CONTEMPORARY CONCEPTS IN CLEAR ALIGNER THERAPY:

BIOMECHANICS, MATERIAL SCIENCE, AND ENVIRONMENTAL CONSIDERATIONS

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İÇİNDEKİLER

CLINICAL BIOMECHANICS OF CLEAR ALIGNER THERAPY: ATTACHMENTS AND STAGING STRATEGIES

Hatice ADEMOĞLU ALADAĞ[1]

Introduction

Clear Aligner Therapy (CAT) is a modern orthodontic treatment approach that uses clear, custom-made plastic aligners to align the teeth. These aligners apply gentle forces to the teeth, causing them to gradually move into the desired position. Among the key advantages of CAT are its aesthetic appeal, comfort, and the ability to remove the aligners during meals and oral hygiene routines. For these reasons, CAT has become a widely preferred option for treating a wide range of orthodontic conditions today. (Rossini et al., 2015)

The History of Clear Aligner Therapy

The development of clear aligner therapy began in the 20th century with dentists' initial experiments using transparent plastic materials to align teeth. Over time, it became clear that teeth could be gradually moved into their target positions using a series of clear aligners, each slightly different from the previous one. This method

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represented a significant paradigm shift, distinctly diverging from the traditional orthodontic treatment approach based on metal brackets and archwires (Weir, 2017). The development of Invisalign by Align Technology and its clinical launch in 1999 marked a significant milestone in this field, as it represented the first commercially available clear aligner system. The system quickly gained popularity among patients seeking a more aesthetic and comfortable alternative to traditional fixed orthodontic treatments. The fact that the clear aligner system developed by Align Technology was deemed marketable in 1998 under the FDA 510(k) process marked a significant turning point in the subsequent introduction and widespread adoption of the Invisalign system (U.S. Food and Drug Administration, 1998).

The Evolving Workflow in Digital Orthodontics

The digital workflow that forms the foundation of clear aligner treatment consists of the following steps: intraoral scanning, digital model creation, virtual setup, phased tooth movement planning, production, and follow-up. Recent advancements have focused on delivering greater accuracy, faster production, and improved patient follow-up at every stage of this process. In particular, improved scanner accuracy has made it possible to integrate digital models more reliably into the clinical decision-making process. Additionally, updates to treatment planning software are moving toward a more systematic evaluation of not only crown movement but also risks related to root position and alveolar margins. However, because digital simulation does not perfectly align with biological reality, the clinician must critically evaluate the virtual plan (Li et al., 2024).

Today, digital planning no longer simply means “aligning teeth on a screen,” but also involves optimizing the force system and sequence of movements. Therefore, the modern approach to clear aligner therapy views digital technology not as an automatic solution but as a tool that enhances the clinical decision-making process. The quality of the initial planning is of critical importance, particularly for reducing the need for additional aligners and increasing the predictability of movement (Martínez-Lozano et al., 2024).

Current Approaches in Biomechanics

Biomechanics lies at the heart of recent developments in clear aligner therapy. Unlike fixed orthodontic systems, force transmission in clear aligners is determined by the elastic properties of the aligner material, aligner geometry, the aligner edge (trimline design), the use of attachments, and the phased planning of movement. Therefore, the biomechanics of clear aligner therapy involves a highly variable structure that cannot be explained solely by “aligners being worn.” Recent reviews indicate that the current focus is not so much on the magnitude of the force, but rather on its direction, duration, mode of activation, and the manner in which it is transmitted to the tooth (Li et al., 2024).

In particular, rotational, extrusion, root torque, and extensive translational movements are considered less predictable with clear aligners. Key reasons for this include limited force transfer between the aligner and the tooth surface, dependence on retention and contact surfaces, force loss in the material over time, and individual variability in the biological response. Current literature suggests that, to manage these movements more successfully, the design of the attachment, the phasing strategy, and, when necessary, the use of auxiliary elastic or hybrid mechanisms should be evaluated together (Arveda et al., 2025; Wang et al., 2025).

Attachments

In clear aligner therapy, clinical effectiveness is strongly influenced by the use of auxiliary components such as attachments.

These small composite features are bonded to selected tooth surfaces to increase the biomechanical efficiency of the aligner system. In addition to improving appliance retention, attachments assist in producing planned tooth movements, particularly movements that are difficult to achieve predictably, such as rotation, extrusion, and controlled tooth displacement (Simon et al., 2014b).

The early description of attachments can be traced to Martz in 1988, who presented a removable appliance for tooth positioning and recommended the use of composite “buttons” to create anchorage areas on the appliance, thereby facilitating tooth movement (Yangın et al., 2025).

These auxiliaries enhance the predictability of clinical results by changing the way forces are transmitted from the aligner to the teeth (Houle et al., 2017). Evidence also indicates that the effectiveness of orthodontic tooth movement may be affected by several attachment-related factors, such as their location, design, size, and number (Takara et al., 2022). Each attachment design must be fully compatible with the intended tooth movement; in this context, factors such as surface contact area, the plate’s flexure/deflection points, and centers of resistance are of critical importance for biomechanical success. Additionally, proper orientation of the attachment in relation to the plate’s insertion path can contribute to more effective force transmission (Cortona et al., 2020).

The use of attachments is critical for effective treatment. Clinical studies—such as those by Ravera et al. (2016), Garino et al. (2016), and Groody et al. (2023)—and studies based on finite element analysis—such as those by Cortona et al. (2020); Yang et al. (2023)—have demonstrated the importance of attachment use in improving root control. Additionally, in vitro studies (Simon et al., 2014a) have shown that without attachments, the transfer of force from the aligner to the teeth is limited.

It should be noted that attachments do not actively generate force; rather, they are effective by creating a passive barrier in the path of the aligner material. Due to the mismatch between the tooth's current position and the planned position of the aligner material, the clear aligner plastic undergoes elastic deformation. The force vector resulting from this elastic deformation subsequently exerts its effect on the tooth (Juan Pablo Gomez Arango, t.y.).

Structurally, attachments can be described as having three principal components: the active surface, the passive surface, and the base. The active surface is the region that engages with the aligner and contributes to the development of force vectors needed for the intended tooth movement. The passive surface, by comparison, forms the buccal contour of the attachment. This surface provides stability to the attachment and supports the plate's adaptation with minimal interference (Yangın et al., 2025).

Position of Attachments

The location of attachments plays an important role in determining the optimal point of force delivery and the retentive capacity of the aligner. In accordance with biomechanical principles, the moment generated increases as the point of force application moves farther away from the tooth's center of resistance. Accordingly, attachments positioned near the occlusal surface may create a greater moment than those placed close to the gingival margin (Jones et al., 2009). To minimize the risk of unwanted plastic deformation, a minimum distance of 1.5 mm should be maintained between the attachment and the gingival margin, as well as other limiting surfaces (Staff, 2006).

For rotational tooth movements, placing attachments near the mesial and distal corners of the tooth can help increase the rotational moment. In cases requiring mesio-palatal rotation, attachment location may therefore play an important role in enhancing movement efficiency. However, when the attachment is incorrectly positioned, the force delivered by the aligner may generate tipping effects instead of the intended rotational movement, leading to unwanted tooth displacement (Nanda et al., 2021).

Recent evidence from a finite element analysis study indicates that the placement of horizontal rectangular attachments on the lingual surfaces of first molars may generate higher tipping moments than labial placement, especially during transverse arch expansion. These findings emphasize the critical role of attachment location in aligner biomechanics (Yangın et al., 2025).

Attachment Size

Attachment size plays a role comparable to attachment positioning in the expression of intended tooth movements. As a general principle, more demanding or complex movements tend to require attachments with larger dimensions. However, larger attachments may be associated with aesthetic concerns, particularly when used in the anterior dentition. Optimizing attachment dimensions according to both biomechanical requirements and aesthetic expectations may contribute to shorter treatment times and improved treatment outcomes.

According to Ahmad et al., attachment dimensions play an important role in the biomechanics of clear aligner therapy (Ahmad et al., 2023). Increases in attachment thickness, length, and width are generally associated with greater force and moment generation. However, their effect on the moment-to-force ratio appears to be limited. Larger attachments may also improve the alignment between the applied force direction and the planned direction of tooth movement. Therefore, selecting an appropriate attachment size may help achieve the desired force magnitude.

Classification of Attachments

Attachments used in clear aligner systems are generally classified according to their function or optimization status (Yangın vd., 2025).

