in 58.4% of patients and polyvinyl chloride in 12.1%, and the presence of micro- and nanoplastics within the plaque was associated with a higher risk of myocardial infarction, stroke, or death during follow-up (hazard ratio, 4.53; 95% confidence interval, 2.00-10.27). Although this study does not concern orthodontic materials specifically, it provides strong evidence that microplastic accumulation in human tissues may correlate with clinically meaningful adverse outcomes.

In this context, the work of Warunek et al. (2026) is particularly significant for orthodontics because it brings the broader toxicological concern into direct relation with dental materials. Their findings showed that orthodontic-derived microplastics may affect macrophage differentiation and homeostasis, suggesting a capacity to alter immune behavior and potentially contribute to pro-inflammatory responses. This is a notable observation because macrophages are central regulators of inflammation and tissue reaction to foreign materials. Therefore, even though direct clinical harm from aligner-derived particles has not yet been demonstrated in patients, the available mechanistic evidence supports the view that such particles deserve serious biological consideration rather than dismissal.

From a clinical orthodontic perspective, this issue should still be interpreted with balance. The current evidence does not support alarmist conclusions or justify discouraging the use of clear aligners as a treatment modality. Clear aligner therapy remains an effective and widely accepted orthodontic option with substantial benefits in esthetics, comfort, and oral hygiene management. However, the literature does support a precautionary interpretation. Clinicians should be aware that material selection, wear time, cleaning regimens, and replacement schedules may all influence the stability of aligner polymers and potentially their degradation behavior. While definitive chairside recommendations cannot yet be derived from the evidence, the topic highlights the importance of material quality, patient compliance, and the need for scientifically validated maintenance protocols rather than empiric or overly aggressive cleaning practices (Daniele et al., 2021; Delgado et al., 2025; De Stefano et al., 2025).

Another important point emerging from this review is the methodological immaturity of the field. Studies on aligner-derived microplastics differ substantially in design, analytical methods, exposure models, and outcome reporting, making direct comparison difficult. Some papers focus on material properties, others on damage patterns, and only a few directly quantify particle release (Quinzi et al., 2023; Barile et al., 2025). In dentistry more broadly, authors have emphasized the difficulty of obtaining high-quality evidence on micro- and nanoplastics because of contamination risk, inconsistent analytical techniques, and challenges in distinguishing true particle release from laboratory artifacts (Šimunović et al., 2025; Shariff et al., 2025). These limitations should temper interpretation of the current literature. The field is evolving, but it has not yet reached a level of methodological standardization sufficient for strong quantitative conclusions.

This methodological heterogeneity also affects the biological interpretation of the findings. Most of the available data come from in vitro experiments or simulated conditions that cannot fully reproduce the complexity of the oral cavity. In vivo exposure depends on numerous patient-related variables, including salivary composition, occlusal loading, parafunctional habits, dietary behavior, beverage consumption, oral hygiene routines, and duration of aligner wear. In addition, the clinical relevance of particle size remains uncertain, especially with regard to nanoplastics, which may be more biologically reactive yet more difficult to detect. As a result, the present evidence should be viewed as hypothesis-generating rather than definitive. It identifies a credible concern and establishes a research agenda, but it does not yet allow precise risk estimation.

The environmental dimension of aligner therapy deserves equal attention. Orthodontic clear aligners are often promoted as modern, patient-friendly, and technologically advanced appliances, but their life cycle is inherently material-intensive. A single course of treatment may require a large number of individually manufactured plastic appliances, each used for a relatively short period before disposal. In the context of the broader plastic pollution crisis, such repeated production and disposal cannot be regarded as environmentally neutral (Borrelle et al., 2020; Koelmans et al., 2019). Reviews in dental sustainability have increasingly emphasized that oral healthcare must also be evaluated through the lens of environmental responsibility, including the sourcing, use, and disposal of polymer-based materials (Shinkai et al., 2025).

