Mechanical Properties, Biocompatibility, and Environmental Impact of Direct Printed Orthodontic Aligners - A Literature Review

Nikola Sophie Ortner

Dental Practice, Düsseldorf, Germany

Abstract

AIM: The aim of this study was to perform a systematic review of the orthodontic literature regarding the mechanical properties of thermoformed aligners in comparison to direct printed aligners.
METHODS: This study searched German and English publications in PubMed and Scopus using Boolean operators to find articles on 3D-printed and thermoformed aligners, focusing on mechanical properties, biocompatibility, and environmental impacts. The search was limited to articles from the past 10 years. Publication types such as systematic reviews, comments, and conference abstracts were excluded.
RESULTS: A total of 606 potentially relevant studies were identified, of which 16 were included in the investigation after applying selection criteria based on the PICO research approach. Directly printed aligners demonstrated several advantages in biocompatibility, mechanical properties, and environmental impact. However, some studies indicated adverse effects of resin aligners, attributed to variations in the manufacturing process.
CONCLUSION: Within the limitations of this study, it was determined that three-dimensional printing technology offers numerous high-quality benefits compared to conventional thermoforming. The mechanical properties of 3D printed materials are influenced by the printing and post-processing methods, as well as the different 3D printers employed, leading to expected variations in their therapeutic effectiveness.

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1 Introduction

The increasing popularity of transparent aligners in orthodontic treatment has led to a growing need for comparisons between different manufacturing methods. Particularly, the trend towards direct 3D printing of aligners compared to thermoformed aligners is the focus of this study.

The disadvantages of conventional treatment methods and the growing demand from patients for alternative "invisible" solutions have contributed to the popularization of transparent aligners. These aligners are used in series based on precise impressions or digital scans of patients' teeth to gradually achieve the planned tooth alignment (Rossini et al., 2015). The clear, transparent appearance and the ability to remove aligners during meals and for oral hygiene, along with increased comfort and ease of use, are significant advantages (Shalish et al., 2012).

The development of aligners originally began as an instrument for the final stages of orthodontic treatment or for correcting minor dental misalignments (Kesling, 1946). Over time, advancements led to clear aligners being used for the treatment of moderate to severe malocclusions as well. In addition to Invisalign™ and Clear-Aligner™, there are now numerous other brands of aligners available (Hennessy et al., 2016; Ercoli et al., 2014).

The production of clear aligners from thermoplastic materials is a complex process associated with various challenges. The environmental impact of resins used for 3D models is not yet sufficiently documented, and the high energy consumption as well as significant material waste pose problems (Khosravani & Reinicke, 2020). Aligners manufactured through thermoforming undergo significant changes in their material properties, particularly regarding thickness, transparency, and water absorption (Ryu et al., 2018; Bucci et al., 2019). Thickness homogeneity plays a crucial role in the effectiveness of the generated forces (Weir, 2017; Lombardo et al., 2020; Proffit et al., 2018). Interaction with the intraoral environment, including body temperature, humidity, and saliva, affects the original dimensions and mechanical properties of the aligners (Bradley et al., 2015; Ryokawa et al., 2006; Shirey et al., 2023). As an alternative to conventional methods, the introduction of 3D direct printing of transparent aligners using specialized resins has the potential to usher in the fourth revolution in orthodontics (Shivapuja et al., 2019).

The 3D printing technique for clear aligners utilizes an additive manufacturing process, where resin is deposited layer by layer (Groth et al., 2014). Specialized software tools such as Rayware, PreForm, and UNIZ Dental are used for nesting, support design, and slicing during the printing process (Pratsinis et al., 2022). When selecting resin for 3D printing, physical, mechanical, optical, and biological properties must be considered (Can et al., 2022). Examples of approved resins for direct 3D printing of clear aligners include Tera Harz TC-85 DAC and 3D:1M (Lee et al., 2022; Can et al., 2022).