Attachments by Function

Functionally, attachments can be divided into active and passive types. Passive attachments mainly serve to improve the retention of the aligner, while active attachments contribute to the execution of planned tooth movements (Yangın et al., 2025).

Conventional and Optimized Attachments

Another commonly used classification separates attachments into conventional and optimized types. Optimized attachments, which are specific to the Invisalign system, are designed according to the anatomical characteristics of the tooth and the planned movement to be achieved (Tai, 2018). Conventional attachments, by comparison, include attachments with standard designs that are not tailored to a particular tooth or specific movement.

Comparison of Conventional and Optimized Attachments

In numerous previous studies, the effectiveness of optimized and conventional attachments has been compared and evaluated for various tooth movements. The first optimized attachment design developed by Invisalign was the optimized rotation attachment. Karras et al. retrospectively compared the effectiveness of optimized rotation attachments with conventional attachments in correcting the rotation of canines and premolars. The study results showed that the success rates of optimized attachments were slightly higher and that these differences were statistically significant (Karras et al., 2021).

Hassanaly et al. retrospectively assessed 147 incisors by comparing vertical conventional attachments with optimized attachments. Their findings indicated that optimized attachments provided better rotational correction in lateral incisors, whereas vertical conventional attachments were more effective for mesiodistal angulation correction. Among the attachment designs evaluated for torque movements, horizontal attachments demonstrated the highest effectiveness (Hassanaly et al., 2024).

In their retrospective evaluation of Invisalign treatment for deep overbite, Burashed and Sebai compared cases treated with optimized attachments with those treated with conventional attachments. The results indicated that optimized attachments were not more effective than conventional attachments in overbite correction. The study further emphasized that deep overbite correction is a difficult and less predictable movement, independent of the attachment design employed (Burashed & Sebai, 2023).

The same researchers also evaluated the correction of anterior open bite using two groups: one with horizontal conventional attachments and the other with optimized extrusion attachments. It was reported that open bite was successfully corrected in both groups; however, it was shown that optimized attachments shortened the treatment duration (Burashed, 2023).

In their study on anterior tooth extrusion with the Invisalign system, Karras et al. compared optimized extrusion attachments with conventional attachment designs. The findings indicated a marginally greater mean extrusion with optimized attachments; however, this difference was limited to 0.14 mm, or 4.3%, and did not reach clinical or statistical significance. Similar to their reports on conventional attachment designs used for rotation, the study did not clearly describe the specific characteristics of the conventional extrusion attachments, such as their position, size, orientation, or angulation (Karras et al., 2021).

In a retrospective study by Stephens et al., three different approaches were compared for correcting mandibular canine derotation using Invisalign aligners. In two groups, optimized rotation attachments were used, and the aligner change protocol was applied weekly or every two weeks. In the third group, conventional vertical rectangular attachments were used with a two-week change protocol. The results showed that the highest success rate was achieved in the group using optimized attachments with a weekly change protocol (81.5%). This was followed by the group using an optimized attachment system, which was changed every 14 days (76.5%). The group using conventional attachments had the lowest rate of rotational movement (63.1%); however, it was also noted that the initial rotations in this group were more severe (Stephens et al., 2022).

Overall, while optimized attachments may offer advantages for certain types of tooth movement—particularly in terms of rotation and reducing treatment duration—current studies indicate that they are not superior to conventional attachments for all types of tooth movement. Attachment effectiveness is influenced by numerous factors, including the type of movement, tooth morphology, the severity of the initial malposition, the aligner removal protocol, and biomechanical planning.

The Function of Attachments

Attachments have two primary functions: mobilization and retention.

Active Attachments

Active attachments are used when the existing tooth morphology is inadequate to support the planned movement or when root movement cannot be predictably achieved even in the presence of favorable anatomy. In conical premolars and canines requiring rotation, or in teeth requiring extrusion, the aligner may slide over the tooth surface if no attachment is present, thereby reducing the expression of the planned movement. This phenomenon, referred to as the "traffic cone effect," occurs when the aligner seats on the tooth like a cone and moves relative to the tooth instead of delivering an effective force during rotation or extrusion. Active attachments are therefore incorporated to improve aligner engagement and facilitate the desired tooth movement (Yangın et al., 2025).

Passive Attachments

Passive attachments function mainly by increasing the retentive capacity of the aligner. These attachments may be particularly advantageous in patients with microdontia, missing teeth, reduced clinical crown height, or incompletely erupted teeth. However, the need for enhanced aligner retention is not limited to such conditions; it may also arise in cases with normal tooth morphology and dentition, depending on the clinical requirements of the treatment (Yangın et al., 2025).

Stagıng Of Orthodontıc Tooth Movement

Metha et al. (2023) defined the "staging of orthodontic tooth movement" as "the sequential division of the anticipated tooth movement using clear aligners." The importance of this concept lies in understanding the fundamental principles of orthodontic tooth movement and how these principles are applied using clear aligners (Tuncay, 2006).

The concept of staging should not be confused with the concept of "stadification," which defines the amount of linear and/or angular movement planned for each tooth in each aligner. While "stadification" refers to the amount of movement to be applied to individual teeth at each aligner stage, “staging” relates to how many teeth will be moved simultaneously during the clear aligner treatment process and which teeth will be left stationary for anchorage purposes (Martínez-Lozano et al., 2024).

Fundamental Principles of Clear Aligners

A clear understanding of the complexity and relevance of staged tooth movement in clear aligner therapy requires an overview of the core principles that characterize these systems and distinguish them from traditional fixed orthodontic appliances with brackets (Ali Baeshen et al., 2023).

There are three fundamental principles in clear aligner treatment:

Closed system

Pushing surfaces

Differential anchorage

A closed system refers to a biomechanical arrangement in which forces cannot be dissipated at the terminal ends of the system. By contrast, conventional multi-bracket fixed orthodontic appliances are generally considered open systems, as surplus energy can be released through the most distal elements. A typical example is observed during alignment and leveling with round nickel-titanium archwires in cases of severe crowding. While the archwire returns toward its original shape and draws the teeth into the planned arch form, it generates force and energy within the system. The excess component of this energy becomes evident as wire protrusion distal to the tube of the last molar (Martínez-Lozano et al., 2024).

In clear aligner therapy, the appliance surrounds the crowns of the teeth, creating a closed biomechanical system. In the absence of sufficient space within the dental arch, the forces introduced into this system cannot be readily dissipated and may therefore result in undesired tooth displacement. This may appear clinically as dental intrusion or as the "watermelon seed effect," as described in the literature (Morton et al., 2017; Upadhyay & Arqub, 2022).

The clinical significance of working within a closed system is that the dentist must consistently ensure sufficient space is created during treatment planning. (Ali Baeshen et al., 2023). This space can be created through planned expansion, buccal angulation of crowns, interproximal enamel reduction, tooth extractions, or distalization. Visually creating space is one of the fundamental elements of sequencing movements.

In clear aligner therapy, the aligners act as the active element because they apply pressure to the teeth via "pressure surfaces" (Kundal, 2020). Each aligner is designed to have a slightly different shape than the teeth it covers and applies force to millions of points on the dental crowns, thereby slightly altering the position of each tooth. The flexibility of the aligner material enables a controlled adaptation process known as the "interphase" (Barone et al., 2017; Brezniak, 2008); this process is critical to the effective functioning of invisible orthodontics.

Differential anchorage (Hahn et al., 2010) is one of the most valuable features of clear aligner orthodontics. This concept refers to the planning of staged movements such that the anchorage value represented by the non-moving teeth is always greater than that of the moving teeth (Nabbout & Baron, 2018). This approach minimizes the movement of the teeth used for anchorage (Loberto et al., 2023) while maximizing the movement of the target teeth. Additionally, differential anchorage allows for the modification of anchorage segments during treatment based on the clinician's needs (Kaur et al., 2021). Differential anchorage forms the foundation of the phased planning of orthodontic tooth movement.

Macro-Staging and Micro-Staging

A thorough evaluation of staging in clear aligner therapy requires the distinction between macro-staging and micro-staging as two complementary analytical levels. Considering these concepts separately facilitates the detection of potential challenges during the assessment and follow-up of the virtual treatment plan

Macro-staging refers to the overall biomechanical organization of prioritized tooth movements required to fulfill the goals of the treatment plan. It enables a comprehensive evaluation of the movement sequence within each dental arch. Through analysis of the anchorage pattern as a whole, this approach helps identify whether stable and sufficient anchorage areas are available during the different phases of treatment. In addition, determining whether the planned tooth movements are synergistic or antagonistic is essential, as this may directly affect the predictability and reliability of the final outcomes (Martínez-Lozano et al., 2024).