This does not mean that clear aligners are uniquely problematic compared with all other orthodontic appliances, but their treatment model makes them particularly visible in discussions of sustainability. Their removable design, serial replacement, packaging demands, and disposal pathway all contribute to their ecological footprint. Moreover, if particle release occurs during use, aligners may contribute not only to macro-scale plastic waste but also to micro-scale dissemination of polymer fragments. In this regard, the concerns raised by Panayi et al. (2024) are especially relevant: the modernization of orthodontics through plastics and polymers may offer clinical benefits while also creating new environmental and toxicological questions that were previously underappreciated.

The implications of this review therefore extend in several directions. For researchers, the priority should be the development of standardized experimental protocols for assessing aligner degradation and particle release, including improved methods for quantifying both microplastics and nanoplastics under clinically relevant conditions. Comparative research across materials and manufacturers is also needed, as current evidence suggests that not all thermoplastics behave identically (Daniele et al., 2021; Pozzan et al., 2025). For clinicians, the current data underline the importance of remaining informed about the material properties of aligners and adopting evidence-based guidance regarding their use and maintenance. For manufacturers, the emerging literature creates pressure to invest in safer, more stable, and more sustainable polymers, as well as in more environmentally responsible production and disposal strategies.

This review also highlights the need for greater integration between orthodontics and adjacent scientific fields. Questions concerning aligner-derived microplastics cannot be answered by orthodontic biomechanics alone. They require collaboration with materials science, analytical chemistry, toxicology, environmental health, and sustainability research. Such interdisciplinary work is essential if future studies are to move beyond proof-of-concept observations toward clinically meaningful risk assessment and practical preventive strategies.

Overall, the present evidence suggests that clear aligners may represent a small but scientifically credible source of microplastic exposure and plastic waste. The significance of this source remains to be fully determined, but it is no longer reasonable to ignore the issue. The literature now supports a balanced position: clear aligners remain a valuable orthodontic tool, yet their widespread use should prompt continued investigation into their biological safety and environmental footprint. In this sense, the topic reflects a broader transition in dentistry, where the success of a material or treatment modality can no longer be judged solely by clinical performance, but must also take into account long-term health considerations and sustainability.

Conclusions

Clear aligner therapy represents a major advancement in contemporary orthodontics, offering clear clinical benefits in terms of esthetics, comfort, and treatment acceptability. However, the findings reviewed in this paper indicate that clear aligners should not be regarded solely as efficient orthodontic appliances, but also as polymer-based materials with potential biological and environmental implications. The available evidence suggests that thermoplastic aligner materials may undergo physicochemical and mechanical degradation during use, and that this process can lead to the release of microplastic particles under simulated oral conditions.

Although direct evidence of clinically significant harm from aligner-derived microplastics in humans is still lacking, the broader literature on microplastics provides sufficient reason for concern. Microplastics have already been detected in human tissues and fluids, and experimental studies have demonstrated their potential to induce inflammatory, oxidative, cytotoxic, and immunological effects. In this context, recent evidence showing that orthodontic-derived microplastics may influence macrophage behavior further supports the need for careful investigation of their possible biological relevance in orthodontic patients.

At the same time, clear aligners also raise important environmental questions. Their serial replacement throughout treatment contributes to the growing burden of plastic consumption and disposal in healthcare. Therefore, the issue of aligner-derived microplastics should be understood not only as a matter of potential patient exposure, but also as part of the broader challenge of sustainability in modern dental practice.

Overall, the current evidence supports a balanced but precautionary interpretation. Clear aligners remain a valuable and effective treatment option, yet their widespread use justifies closer attention to material degradation, particle release, long-term biological safety, and environmental impact. Future research should focus on standardized methods for detecting micro- and nanoplastic release under clinically relevant conditions, comparative evaluation of different aligner materials, and the development of safer and more sustainable orthodontic polymers. A deeper understanding of these issues will be essential for ensuring that future orthodontic innovations remain not only clinically effective, but also biologically responsible and environmentally conscious.