Post-processing of the printed aligner material involves cleaning procedures, support removal, and post-curing (Pratsinis et al., 2022). Various models, such as the THC 2 UV Curing System or the Form Cure oven, are used depending on the resin type (Lee et al., 2022; Ahamed et al., 2020; Edelmann et al., 2020). Overall, direct 3D printing of aligners appears to offer several advantages over conventional manufacturing. Digitally designed margins, smooth edges, absence of undercuts, and higher precision contribute to a better fit and increased effectiveness of the aligners. The adjustability of intra-aligner thickness could reduce the need for attachments that compromise transparency (Tartaglia et al., 2021). Despite these advancements, some resins and methods are not yet fully researched for clinical application, and clinical efficacy remains an area for further study and development (Willi et al., 2023).

The aim of this work is to make a comparative assessment of the mechanical properties between directly printed aligners and thermoformed aligners through a comprehensive analysis of the current scientific literature.

2 Methods

The search for relevant publications was conducted using a meticulously designed search strategy to ensure comprehensive coverage of the literature. The search was performed in the Medline (via PubMed) and Scopus databases employing Boolean operators "AND" and "OR" with the terms *((3D Printed) OR (Directly Printed) OR (In-house Aligners) OR (Thermoformed Aligners)) AND ((Aligners) AND ((Mechanical Properties) OR (Force) OR (Geometrical Properties) OR (Cytotoxicity))*. This search yielded a total of 311 results in PubMed and 295 results in Scopus.

This strategy was implemented to identify publications focused on 3D-printed aligners and thermoformed aligners, with an emphasis on examining their mechanical properties, force transmission, cytotoxicity, as well as geometrical and environmental characteristics. Only German and English publications from the past decade were included to ensure the integration of the most recent research.

This meticulously constructed search strategy facilitates a concentration on contemporary and pertinent studies that elucidate specific aspects of mechanical properties, force dynamics, and cytotoxic effects associated with various aligner manufacturing processes.

The studies selected for inclusion in this analysis encompass both in vitro and in vivo research published in English and German. These studies are sourced from the most recent decade, ensuring the relevance and applicability of the findings. The focus is specifically on research that explores the use of retention splints and active aligners for therapeutic purposes. To capture a comprehensive view of clinical applications, both prospective and retrospective clinical studies are considered.

Conversely, certain publication types are excluded from this analysis to maintain a focus on original research and clinically applicable outcomes. Specifically, the exclusion criteria filter out reviews, systematic reviews, commentaries, and conference abstracts. Additionally, studies discussing transfer trays and positioning guides intended for use with temporary skeletal anchorage devices (TADs) are not included, ensuring that the scope remains tightly aligned with therapeutic interventions involving retention splints and active aligners.

Out of a total of 606 potentially relevant studies, 16 were included in this analysis (**Figure 1**). The selection criteria were applied according to the PICO research framework as follows:

- **Population:** Patients undergoing orthodontic treatment or in the retention phase.
- **Intervention:** Treatment with 3D-printed aligners or thermoformed aligners.
- **Comparison:** Properties of 3D-printed aligners compared to thermoformed aligners.
- **Outcome:** Effectiveness of the respective device.

The selected publications consist of in vitro and in vivo studies published within the last ten years. Due to the specific focus of this work on aligners in the context of therapeutic and retention applications, transfer trays for indirect bonding and guides for the placement of temporary skeletal anchorage devices were excluded from the investigation. Additionally, reviews, systematic reviews, commentaries, and conference abstracts were not included in the analysis.