To evaluate the adequacy of macro-staging within a treatment plan, the clinician should consider the following steps:

Identify the overall biomechanical strategy required to correct the malocclusion.

Define the clinical and mechanical conditions that may enhance the predictability of this biomechanical approach.

Evaluate the sources and distribution of anchorage throughout treatment (Martínez-Lozano et al., 2024).

Defining General Biomechanics for the Correction of Malocclusion

At the beginning of treatment planning, the orthodontist must decide between two movement strategies: simultaneous movement, where all or almost all teeth in the arch are moved concurrently, and structured movement, where certain teeth are maintained as anchorage units while movement is limited to selected teeth. Although this decision depends on multiple clinical and biomechanical factors, the complexity of the malocclusion is generally the primary determinant.

This decision is also influenced by several other considerations, including the selected anchorage strategy, the condition of each tooth and its supporting bone and periodontal tissues, and the prescribed aligner wear and change protocol.

When synergistic movements are planned together, the force systems produced by the aligner material can be used more effectively; for this reason, this approach is often preferred in treatment planning.

In clear aligner planning, synergistic mechanics may be observed when posterior and anterior movements are coordinated in a mutually supportive manner. These include transverse–sagittal combinations, such as posterior expansion with anterior retrusion or posterior compression with anterior protrusion; sagittal combinations, such as posterior distalization with anterior proclination; and vertical reciprocal combinations, such as posterior extrusion with anterior intrusion or the reverse pattern (Martínez-Lozano et al., 2024).

On the other hand, antagonistic movements are those that can lead to unwanted tooth movements, reduce the degree to which planned movements are achieved, and cause the arch to collapse by resulting in a loss of "tracking." When analyzing the macro-staging phase, an orthodontist should avoid the simultaneous occurrence of these dynamics. In contrast, antagonistic mechanics occur when simultaneously planned movements create competing biomechanical effects. Examples include combinations of posterior transverse changes with unfavorable anterior sagittal movements, such as posterior expansion with anterior protrusion or posterior compression with anterior retrusion. Similar conflicts may arise when rotation is combined with extrusion, when both anterior and posterior segments are intruded or extruded at the same time, or when posterior distalization is planned together with anterior palatal root torque (Martínez-Lozano et al., 2024).

Defining the clinical conditions necessary for predictable biomechanics

This step requires an individualized approach based on the patient's specific needs. Nevertheless, in macro-staging, predictability can often be improved by establishing the proper timing and sequence of each movement. For example, expansion and proclination may first be used to achieve alignment, while extrusion may be delayed to a later stage. In this way, synergistic movements can be planned together, and the most appropriate auxiliary components can be selected according to the requirements of each treatment phase (Martínez-Lozano et al., 2024)

Determining the Distribution and Sources of Anchorage

In clear aligner treatment, anchorage may be obtained from different sources, either independently or in combination. These include intra-arch anchorage created through differential tooth movement, inter-arch anchorage achieved with elastics, and skeletal anchorage when additional support is required (Martínez-Lozano et al., 2024).

Within macro-staging, certain clinical situations require a more structured sequencing strategy. This is particularly relevant for planned sagittal movements such as distalization or mesialization, absolute vertical displacement of the anterior teeth, and the management of extraction space closure (Department of

Developmental Sciences/Orthodontics, Marquette University School of Dentistry, Milwaukee, Wisconsin, USA, et al., 2021).

Micro-Staging

Micro-staging refers to the biomechanics of movements specific to each tooth. This approach involves analyzing movements planned independently for each tooth across different planes of space, evaluating whether these movements are compatible with one another, and developing space-creation strategies to prevent movement deficiencies and the resulting unwanted intrusion.

The adequacy of micro-staging can be assessed through a tooth-specific biomechanical evaluation. The clinician should:

1. Analyze the individual biomechanical requirements of each tooth.

The first step is to identify the malposition of each tooth and determine which movements are necessary to bring it into the correct position (Martínez-Lozano et al., 2024).

2. Determine the movements requiring space.

As with macro-staging, it is necessary to determine whether the movements required for dental correction can be applied simultaneously or whether it would be more appropriate to divide them into different phases. Although there is no absolute criterion applicable to all cases, it is generally advantageous to begin with movements that create space within the arch, such as expansion or proclination, because movements requiring additional space, such as compression or extrusion, may hinder the occurrence of other movements.

3. Detect interproximal friction points and manage them in a way that facilitates the propulsive effect of the aligner.

The second principle of orthodontics with clear aligners emphasizes the importance of having broad contact surfaces between the tooth and the aligner to ensure the aligner can apply sufficient force. The orthodontist must be able to determine which points or areas of the tooth crown the aligner is applying pressure to at any given moment; when these areas are too small or create excessive friction with adjacent teeth, the orthodontist must adjust the tooth's movement accordingly (Martínez-Lozano et al., 2024).

Finally, more complex movements, particularly "vertical movements," should be deferred because they often require overcorrection or auxiliary appliances (Martínez-Lozano et al., 2024).

Creating visible spaces between the teeth appears to be a noteworthy approach not only for reducing friction but also for improving aligner adaptation and minimizing unwanted movements. (Y. Cao et al., 2023) demonstrated in vitro that the bending effect on the aligner caused by passive extrusive forces during anterior retraction in a case with a first premolar extraction was reduced by planning small diastemas between the anterior teeth.

Interdental spaces are considered beneficial in cases where extraction spaces are closed, because these spaces increase the interproximal aligner surface area and allow the aligner to reach the mesial or distal surfaces of the target teeth, thereby increasing the pushing surface and the system's rigidity (Aligner therapy in treating bimaxillary dentoalveolar protrusion, n.d.).

4. Observation of Early Contacts or Interference During Movement

Early contacts (ghost tooth effect) that occur during movement and manifest most prominently as interference between teeth can pose problems during micro-staging.

To avoid simultaneous interarch collision at a given stage, the movement velocity of the maxillary and mandibular arches may be adjusted separately. Additional strategies include the temporary use of bonded occlusal bite blocks until the crossbite contact is cleared, or the intrusion of one of the affected teeth to decrease the overlap to less than 3 mm, followed by subsequent restoration of its vertical height, as illustrated (Martínez-Lozano et al., 2024).

In clear aligner therapy, the staged organization of orthodontic tooth movements has a major influence on treatment outcomes. By creating the space required within the closed system, defining suitable driving surfaces, and coordinating anchorage distribution, staging contributes directly to biomechanical predictability.

The distinction between macro-staging, which addresses the general biomechanical strategy, and micro-staging, which evaluates tooth-specific movement mechanics, provides a more precise framework for treatment planning and helps reduce the risk of clinical or virtual planning errors.

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PHYSICAL PROPERTIES OF CLEAR ALIGNERS: FROM THERMOFORMING TO CLINICAL PERFORMANCE

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Introduction

Orthodontic treatment using clear aligners (Clear Aligner Therapy—CAT) has rapidly gained popularity over the last two decades, as aesthetic concerns have come to the fore among both adult and adolescent patients. Although the foundation of this treatment modality lies in Kesling's design of plastic positioner devices in 1945 to facilitate sequential tooth movement, modern clear aligner systems underwent a fundamental transformation with the launch of Invisalign® technology in 1997 (Macrì et al., 2022). The integration of computer-aided design and manufacturing (CAD/CAM) technologies into orthodontics has enabled the mass production of clear, removable appliances that allow for tooth movement without adversely affecting patients' aesthetic appearance during treatment.

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The clinical efficacy of clear aligners depends largely on the physical and mechanical properties of the polymeric materials from which these appliances are made. For orthodontic forces to be transmitted in a sufficiently strong, continuous and controlled manner, the material must meet certain mechanical parameters (Zhang et al., 2011). Furthermore, aesthetic and hygienic properties such as transparency, colour stability and surface roughness, which directly affect patient compliance, also play a decisive role in treatment success. For this reason, gaining a thorough understanding of the physical properties of clear aligner materials is of great importance for both clinicians and researchers.

This section aims to address the physical properties of clear aligners from a comprehensive and up-to-date perspective. A wide range of topics will be examined, from the chemical structure of the materials to the effects of the thermal shaping process, and from optical properties to water absorption and thermal behaviour. Each sub-section will be evaluated in the light of current experimental and clinical research; thus, the reader will be provided with a comprehensive foundation for understanding the complex property profile of clear aligner materials.