REFERENCES

1. Barile, C., Cianci, C., Kannan, V. P., Pappalettera, G., Pappalettere, C., Casavola, C., Laurenziello, M., & Ciavarella, D. (2025). Experimental assessment of damage and microplastic release during cyclic loading of clear aligners. *PLOS ONE, 20*(2), Article e0318207. https://doi.org/10.1371/journal.pone.0318207
2. Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G. H., Hilleary, M. A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L. R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., & Rochman, C. M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science, 369*(6510), 1515–1518. https://doi.org/10.1126/science.aba3656
3. Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Uricchio, V. F. (2020). A detailed review study on potential effects of microplastics and additives of concern on human health. *International Journal of Environmental Research and Public Health, 17*(4), Article 1212. https://doi.org/10.3390/ijerph17041212
4. Cox, K. D., Covernton, G. A., Davies, H. L., Dower, J. F., Juanes, F., & Dudas, S. E. (2019). Human consumption of microplastics. *Environmental Science & Technology, 53*(12), 7068–7074. https://doi.org/10.1021/acs.est.9b01517
5. Daniele, V., Macera, L., Taglieri, G., Spera, L., Marzo, G., & Quinzi, V. (2021). Color stability, chemico-physical and optical features of the most common PETG and PU based orthodontic aligners for clear aligner therapy. *Polymers, 14*(1), Article 14. https://doi.org/10.3390/polym14010014
6. De Stefano, A. A., Horodynski, M., & Galluccio, G. (2025). Can clear aligners release microplastics that impact the patient's overall health? A systematic review. *Materials, 18*(11), Article 2564. https://doi.org/10.3390/ma18112564
7. Delgado, J. I., Kehyaian, P., & Fernández-Blázquez, J. P. (2025). Thermoplastics for clear aligners: A review. *Polymers, 17*(12), Article 1681. https://doi.org/10.3390/polym17121681
8. Eliades, T., & Eliades, G. (2024). Intraoral ageing of aligners and attachments: Adverse effects on clinical efficiency and release of biologically-active compounds. *Korean Journal of Orthodontics, 54*(4), 199–209. https://doi.org/10.4041/kjod24.085
9. Feng, Y., Tu, C., Li, R., Wu, D., Yang, J., Xia, Y., Peijnenburg, W. J. G. M., & Luo, Y. (2023). A systematic review of the impacts of exposure to micro- and nano-plastics on human tissue accumulation and health. *Eco-Environment & Health, 2*(4), 195–207. https://doi.org/10.1016/j.eehl.2023.08.002
10. Galloway, T. S. (2015). Micro- and nano-plastics and human health. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 343–366). Springer. https://doi.org/10.1007/978-3-319-16510-3_13
11. Jenner, L. C., Rotchell, J. M., Bennett, R. T., Cowen, M., Tentzeris, V., & Sadofsky, L. R. (2022). Detection of microplastics in human lung tissue using μFTIR spectroscopy. *Science of the Total Environment, 831*, Article 154907. https://doi.org/10.1016/j.scitotenv.2022.154907
12. Koelmans, A. A., Mohamed Nor, N. H., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research, 155*, 410–422. https://doi.org/10.1016/j.watres.2019.02.054
13. Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International, 163*, Article 107199. https://doi.org/10.1016/j.envint.2022.107199
14. Lombardo, L., Arreghini, A., Ramina, F., Huanca Ghislanzoni, L. T., & Siciliani, G. (2017a). Predictability of orthodontic movement with orthodontic aligners: A retrospective study. *Progress in Orthodontics, 18*(1), Article 35. https://doi.org/10.1186/s40510-017-0190-0
15. Lombardo, L., Martines, E., Mazzanti, V., Arreghini, A., Mollica, F., & Siciliani, G. (2017b). Stress relaxation properties of four orthodontic aligner materials: A 24-hour in vitro study. *Angle Orthodontist, 87*(1), 11–18. https://doi.org/10.2319/113015-813.1
16. Marfella, R., Prattichizzo, F., Sardu, C., Fulgenzi, G., Graciotti, L., Spadoni, T., D'Onofrio, N., Scisciola, L., La Grotta, R., Frigé, C., Pellegrini, V., Municinò, M., Siniscalchi, M., Spinetti, F., Vigliotti, G., Vecchione, C., Carrizzo, A., Accarino, G., Squillante, A., ... Paolisso, G. (2024). Microplastics and nanoplastics in atheromas and cardiovascular events. *The New England Journal of Medicine, 390*(10), 900–910. https://doi.org/10.1056/NEJMoa2309822