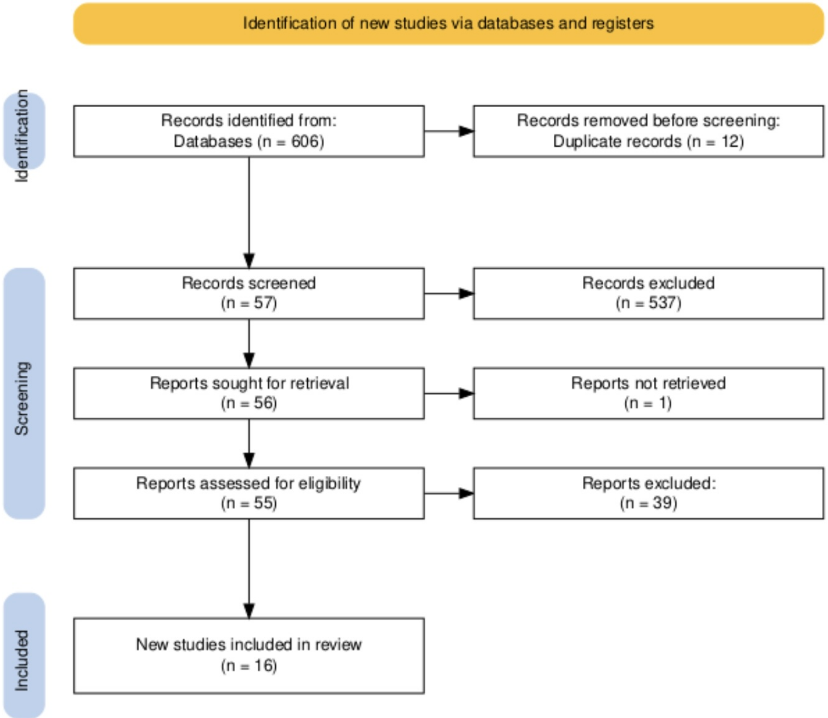

Figure 1. Flowchart for describing study selection.

The data extraction process followed a structured methodological approach based on scientific criteria and selective inclusion. A thorough review was conducted to eliminate duplicates, ensuring each publication was unique in the dataset. Initial selection involved reading abstracts and titles to identify relevant studies, followed by a comprehensive review of the full articles to assess quality and relevance. The final selection considered predefined inclusion and exclusion criteria, resulting in a focused set of studies that provided a solid foundation for the research.

2.1 Statistics

Descriptive statistics, frequency analysis, and content analysis were employed as part of the qualitative methodology to systematically analyze the textual content of the included studies. It is important to note that, given the narrative nature of this study, regression analysis and meta-analysis techniques were not deemed suitable for the analytical framework.

3 Results

By querying the databases with the specified search terms, a total of 606 studies were initially retrieved (MEDLINE/PubMed: $n = 311$; Scopus: $n = 295$). After thorough examination, 16 of the initially identified 606 potentially relevant studies were included in this investigation. After removing duplicates, 594 studies remained. A total of 537 studies were excluded based on titles and abstracts. One publication was excluded due to insufficient availability of the full text, while 39 articles were excluded after reviewing the full text due to a lack of substantive relevance. The remaining 16 articles were used for qualitative assessment. A meta-analysis could not be performed due to methodological heterogeneity among the studies. The results of the studies will be reported in the following sections: (1) Mechanical Properties, (2) Biocompatibility, and (3) Environmental Impact.

3.1 Mechanical properties

The mechanical properties of 3D-printed aligners were analysed and compared to those of thermoformed aligners using multiple in vitro experiments and two in vivo studies (Supplemantary **Table S1**). Some studies found that 3D-printed aligners exhibit superior mechanical properties. A notable mechanical characteristic of directly printed Tera Resin TC-85 aligners (Graphy, Seoul, Korea) described in the literature is the so-called shape memory property. While the TC-85 aligners returned to their original shape after deformation at temperatures up to 80 °C, thermoformable materials showed only minimal recovery. The increased flexibility and viscoelastic nature of the 3D-printed aligners allowed for improved control of aligner design and thickness, resulting in a consistent, gentle force application on the teeth (Lee et al., 2022; Atta et al., 2024). Another study demonstrated that 3D-printed aligners also had a lower force profile compared to thermoformed aligners, analysing force application in the vertical dimension at intraoral temperatures (Hertan et al., 2022).

Furthermore, the customisation of directly printed aligners by varying thickness showed that the generated forces and moments can be optimised. According to Gran et al. (2023), strategically increasing the labiolingual thickness of 3D-printed aligners presents a promising option and can reduce side effects during tooth movements. By varying the thickness, a controlled tipping motion and high-quality biomechanics could be achieved. Another way to customise resin aligners is by adding chitosan nanoparticles to the clear plastic to reduce the number of *Streptococcus mutans*. The incorporation of biocompatible chitosan nanoparticles into the plastic allows the aligner to add an antibacterial element without compromising its biological, mechanical, and physical properties (Taher & Rasheed, 2023).