Polymeric Materials Used in Transparent Plates

The materials used in the production of transparent plates are predominantly selected from the thermoplastic polymer group. The primary reasons for choosing these polymers include their ability to be shaped under heat and pressure, their biocompatibility, optical clarity, and specific mechanical properties. The most commonly used materials today are polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (PU) and their polymeric blends (Macrì et al., 2022; Tamburrino et al., 2020).

Polyethylene Terephthalate Glycol (PETG)

Polyethylene terephthalate glycol (PETG) is an amorphous copolymer of polyethylene terephthalate (PET) and is one of the most frequently preferred materials for the production of transparent sheets. There are several reasons behind the widespread use of PETG: excellent impact and tear resistance, superior barrier properties, chemical resistance and high transparency are among the foremost (Daniele et al., 2020). Due to its low tendency to crystallise, PETG retains its amorphous structure and exhibits high transparency values across the visible light spectrum; this property ensures that the sheets remain virtually invisible when worn in the mouth (Quinzi et al., 2022).

Research indicates that PETG possesses the highest values for visible light transmittance in the short-wavelength range, thereby offering the superior transparency profile among commercial aligners (Quinzi et al., 2022). Many commercial aligner brands, such as Essix Plastic, Erkodur and Ghost Aligner, are manufactured using PETG-based materials. The flexural modulus of PETG is measured at approximately 2,000 MPa; this value enables the aligner to maintain sufficient rigidity whilst providing the necessary elastic recovery. It has been demonstrated that a 70/30 ratio of the PETG/PC2858 blend exhibits the best combination of tensile strength, impact resistance and elongation at break (Macrì et al., 2022).

Thermoplastic Polyurethane (PU)

Thermoplastic polyurethane (PU) is a polymer that is increasingly used in the production of transparent sheets due to its excellent mechanical and elastomeric properties, chemical and abrasion resistance, and superior adhesion properties (Zhang et al., 2011). PU’s exceptional flexibility is the primary reason leading manufacturers such as Align Technology Inc. (Santa Clara, CA, USA) prefer this material; as it is reported to provide more predictable tooth movement by applying lighter and continuous forces (Tamburrino et al., 2020). Whilst Invisalign® aligners were initially manufactured from a single-layer polyurethane material known as EX30 (Exceed-30), this material has since been replaced by a more flexible, multi-layered PU-PETG blend called SmartTrack (LD30).

Compared to PETG, PU exhibits a higher elastic elongation capacity and better force distribution. In their study comparing the mechanical properties of PETG and PU materials, Tamburrino et al. (2020) demonstrated that both materials are clinically suitable for orthodontic force transmission, but exhibit distinct behavioural profiles at different thicknesses. Whilst the difference in stiffness between the two materials at a thickness of 0.9 mm was largely found to be statistically insignificant, it was observed that PU exhibited significantly higher stiffness values in the canine region. It was also emphasised that polymer blends containing PU, particularly the PETG/PC/PU composition at a 70/10/20 ratio, offer the best mechanical properties compared to other commercial products (Macrì et al., 2022).

Polycarbonate and Other Polymers

Polycarbonate (PC) constitutes another important class of polymers used in the production of transparent sheets due to its durability, hardness and transparency (Zhang et al., 2011). Rather than being used in its pure form, it is generally incorporated into polymer blends by mixing it with PETG or PU in specific ratios. This enhances the final material’s impact resistance and improves its thermal stability. The most commonly produced types of polycarbonate are manufactured using a combination of BPA and carbonyl chloride ($COCl_2$) (Yaşar, 2001). Polypropylene (PP) is also preferred by some sheet manufacturers; it offers certain advantages, particularly in terms of fatigue resistance and chemical stability. However, the transparency values of PP-based materials are lower compared to PETG and PU, and this can constitute an aesthetic disadvantage (Macrì et al., 2022). As a thermoplastic, polypropylene can be shaped using various plastic processing methods (Ekşi, 2007).

The Effect of the Thermal Forming Process on Physical Properties

Thermoforming is the process of shaping thermoplastic sheets onto a dental model using heat and vacuum, and is the most commonly used production method for transparent plates. However, this process induces thermal and mechanical stress that can fundamentally alter the material's physical and mechanical properties. Research has shown that following thermal forming, numerous parameters—including transparency, water absorption, surface hardness, flexural modulus and tensile strength—exhibit statistically significant differences (Ryu et al., 2018).

Thickness Changes

During the thermal forming process, a significant reduction in sheet thickness occurs as the thermoplastic sheet is drawn over the mould. Studies have shown that this reduction in thickness varies significantly depending on the material, the model's dimensions and shape. Lee et al. (2022) reported that following the vacuum thermoforming process, the thickness of the thermoplastic material decreased to between 57.5% and 92.6% of its initial value. Park et al. (2023), in their thermal forming studies using a 10 mm thick square block model, found that the reduction in thickness varied between approximately 74.9% and 92.6%.

Bucci et al. (2019), in a prospective clinical study conducted on clear aligners obtained from 18 patients, demonstrated that aligner thickness exhibited significant variations depending on the anatomical region. In this study, significant thickness variations were observed between the anterior and posterior regions; it was reported that active aligners containing attachments exhibited a more irregular thickness distribution compared to passive aligners. Thickness is among the most fundamental factors determining the magnitude of forces transmitted to the teeth via clear aligners (Kim et al., 2023). Consequently, regional variations in thickness may lead to deviations from the force values anticipated by clinicians in their treatment plans.

Effects on Surface Roughness

The thermal shock caused by the thermoforming process leads to significant morphological changes on the material surface. Condò et al. (2024), in their detailed study on PETG material, reported that following thermal forming, the average surface roughness (Ra) increased by approximately 1,233%, whilst the root mean square roughness (Rq) increased by approximately 1,129%. This dramatic increase is a striking finding when compared to the relatively modest losses in the material’s mass (10%) and thickness (15%). The researchers suggest that this increase in surface roughness plays a critical role in explaining the reductions in permeability observed with thermal forming, as well as the tendency for biofilm adhesion and colour change (Condò et al., 2024).

In their systematic study examining four different thermoplastic materials (Duran, Essix A+, Essix ACE and eCligner), Ryu et al. (2018) determined that surface hardness increased in all materials following thermal forming. Whilst transparency decreased significantly in Duran and Essix A+ samples following thermal shaping, no significant difference was observed between pre- and post-thermal shaping values in eCligner and Essix ACE samples.

Transparency and Optical Properties

Transparency is the most fundamental aesthetic property of clear aligners and directly influences patients' acceptance of treatment and their compliance with long-term use. Patients undergoing orthodontic treatment, particularly adults and adolescents, demonstrate a high sensitivity regarding the visibility of the treatment. Therefore, determining the optical properties of aligner materials is of great importance for both product development and clinical application.

The Relationship Between Degree of Crystallisation and Transparency

The optical properties of clear aligner materials depend largely on the arrangement of the polymer chains, i.e. the degree of crystallisation. Quinzi et al. (2022) conducted a comparative analysis of five different commercial aligners (Erkodur, Essix Plastic, Ghost Aligner, Zendura and Invisalign) using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR-ATR) and differential scanning calorimetry (DSC). This study revealed that all samples examined had a low degree of crystallisation, a finding that was particularly pronounced in PETG-based materials. It was determined that PETG-based materials exhibited the highest values in the short-range order and the superior transparency in the visible light spectrum.

The thermal forming process can lead to local crystallisation by subjecting the initially homogeneous polymer matrix to mechanical and thermal stress, which may result in a reduction in optical transparency. Ryu et al. (2018) found that transparency values in 0.5 mm thick Duran and Essix A+ samples decreased to a statistically significant extent following thermal forming. It was emphasised that this effect is more pronounced in thin sheets; as during thermal forming, thin materials undergo greater deformation and consequently their optical properties are more severely compromised.

Colour Stability

The colour stability of transparent sheets is a significant clinical concern due to their exposure to colouring agents (red wine, coffee, etc.) in the oral environment for 14 days. Quinzi et al. (2022) reported that when PETG and PU-based aligners were immersed in red wine and coffee for 14 days, perceptible colour changes were observed in both groups (NBS values ranging from 1.5 to 3), and that this was associated with a loss of transparency due to surface contamination. Invisalign aligners exhibited the most striking colour changes in this context; following red wine immersion, NBS values rose to as high as 35. The researchers attributed this finding to the wrinkled surface morphology caused by the thermal shaping process and the formation of indentations that trap contaminants on the surface.