17. Panayi, N., Papageorgiou, S. N., Eliades, G., & Eliades, T. (2024). Microplastics and orthodontic aligners: The concerns arising from the modernization of practice through polymers and plastics. *Journal of the World Federation of Orthodontists, 13*(6), 259–264. https://doi.org/10.1016/j.ejwf.2024.10.001
18. Pozzan, L., Bertolami, V., Gabbana, B., Morona, J., Belašič Zibar, T., Turco, G., Porrelli, D., & Contardo, L. (2025). Mechanical properties of thermoplastic materials for clear orthodontic aligners: A new three-dimensional experimental setting. *Orthodontics & Craniofacial Research*. Advance online publication. https://doi.org/10.1111/ocr.70067
19. Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Science of the Total Environment, 702*, Article 134455. https://doi.org/10.1016/j.scitotenv.2019.134455
20. Quinzi, V., Orilisi, G., Vitiello, F., Notarstefano, V., Marzo, G., & Orsini, G. (2023). A spectroscopic study on orthodontic aligners: First evidence of secondary microplastic detachment after seven days of artificial saliva exposure. *Science of the Total Environment, 866*, Article 161356. https://doi.org/10.1016/j.scitotenv.2022.161356
21. Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M., & Giorgini, E. (2021). Plasticenta: First evidence of microplastics in human placenta. *Environment International, 146*, Article 106274. https://doi.org/10.1016/j.envint.2020.106274
22. Shariff, K. U., Le, A., Goodwin-Loughton, E., Chung, M., Ali, A., Farella, M., & Venugopal, A. (2025). Microplastics and nanoplastics in clinical dentistry and orthodontics: Leaching, health implications, and future directions: A narrative review. *Progress in Orthodontics, 26*(1), Article 49. https://doi.org/10.1186/s40510-025-00597-9
23. Shinkai, R. S. A., Biazevic, M. G. H., Michel-Crosato, E., & de Campos, T. T. (2025). Environmental sustainability related to dental materials and procedures in prosthodontics: A critical review. *Journal of Prosthetic Dentistry, 133*(6), 1466–1473. https://doi.org/10.1016/j.prosdent.2023.05.024
24. Šimunović, L., Bačić, I., & Meštrović, S. (2025). Micro- and nanoplastics in dentistry: Challenges in obtaining high-quality evidence. *Materials, 18*(18), Article 4269. https://doi.org/10.3390/ma18184269
25. Souza-Silva, T. G., Oliveira, I. A., da Silva, G. G., Giusti, F. C. V., Novaes, R. D., & de Almeida Paula, H. A. (2022). Impact of microplastics on the intestinal microbiota: A systematic review of preclinical evidence. *Life Sciences, 294*, Article 120366. https://doi.org/10.1016/j.lfs.2022.120366
26. Warunek, J., Warunek, S., Calderon, M., Franks, J., Watkins, S., Turnquist, H., & Al-Jewair, T. (2026). Orthodontic derived microplastics impact macrophage differentiation and homeostasis. *Progress in Orthodontics, 27*(1), Article 3. https://doi.org/10.1186/s40510-026-00608-3
27. Winiarska, E., Jutel, M., & Zemelka-Wiącek, M. (2024). The potential impact of nano- and microplastics on human health: Understanding human health risks. *Environmental Research, 251*(Pt 2), Article 118535. https://doi.org/10.1016/j.envres.2024.118535
28. Wright, S. L., & Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environmental Science & Technology, 51*(12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423
29. Yong, C. Q. Y., Valiyaveettil, S., & Tang, B. L. (2020). Toxicity of microplastics and nanoplastics in mammalian systems. *International Journal of Environmental Research and Public Health, 17*(5), Article 1509. https://doi.org/10.3390/ijerph17051509