In the in vivo study by Can et al. (2022), TC-85 printed aligners were used, consisting of ten unused control aligners and six aligners recovered after one week of wear. The aligners were examined using attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) and underwent an instrumented indentation test (IIT) to evaluate their mechanical properties (Riaz et al., 2016). The results showed no significant differences in mechanical properties between the recovered and control aligners, indicating that the mechanical properties were not compromised after one week of wear. However, the study highlighted concerns regarding the elevated relaxation index and reduced Martens hardness (Sayahpour et al., 2024; Can et al., 2022). The ability of 3D-printed aligners to withstand high loads was also demonstrated in the in vitro study by Jindal et al. (2019). A comparison of geometric inaccuracies between conventionally manufactured thermoformable Duran aligners and 3D-printed aligners made from dental long-term (LT) resin using an SLA printer (Form 2, Formlabs Inc., Stereolithography) revealed that 3D-printed clear aligners were geometrically more precise after curing, with an average relative tooth size difference of 2.55%, compared to 4.41% for thermoformed aligners (Jindal et al., 2019; Rajasekaran et al., 2023; Vas et al., 2024).

Thermoplastic polyurethane aligners, which are produced similarly to polyethylene glycol terephthalate (PETG) aligners in the thermoforming process, demonstrated in an in vitro study by Tarek et al. (2023) that artificial aging through thermocycling and mechanical loading affects force/torque. Specifically, aging in deionized water led to a significant reduction in generated force and torque under both thermal cycling and mechanical stress, with mechanical loading proving to be a more dominant factor in changing the mechanical properties of the aligners compared to thermal cycling (Tarek et al., 2023).

The simulated oral environment also had a significant impact on the mechanical properties of the directly 3D-printed aligners. The mechanical properties of four aligner materials—EX30, LD30, Material X, and OD-Clear TF—were evaluated under various conditions, focusing on the impact of a simulated oral environment on the performance of directly 3D-printed aligners (Shirey et al., 2023). The analysis revealed notable differences in elastic modulus, maximum tensile strength, and stress relaxation among the materials (Shirey et al., 2023). Notably, the presence of moisture in the simulated oral environment appeared to have a more pronounced influence on the mechanical properties of directly 3D-printed aligners (Shirey et al., 2023). According to Shirey et al. (2023), this could lead to challenges in generating and maintaining sufficient force levels for tooth movement.

In a further study comparing in-house and commercially thermoformed aligners to directly printed aligners, the former showed more favourable mechanical properties. Specifically, in-house thermoformed aligners made from PETG demonstrated better properties regarding wear resistance, stiffness, and force decay. Conversely, the directly printed aligners exhibited a higher indentation relaxation time (RIT) after one week of wear, indicating a greater force drop. The Martens hardness and elastic modulus were comparable between the thermoformed and directly printed aligners. However, the authors noted that although the directly printed aligners were manufactured under nitrogen, there may have been incomplete polymerisation, which could be responsible for the lower mechanical properties (Sayahpour et al., 2024).

The mechanical properties of TC-85 Tera Resin aligners were affected by different post-curing conditions, including exposure to nitrogen or air, as well as rinsing protocols involving centrifugation, ethanol, isopropanol, and a combination of isopropanol and water. The presence of oxygen had detrimental effects on the polymerisation process (Simunovic et al., 2024). In additive manufacturing methods such as stereolithography (SLA) and digital light processing (DLP), achieving a high conversion rate is crucial (Simunovic et al., 2024). This rate, which reflects the extent of polymerisation, has a direct impact on the material properties and can be hindered by the presence of oxygen (Simunovic et al., 2024). The higher the conversion rate, the denser the polymer network, which improves material strength and durability (Simunovic et al., 2024). The rinsing protocol is also highly relevant for material performance. Both the standard protocol, involving centrifugation followed by nitrogen polymerisation, and the groups treated with ethanol and nitrogen demonstrated enhanced wear resistance (Simunovic et al., 2024). Sayahpour et al. (2024) emphasised that a standardised protocol for manufacturing directly printed aligners is essential.