Bernard et al. (2020), in their study examining colour measurement of orthodontic aligners using colorimetric and spectrophotometric methods, identified significant colour changes between aligners exposed to different staining sources and cleaning methods. It has been reported that PETG-based materials are more resistant to colour change, whilst PU-based materials exhibit greater colour deviation, particularly when in contact with beverages containing tannic acid. Fang et al. (2020) demonstrated that Invisalign material largely retained its mechanical properties and stress-relaxation performance following use in the oral environment; however, they observed signs of damage in the surface morphology and changes in the material structure indicating trace-level release of allergenic elements.

Water Absorption and Solubility

Water absorption is a critical physical parameter that indirectly affects both the mechanical and aesthetic properties of transparent aligner materials; together with thermal and chemical stresses, it can accelerate the material’s degradation process. Polymeric materials are subject to water absorption from the intraoral environment through exposure to saliva and beverages; this can lead to chain plasticisation, swelling and dimensional changes.

Ryokawa et al. (2006) reported that a thickness increase ranging from 100.3% to 119.9% was observed in thermoplastic materials examined in a simulated oral environment due to water absorption; this finding was interpreted as supporting the hypothesis that the material’s mechanical properties vary depending on external factors. Bucci et al. (2019), however, evaluated thickness changes in aligners collected from active clinical use via a prospective study and identified statistically significant thickness losses on the occlusal surfaces following 10 days of intraoral exposure. These losses were attributed to both thermal and chemical dissolution, as well as wear processes.

Ryu et al. (2018) observed an increase in water absorption capacity in all materials following thermal shaping. In terms of water solubility, significant increases were noted in the Duran, Essix A+ and Essix ACE samples, whilst this change was not found to be statistically significant in the eCligner samples. Similarly, in their study examining the dynamic mechanical and thermal properties following thermal shaping and ageing, Dalaie et al. (2021) suggested that water absorption could accelerate the thermal and mechanical degradation of the material by increasing viscous flow.

Surface Properties and Biofilm Formation

The surface properties of clear aligners have a decisive impact on both the long-term aesthetic appearance of the device and oral health. In particular, surface roughness and wettability are key parameters that directly influence the adhesion of microorganisms and the formation of biofilm. Rough surfaces provide larger and more sheltered areas for bacterial colonisation; this can negatively affect both oral hygiene and potential odour issues in patients.

In their study comparing the roughness and wettability properties of various plaque materials, Suter et al. (2020) identified significant differences between different materials and manufacturing methods. Roughness and surface energy properties are clinically significant in terms of biofilm adhesion and plaque removal efficacy. Indeed, the relationship between surface roughness and biofilm formation has been consistently demonstrated in various studies.

Thermal Properties and Dynamic Mechanical Analysis

The thermal properties of transparent aligner materials are of great clinical importance as they determine how the material will behave both during the manufacturing process and under intraoral usage conditions. Temperature in the oral environment is directly influenced by the consumption of hot and cold beverages; this can lead to thermal fluctuations ranging from 10°C to 60°C. These thermal variables can directly affect the material’s viscoelastic behaviour and, consequently, the magnitude of the applied orthodontic forces.

In their study examining the dynamic mechanical and thermal properties following thermal shaping and ageing processes, Dalaie et al. (2021) demonstrated that both thermal shaping and ageing exert significant effects on the storage modulus (E'), loss modulus (E'') and damping factor (tan δ). Thermal ageing alters the material's glass transition temperature (Tg) and may adversely affect its long-term mechanical behaviour. These findings suggest that the clinical performance of plaque materials in transmitting orthodontic forces may vary depending on biological or thermal ageing.

Tamburrino et al. (2020) suggested that all physical parameters, particularly thermal properties, should be re-evaluated following thermal shaping to enable clinicians to make informed choices between plate materials; as the initial properties of the raw material sheet may not align with clinical performance due to changes occurring during the production process. Lee et al. (2022) investigated the thermal properties of 3D-printed splints manufactured from light-cured shape-memory resin; they reported that these materials exhibit suitable viscoelastic behaviour capable of providing controlled shape changes in accordance with programmed tooth movements.

Stress Relaxation and Force Decay

One of the most important physical mechanisms determining the clinical performance of clear aligners is stress relaxation. This phenomenon manifests itself as the material gradually relaxes to lower stress levels over time under constant deformation conditions, resulting in a progressive decrease in the applied force. Stress relaxation is directly related to polymer chain mobility and is therefore significantly influenced by temperature, humidity and chemical exposure.

Fang et al. (2013) investigated the dynamic stress relaxation of orthodontic thermoplastic materials in a simulated oral environment. It was observed that all tested materials exhibited the most pronounced decrease in force within the first two days following insertion, after which they reached a relatively stable plateau for the remainder of the two-week wear period. When evaluated from the perspective of the system's design logic, this observation indicates that stress relaxation dynamics play a decisive role in the aligners' adaptation to the 14-day wear cycle.

Siotou et al. (2025) examined aligners from 32 patients using the Clear Aligner system after seven, ten and fourteen days of intraoral use; they evaluated mechanical parameters such as the elastic modulus, ultimate tensile stress and yield stress. This study found that the material largely retained its mechanical properties over a 14-day period. However, it was reported that slight but significant mechanical degradation occurred with intraoral exposure; it was emphasised that the extent of this degradation depended on both the duration of the replacement period and the intensity of intraoral use. This finding offers important clinical implications from a biomechanical perspective: it suggests that aligner replacement protocols must be planned in accordance with the material's stress-relaxation profile to ensure the continued effectiveness of orthodontic movement.

The Effect of Production Method on Physical Properties: Thermoforming and 3D Printing

In addition to the traditional thermoforming method used in the production of clear aligners, 3D printing technologies such as stereolithography (SLA), digital light processing (DLP) and selective laser sintering (SLS) have become increasingly widespread in recent years. Both production methods affect the physical properties of the resulting sheets in different ways, resulting in distinctly different property profiles.

Sheets produced using the thermoforming method exhibit certain limitations in terms of dimensional accuracy. Chief among these limitations are the uneven thickness variations resulting from the thermoplastic sheet being drawn over the mould during thermal forming. Park et al. (2023) reported that whilst a reduction in thickness was observed in plates produced via thermoforming, an increase in thickness was detected in 3D-printed plates; they also noted statistically significant differences in transparency between the two thermoforming groups (TS and TM) and the 3D-printed groups. Jindal et al. (2019), in their study comparing plates produced by thermoforming and 3D printing from geometric and mechanical perspectives, demonstrated that both methods have their own distinct advantages and disadvantages; in particular, significant differences were identified in terms of dimensional accuracy and force transmission profile.

A significant advantage of 3D-printed plates is that they eliminate the adverse effects caused by the thermoforming process. The direct printing method prevents undesirable changes in the material's mechanical, dimensional and aesthetic properties, thereby providing higher geometric accuracy, better fit, superior mechanical resistance and improved reproducibility (Maspero and Tartaglia, 2020). However, 3D-printed plates require materials different from conventional ones, such as photopolymerisation resins or polymer powders; this in itself necessitates the determination of new properties.

The Clinical Significance of Physical Properties

The clinical significance of the physical properties of clear aligners is multifaceted; these properties directly influence both treatment efficacy and patient comfort and compliance. In their systematic review comprehensively evaluating the physical and mechanical properties of different clear aligner materials, Srinivasan et al. (2024) highlighted the profound link between clinical efficacy and material properties.

Variations in aligner thickness across different anatomical regions can lead to deviations from the force distribution anticipated by the clinician. This is of particular importance in precise treatment protocols where sub-millimetric tooth movements are planned. Furthermore, whilst the surface roughness of the aligner affects oral hygiene, discolouration and loss of transparency may also negatively impact patient compliance. Water absorption, by compromising the material's dimensional stability, can directly affect the fit of the plate, thereby reducing the effectiveness of the forces transmitted to the teeth. Stress relaxation, however, is a phenomenon that gains clinical significance in situations where forces falling below a certain threshold can no longer achieve the desired tooth movement (Srinivasan et al., 2024).

Macrì et al. (2022) have suggested that the composition and ratio of the polymer blend play a critical role in determining the properties of the final material. In this context, it is observed that new-generation clear aligner systems optimise polymer compositions to provide more predictable force transmission and maintain aesthetic properties over the long term. Whilst the 70/10/20 ratio triple blend of PETG/PC/PU offers the best combined mechanical properties in this field, proprietary multi-layered materials such as SmartTrack serve as concrete evidence of the extensive engineering efforts manufacturers have invested to enhance aligner performance.