The results of various studies are currently not directly comparable due to numerous discrepancies in printing and post-processing procedures, leading to significant variations (Sayahpour et al., 2024). Although the same resin and post-curing process were used, the mechanical properties of 3D-printed aligners differed depending on the 3D printer, which could affect their clinical effectiveness. LCD (Liquid Crystal Display) printers generally exhibited higher values for Martens hardness (HM), indentation modulus (EIT), and elastic modulus (ηIT) than DLP printers (Papageorgiou et al., 2019). Zinelis et al. (2022) attribute these differences to the varying technologies used to expose the entire resin layer to light, despite both DLP and LCD curing the full layer simultaneously. DLP technology utilises a projector with micro-mirrors to focus light on specific areas of the resin layer, while LCD technology uses LCD panels to block light from curing certain areas of each layer. The direction in which the print is oriented (horizontal or vertical) did not significantly affect the mechanical properties of resin-based 3D-printed aligners. As a result, Camenisch et al. (2023) suggest that dentists can treat directly printed aligners as isotropic materials, meaning they are likely to perform similarly in the mouth regardless of different activation forces.

3.2 Biocompatibility

Since the biocompatibility of directly printed three-dimensional aligners has been scarcely researched, the study by Pratsinis et al. (2022) addressed this topic. The study examined the effects of TC-85 aligners regarding cytotoxicity and estrogen activity by immersing ten sets of aligners in sterile deionized water over a period of two weeks. The release of factors was evaluated in human gingival fibroblasts (HGF), along with estrogen-sensitive MCF-7 and estrogen-insensitive MDA-MB-231 breast cancer cell lines (Papageorgiou et al., 2019). The results showed no cytotoxic factors for HGF and no estrogenic effects. However, the authors raised concerns about the oral environment, highlighting its challenging nature for polymers due to the presence of moisture and simultaneous multiaxial stresses (Pratsinis et al., 2022). Shirey et al. (2023) also described that the oral environment can significantly influence the mechanical properties of directly printed aligners.

Martina et al. (2019) also evaluated the cytotoxicity of aligners. This time, however, it involved thermoplastic materials analysed on HGF. Samples of Duran, Biolon, Zendura, and SmartTrack were examined and compared. Each of the materials showed a slight cytotoxic reaction after two weeks, with the highest degree observed in Biolon and the lowest in Duran (Martina et al., 2019). The thermoforming process led to an increase in the cytotoxicity of the materials (Premaraj et al., 2014). However, according to Martina et al. (2019), this toxicity could be considered clinically irrelevant. The authors emphasised that the intraoral environment could not be taken into account in this study and that the properties of the aligners may change due to intraoral aging (Martina et al., 2019).

In summary, both studies focus on the cytotoxicity of various aligners on HGF. HGF were specifically chosen because they, along with the cells of the oral mucosa, are the main components of oral tissues. As the aligners come into direct contact with the gums during wear, individuals are consequently exposed to the potentially harmful effects of both materials (Mockers et al., 2002).

3.3 Environmental impact

Thermoplastic materials used in aligner production are plastic products susceptible to environmental and mechanical degradation, which may result in the release of microplastic particles (MPs) (Schwabl et al., 2019). The research conducted by Quinzi et al. (2023) investigated whether orthodontic aligners can release MPs for the first time. Aligners from seven different manufacturers were subjected to a seven-day test with artificial saliva to simulate the friction that occurs during chewing. The released particles were then analysed using specialised techniques. The small polymer fragments that can detach could be additional microplastic particles and may lead to health issues for patients. This in vitro study revealed that mechanical friction caused the release of MPs from clear aligners, with Arc Angel aligners releasing the highest number of MPs and Invisalign aligners the lowest (Schwabl et al., 2019; Quinzi et al., 2023).