Conclusion

The physical properties of transparent aligners constitute a multidimensional set of parameters, not limited to a simple polymeric material profile, but rather involving complex interrelationships. The base materials used (PETG, PU, PC and various blends thereof), the production process (thermoforming or 3D printing), the conditions of use in the oral environment and patient behaviour all combine to shape the final physical performance.

Research consistently demonstrates that the thermal forming process can adversely affect numerous parameters, such as transparency, surface roughness and water absorption. During the period of intraoral use, degradation processes such as stress relaxation, thickness reduction and colour change inevitably progress. However, it is observed that the responses of different materials to these changes vary significantly; this situation makes the selection of the material best suited to clinical conditions a critical decision point.

The future of clear aligner technology will be a product of innovations in both polymer chemistry and digital manufacturing processes. The ideal clear aligner material must simultaneously meet multiple requirements, including high transparency, colour stability, resistance to water absorption and dimensional changes, sufficient and sustainable force transmission, and superior biocompatibility. The development of materials that balance these multifaceted expectations remains a key priority for both academic research and commercial product development.

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ENVIRONMENTAL AND CLINICAL IMPLICATIONS OF CHEMICAL SAFETY, MİCROPLASTIC EMİSSİONS, AND WASTE MANAGEMENT IN CLEAR ALIGNERS

Elif Nadide AKAY POLAT[1]

Introduction

Over the past two decades, clear aligners have become a prominent alternative to conventional bracket systems in orthodontic treatment. Characterized by their aesthetic appeal, comfort, and removability, these systems have substantially improved patient satisfaction and are advancing through innovations in biomaterial technology and computer-aided design.

However, the expansion of clear aligner use has introduced significant environmental concerns within orthodontic practice. Data indicate that clear aligner therapy generates over 1,000 tonnes of plastic waste annually (Boonchanachai et al., 2025), with estimates rising to approximately 15,000 tonnes when the entire production chain is considered (Palmieri et al., 2024). The magnitude of this

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issue is further underscored by low recycling rates, which are approximately 12% in Asia and 29% in Europe.

Regarding material safety, thermoplastic aligners experience mechanical and thermal degradation during clinical use. This degradation is associated with the release of microplastic particles and chemical compounds, including bisphenol A (BPA) and phthalates (Peter et al., 2023; De Stefano et al., 2025). These findings, which present notable health concerns, are receiving growing attention in the orthodontic literature.

This chapter examines the composition and manufacturing methods of clear aligners, chemical leaching, biosafety, microplastic release, environmental burden, life cycle assessment, waste management, and sustainable orthodontic strategies based on current scientific literature.

Composition and Manufacturing Methods of Clear Aligners

The materials used in the fabrication of clear aligners can be broadly classified into four main groups: single-layer thermoplastics, elastomeric polyurethane systems, multilayer composite structures, and photopolymer resins. Each material presents its own combination of mechanical properties, transparency, and biosafety, all of which are crucial in determining the characteristics of the finished aligner. Table 1 provides a side-by-side comparison of their characteristics, making it easy to compare. As for manufacturing, two primary approaches dominate this field, each shaping the production process in distinct ways.

Conventional Thermoforming (Vacuum Pressing)

This technique involves fabricating dental stone or resin models for every aligner stage. Thermoplastic sheets are subsequently heated and molded onto these individual models, then precisely trimmed to fit. As both rigid models and polymer aligner waste are generated with each step, this method produces significant clinical waste, primarily consisting of single-use models and discarded aligner material, which contributes to both environmental burden and disposal challenges.

The most widely used materials in thermoformed clear aligners are polyethylene terephthalate glycol (PETG) and thermoplastic polyurethanes (TPU). PETG offers high optical clarity and ease of thermoforming owing to its amorphous structure, while TPU provides a more controlled force delivery profile through its viscoelastic behavior. The choice between these two materials directly influences both clinical efficacy and biosafety risk (Delgado et al., 2025; Gözüpek et al., 2024).

Direct 3D Printing

Imagine a process where precision meets efficiency: digital design eliminates the need for intermediate models, delivers high-dimensional accuracy and reproducibility, enables superior occlusal fit, and prevents mechanical degradation caused by the thermal processing of thermoforming. In addition, digital design generates less material waste than thermoforming, which requires multiple intermediate steps and mold disposal. These models are increasingly preferred for direct 3D printing (Kılınç et al., 2021). The waste cycles associated with different production methods for clear aligners are illustrated in Figure 1.

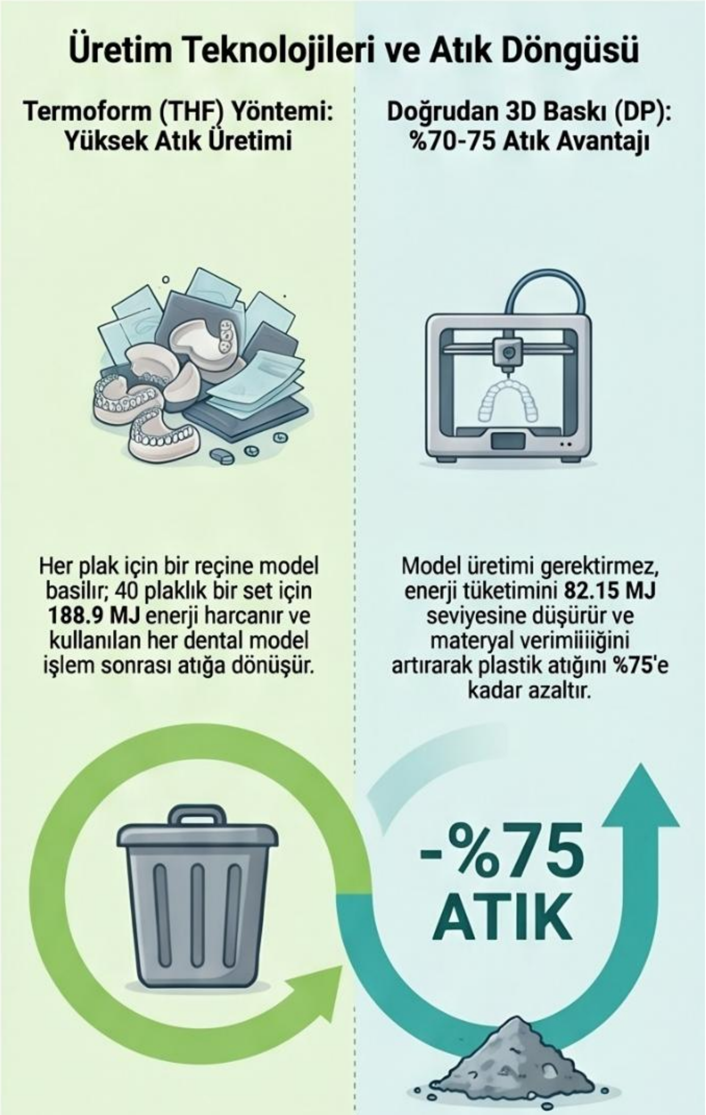


Figure 1. Waste cycles associated with different production methods for clear aligners.

However, despite its advantages, digital production methods raise important concerns. Consider that inadequate polymerization may release residual monomers, leading to cytotoxic effects.

Moreover, photopolymer resins have been reported to release microplastics and contribute to environmental degradation during intraoral use (Panayi et al., 2024).

Table 1. Comparative characteristics of clear aligner materials

Property	PETG	TPU	Multilayer Composite	Photopolymer (3D)
Structure	Amorphous thermoplastic	Elastomeric polymer	Multilayer / phase-separated	Cross-linked polymer
Force delivery	Initially high, rapid decline	Lower but sustained	Optimised, stable	Variable, production-dependent
Ageing behaviour	Hydrolysis, increased brittleness	Deformation and creep	Risk of inter-layer delamination	Residual monomer effects
Recycling potential	Theoretical, limited in practice	Low	Very low (complex structure)	Uncertain / potential risk
Microplastic potential	Moderate–high	Moderate	Complex particle profile	High potential

(Delgado et al., 2025; Gözüpek et al., 2024)

Chemical Safety and Microplastic Release in Clear Aligners

For many years, biosafety concerns related to clear aligner materials focused mainly on the release of BPA. Early systematic reviews assessed chemical safety largely by measuring this compound (Iliadi et al., 2020; Peter et al., 2023). More recently, studies on microplastics and nanoplastics have broadened this perspective.