The size of the microparticles is particularly significant. While larger particles require active endocytosis, smaller particles can passively cross membranes (Kettiger et al., 2013;

Triebskorn et al., 2019; Schwabl et al., 2019; Yang et al., 2022). Large particles of 20 μm and more are generally excreted through the digestive tract (Schwabl et al., 2019; Wieland et al., 2022). In the study by Quinzi et al. (2023), MPs with a diameter of 5-20 μm were found in all tested aligners. In most groups, the MPs measured 20 μm or more. MPs under 5 μm were only detected in F22 aligners, Lineo aligners, and Invisalign aligners, albeit in small percentages. MPs originating from F22 and Invisalign aligners appeared as aggregates of microspheres and could therefore lead to further detachment of smaller microparticles with higher toxicity in the gastrointestinal tract (Quinzi et al., 2023).

Compared to directly 3D-printed clear aligners, the thermoformed materials exhibited increased cytotoxicity, which, according to Martina et al. (2019), is likely due to the release of monomers at elevated temperatures during the thermoplastic process. Currently, there is no information in the literature regarding the release of MPs from directly 3D-printed aligners, indicating a need for further research.

4 Discussion

Direct printing of aligners offers a viable alternative to thermoformed aligners by accelerating production, reducing plastic consumption, and optimising biomechanical properties and biocompatibility. This systematic review provides a comprehensive overview of the available evidence on 3D-printed and thermoformed aligners, focusing on clinically relevant material properties. Fourteen of the sixteen studies were published in the last three years (2022-2024), indicating a growing interest in this topic. A significant finding of this review is that directly printed aligners offer numerous advantages over thermoformed aligners. One advantage is the quicker manufacturing process and greater design flexibility, allowing for adjustments in material thickness and precise control of the gap between the aligner and teeth. This results in a tighter fit and improved tracking of programmed movements (Tartaglia et al., 2021; Grant et al., 2023).

Direct printing and the shape-memory effect allow for a wide range of applications. The option to adjust the thickness of aligners for different tooth movements and anatomical areas adds a new dimension to conventional aligner therapy. In the future, 3D-printed aligners could be designed with varying thicknesses within a single aligner, covering different areas with different thicknesses (Gran et al., 2023). This feature could also be used to integrate elements known from functional orthodontic appliances, such as Twinblock bites or SARA (Sabbagh Advanced Repositioning Appliance) splints (Graf, 2022).

A disadvantage of conventional thermoformed aligners is the loss of force due to stress relaxation, which could be overcome by 3D-printed aligners (Tarek et al., 2023). Directly printed aligners can exert a constant and gentle force on the teeth due to their shape-memory effect. Since this type of aligner has a high restorative force at temperatures of 37°C and 80°C, they can also be cleaned at high temperatures, contributing to enhanced hygiene and a reduction in bacterial accumulation within the aligners (Lee et al., 2022; Atta et al., 2024). Additionally, a study showed that the addition of chitosan nanoparticles to the clear plastic can further reduce the accumulation of bacterial colonies, particularly *Streptococcus mutans* (Taher & Rasheed, 2023).

However, studies have also highlighted the disadvantageous mechanical properties of additively manufactured aligners (Shirey et al., 2023; Sayahpour et al., 2024). In the study by Sayahpour et al. (2024), in-house thermoformed aligners made of PETG demonstrated better mechanical properties in terms of wear resistance, stiffness, and force degradation compared to directly printed aligners. Sayahpour et al. (2024) raised concerns regarding the post-printing phase. Although the post-printing polymerization in this study was conducted under nitrogen, the lower mechanical properties of directly printed aligners may indicate incomplete polymerization. This not only affects the mechanical properties and clinical performance of the aligners but also suggests a risk of residual monomers (Sayahpour et al., 2024).

Resin-based composites (RBCs) consist of complex polymers that transition from a viscous liquid to a hardened solid through a polymerization reaction (Cervino et al., 2020). This reaction is triggered by external energy and initiators (Riva et al., 2020). The depth of cure depends on the irradiation time, wavelength, light intensity, and the distance from the material surface (Zhan et al., 2021). Incomplete conversion, aging, mechanical wear, hydrolysis, and enzymatic degradation can result in the release of uncured monomers, initiators, and other additives into the oral cavity (Guo et al., 2022; Berghaus et al., 2023; Gitalis et al., 2019; Caldas et al., 2019; Bapat et al., 2021; Shahi et al., 2019; Mulligan et al., 2022; Palka et al., 2021). Since these materials are in long-term contact with the tissues of the oral cavity, understanding the biocompatibility and toxicity of biomaterials in dentistry is crucial (Mulla et al., 2023).