Chemical Leaching and BPA Safety

The chemical behavior of aligner materials differs depending on the type. For example, PETG-based materials tend to leach more polymers than SmartTrack or photopolymer resins. While most major aligner systems reportedly do not release detectable BPA under clinical conditions, how to interpret these findings remains uncertain in light of updated regulatory limits (Peter et al., 2023; Yazdi et al., 2023).

Furthermore, in 2023, the EFSA reduced the tolerable daily intake of BPA from 4 µg/kg/day to 0.2 ng/kg/day—a twenty-thousand-fold reduction. How the previously 'safe' leaching threshold should be re-evaluated in light of this revision, particularly given that aligner use may continue for several years, has yet to be clearly established.

Microplastic and Nanoplastic Release

The potential for clear aligners to release microplastics and nanoplastics is a growing focus in biosafety research. Microplastics, which are smaller than 5 millimeters, and nanoplastics, under 1 micrometer, are especially concerning because they can cross biological barriers.

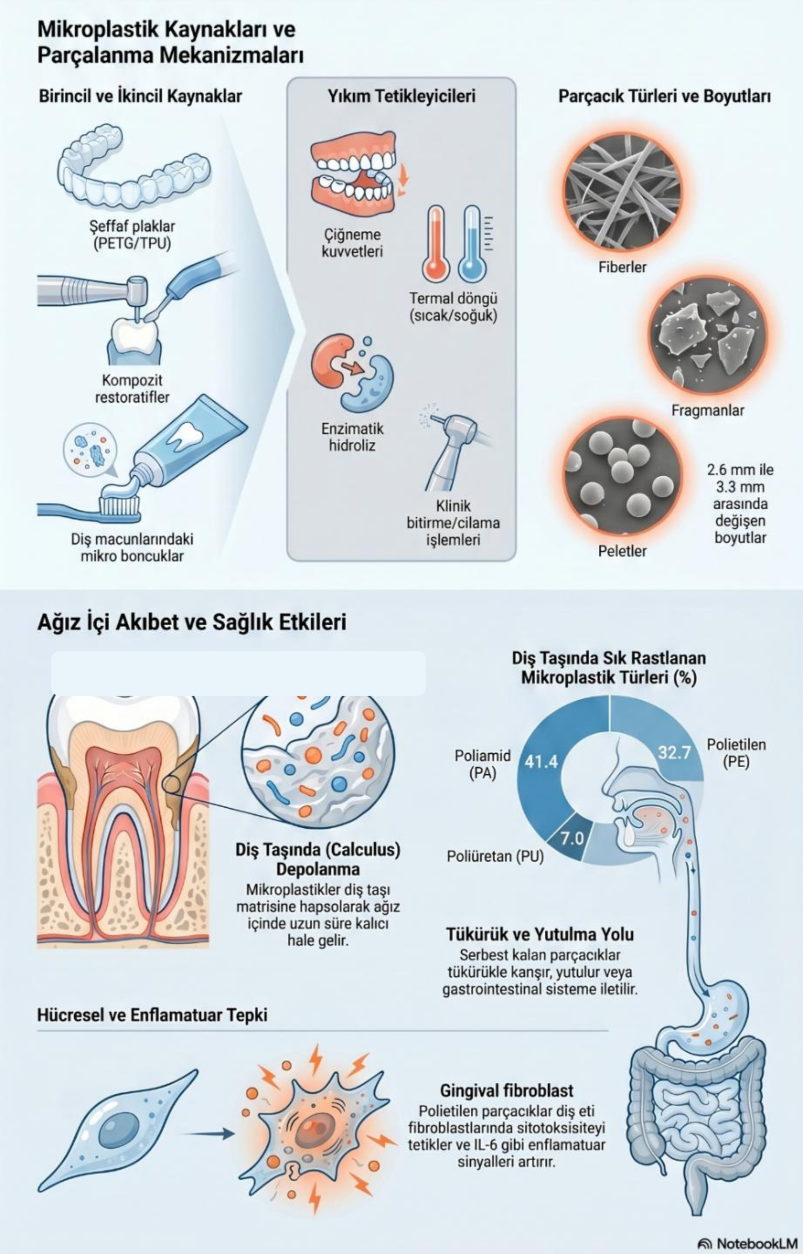
Formation Mechanisms

Microplastics from dental materials can come from two main sources (Di Spirito et al., 2025). Primary microplastics are introduced directly in products like certain toothpastes. Secondary microplastics are formed when PETG- and TPU-based clear aligners undergo mechanical wear, heat, or hydrolysis.

Daily use of aligners—including putting them in and taking them out, chewing, and friction against teeth—leads to micro-cracks and eventually causes small particles to break off. Variations in temperature, moisture, and pH in the mouth speed up this process through chemical reactions (De Stefano et al., 2025). Simulated oral studies show that friction increases microplastic release from TPU and PETG materials (Panayi et al., 2024).

Biological Effects

Studies have found microplastics in the saliva of patients using aligners, and these particles can be swallowed, enter the digestive system, and even reach the bloodstream (Di Spirito et al., 2025). According to De Stefano et al. (2025), such particles may cross the intestinal wall and accumulate in organs like the liver, kidneys, and lymph nodes. Evidence that nanoplastics might cross the blood-brain barrier is especially significant. Figure 2 illustrates how microplastics are formed in the mouth and their effects on health.



Mikroplastikler diş taşı matrisine hapsolarak ağız içinde uzun süre kalıcı hale gelir.

Serbest kalan parçacıklar tükürükle karışır, yutulur veya gastrointestinal sisteme iletilir.

Polietilen parçacıklar diş eti fibroblastlarında sitotoksisiteyi tetikler ve IL-6 gibi enflamatuar sinyalleri artırır.

Figure 2. Intraoral mechanisms responsible for microplastic fragmentation and their effects on human health.

Biofilm Adaptation

Microplastic surfaces constitute a sheltered micro-habitat for pathogens. Plastic particles derived from dental materials have been reported to promote biofilm formation and increase resistance to antimicrobial agents (Di Spirito et al., 2025). Bacteria such as E. faecalis have been observed to enhance antibiotic resistance on plastic surfaces. This suggests that the oral microbiota balance may be disrupted in patients using clear aligners.

From an environmental perspective, microplastics originating from clear aligners enter waste streams and reach aquatic and soil ecosystems, where they interact with persistent organic pollutants (POPs) and amplify biological toxicity. The need for standardized measurement methods—most notably FTIR and Raman spectroscopy—is becoming increasingly apparent in this field.

Regulatory Framework and Sustainability Policies

Given their duration of intraoral use and tissue contact, clear aligners are classified as Class IIa medical devices under the EU Medical Device Regulation (EU MDR 2017/745). Although this classification encompasses market access and clinical safety obligations, it does not provide a binding protocol for the disposal of used aligners.

Two policy instruments remain on the agenda to address this structural gap. The implications of the Packaging and Packaging Waste Regulation (PPWR, 2025/40) for the medical device sector, and the integration of the Extended Producer Responsibility (EPR) model into orthodontic practice, are regarded as mechanisms that could make it possible to hold manufacturers accountable across the full life cycle of their products.

Environmental Burden and Life Cycle Assessment

The environmental dimension of clear aligner therapy requires consideration not merely of waste volume, but of the entire process from raw material extraction to disposal. Life cycle analysis (LCA) is the most well-established tool for this holistic assessment and is increasingly employed for comparative evaluations across different orthodontic systems.

Peluso et al. (2026) reported that metal bracket systems generate higher CO_2 emissions during manufacturing; however, owing to their recyclability, they leave a lower overall environmental burden across the full life cycle (Table 2). Clear aligner systems, by contrast, are placed at a marked disadvantage at the end-of-life phase due to the inadequate recycling infrastructure for thermoplastic materials.

Table 2. Comparative environmental impact of conventional bracket systems and clear aligners

Parameter	**Conventional Bracket Systems**	**Clear Aligner Systems**
Waste type	Metal (steel/NiTi), ceramic	Thermoplastic polymers (PETG, TPU, PU)
Production CO_2 emissions	High in production phase (mining/processing)	Moderate in raw material logistics, low in production
Energy consumption	Moderate	High (continuous production and logistics)
Recycling potential	Higher (metallurgical cycle)	Low (Asia 12%, EU 29%; contamination risk)
Microplastic generation	None	Release during use phase
LCA focus	Material durability and metallurgical burden	Single-use waste and microplastic accumulation

(Peluso et al., 2026; Boonchanachai et al., 2025)

While Boonchanachai et al. (2025) report that clear aligner therapy generates more than 1,000 tonnes of plastic waste annually, Palmieri et al. (2024) estimate that this figure may reach approximately 15,000 tonnes when the entire production chain is taken into account. Given that recycling rates stand at 12% in Asia and 29% in Europe, it is evident how far the current situation falls short of sustainability.

The majority of existing studies cover only the 'cradle-to-gate' phase, while full-life-cycle data encompassing the use and disposal phases remain insufficient. Eliades et al. (2025) recommend standardizing LCA-based decision-making processes and fostering environmental responsibility at both the manufacturer and clinician levels.

Waste Management Strategies

The management of clear aligner waste should be addressed at three complementary levels: production optimization, clinical practice protocols, and take-back systems. Boukhris et al. (2025) emphasize that waste segregation systems in dental clinics are generally inadequate and that a lack of staff training exacerbates this problem.

4R Protocol at the Clinical Level

The sustainability protocol for orthodontic practice is built on four core principles (Macrì et al., 2024; Sakchhi et al., 2025):

REDUCE: Eliminate unnecessary aligner steps by optimizing digital treatment planning and minimizing the production of intermediate models.

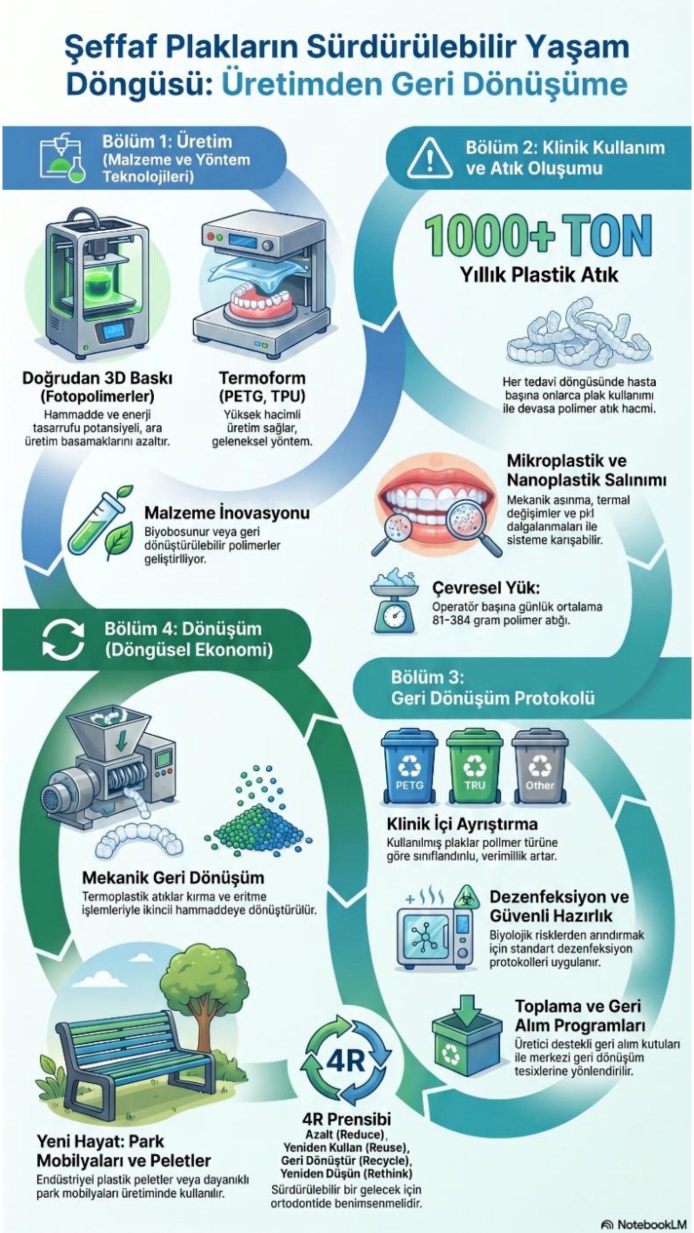
RETHINK: Incorporate environmental impact criteria into material selection; inform patients of chemical exposure and microplastic risks.

RECYCLE: Collect used aligners separately from general waste; incorporate them into manufacturer take-back programs.

REUSE: Prioritize recyclable or biodegradable resins in the production of clinical models.

Manufacturer-Based Take-Back Programmes

Industry-level recycling initiatives aim to collect used aligners through dedicated collection systems and convert them into secondary raw materials. The majority of existing programmes remain at the level of 'downcycling' (secondary recycling) or 'quaternary recycling' (energy recovery through incineration). Primary recycling capacity is still limited. Progress in this area requires that manufacturer commitments be underpinned by legal obligations. The life cycle of clear aligners, from production through to recycling stages, is illustrated in Figure 3.



Şeffaf Plakların Sürdürülebilir Yaşam Döngüsü: Üretimden Geri Dönüşüme

Bölüm 1: Üretim (Malzeme ve Yöntem Teknolojileri)

Doğrudan 3D Baskı (Fotopolimerler)
Hammadde ve enerji tasarrufu potansiyeli, ara üretim basamaklarını azaltır.

Termoform (PETG, TPU)
Yüksek hacimli üretim sağlar, geleneksel yöntem.

Malzeme İnovasyonu
Biyobosunur veya geri dönüştürülebilir polimerler geliştirlliyor.

Bölüm 2: Klinik Kullanım ve Atık Oluşumu

1000+ TON
Yıllık Plastik Atık
Her tedavi döngüsünde hasta başına onlarca plak kullanımı ile devasa polimer atık hacmi.

Mikroplastik ve Nanoplastik Salınımı
Mekanik aşınma, termal değişimler ve pH dalgalanmaları ile sisteme karışabilir.

Çevresel Yük:
Operatör başına günlük ortalama 81-384 gram polimer abğı.

Bölüm 3: Geri Dönüşüm Protokolü

Klinik İçi Ayrıştırma
Kullanılmış plaklar pollmer türüne göre sınıflandınlu, verimillik artar.

Dezenfeksiyon ve Güvenli Hazırlık
Biyolojik risklerden arındırmak için standart dezenfeksiyon protokolleri uygulanır.

Toplama ve Geri Alım Programları
Üretici destekli geri alım kutuları ile merkezi geri dönüşüm tesixlerine yönlendirilir.

Bölüm 4: Dönüşüm (Döngüsel Ekonomi)

Mekanik Geri Dönüşüm
Termoplastik atıklar kırma ve eritme işlemleriyle ikincii hammaddeye dönüştürülür.

Yeni Hayat: Park Mobilyaları ve Peletler
Endüstriyel plastik peletler veya dayanıklı park mobilyaları üretiminde kullanılır.

4R Prensibi
Azalt (Reduce), Yeniden Kullan (Reuse), Geri Dönüştür (Recycle), Yeniden Düşün (Rethink)
Sürdürülebilir bir gelecek için ortodontide benimsenmelidir.

Figure 3. Life cycle of clear aligners from production to recycling stages.

Conclusion

The findings reviewed in this chapter demonstrate that clear aligner therapy gives rise to two distinct yet intersecting areas of concern: plastic waste burden and chemical/biological risks.

In terms of plastic waste, the production volume estimated at between 1,000 and 15,000 tonnes per year, combined with recycling rates as low as 12-29%, calls for urgent intervention. Thermoforming and 3D printing methods each generate different waste profiles, and the single-use thermoplastic design makes recycling technically challenging. Metal bracket systems, by contrast, leave a lower overall environmental burden across the life cycle owing to the advantage of metallurgical recyclability.

With regard to chemical and biological risks, the existing literature demonstrates that PETG- and TPU-based materials release microplastics and chemical components during intraoral use. Although detectable BPA release under clinical conditions has been found to be low for major systems (Peter et al., 2023; Yazdi et al., 2023), EFSA's 2023 threshold revision calls this assessment into question. Microplastic research has documented the presence of aligner-derived particles in saliva, the gastrointestinal tract, and environmental matrices; however, the long-term health effects have yet to be sufficiently elucidated.

Three priority areas emerge from the existing research gaps: (1) the quantification of microplastic release using standardised methods such as FTIR/Raman spectroscopy; (2) the development of full LCA models covering 'cradle-to-grave'; and (3) the comparative evaluation of the effectiveness of manufacturer recycling programmes.

Sustainable orthodontic practice requires the concurrent implementation of material innovation, LCA-based evaluation, manufacturer recycling programmes, and binding regulatory frameworks. Without interdisciplinary collaboration among clinicians, manufacturers, researchers, and policy-makers, these objectives cannot be achieved.

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