Biocompatibility defines the reactions of organisms to biomaterials and refers to their ability to elicit an appropriate host response (Mulla et al., 2023). Toxicity, in contrast, refers to the damage a biomaterial inflicts on the organism (Bapat et al., 2021). Toxic reactions, such as cytotoxicity, must therefore be avoided for a biomaterial to be classified as biocompatible (Bapat et al., 2022; Shahi et al., 2019; Mulligan et al., 2022; Schmal & Galler, 2017; Arab-Nozari et al., 2023).

The study by Pratsinis et al. (2022) demonstrated that the resin for 3D-printed aligners is safe to use and does not exhibit cytotoxic or estrogenic effects. However, they highlighted the challenges that the oral environment poses for polymers. Since this study focused solely on the hydrolysis of directly printed aligners, future studies should consider additional factors such as enzymatic reactions of saliva, masticatory forces, chemical effects of food, thermal changes, and the impact of the oral microbiota.

Environmental influences on the polymer degradation potential are crucial for obtaining clear indications regarding the biocompatibility of the materials used. Only through a comprehensive investigation of these variables can reliable and practical statements about the long-term compatibility and safety of 3D-printed aligners be made (Pratsinis et al., 2022). In contrast, thermoplastic aligner materials have shown cytotoxic reactions in the study by Martina et al. (2019), although the authors emphasise that this toxicity can be considered clinically irrelevant. Since the cytotoxicity of thermoplastic materials is likely due to the thermoforming process (Martina et al., 2019), direct manufacturing of aligners using 3D printing appears to offer a more biocompatible alternative. However, caution should be exercised in the clinical application of directly printed aligners, as the potential presence of residual monomers from incomplete polymerisation could exhibit cytotoxic, mutagenic, and estrogenic effects, potentially leading to allergies and hypersensitivities (Simunovic et al., 2024).

A study has already raised concerns about the leaching of TC-85 aligners, as high amounts of UDMA monomer were released (Baldion et al., 2021; Willi et al., 2023). Resins are highly cytotoxic before the 3D printing process, making an appropriate post-polymerisation procedure highly relevant (Ahamed et al., 2020). Cytotoxicity can be influenced by various parameters, including material composition, printing conditions, and post-processing procedures such as washing and post-curing. The post-curing environments, rinsing protocols, and the use of different 3D printers significantly impact the mechanical properties of TC-85 aligners. The presence of oxygen negatively affects the conversion rate during the polymerisation process, potentially compromising material strength and durability. Therefore, a standardised protocol for the production of directly printed aligners is essential (Sayahpour et al., 2024; Simunovic et al., 2024; Zinelis et al., 2022; Wulff et al., 2022).

Since microplastics are not only environmentally harmful but also pose health risks, Quinzi et al. (2023) were the first to investigate the release of microplastics (MPs) from conventionally manufactured aligners, demonstrating the detachment of MPs due to mechanical friction. Not only are the conventional aligners non-recyclable, but the resin plastic produced during the curing process is also non-recyclable. These materials pose environmental hazards and health risks due to the release of MPs (Kandil, 2019). Directly printed aligners have not yet been studied in relation to MPs; however, the use of directly printed aligners could avoid the disposal of models in the future, which would have positive environmental impacts.

This review has several limitations. It relies mainly on in vitro studies, meaning its relevance to real clinical scenarios may be limited. Additionally, the methods applied vary, making it difficult to compare results. Furthermore, the existing evidence may not be sufficient to draw definitive conclusions, as further research is needed to verify and expand the findings. Therefore, it is advisable to interpret the results of this study with caution and to conduct more well-controlled studies to deepen the understanding in this field.

Conclusions

The use of 3D-printed appliances in orthodontics has the potential to revolutionise treatments and improve patient experiences. Although 3D printing in orthodontics has advanced in recent years, the technology is still in its infancy. The direct printing of aligners is also in an early developmental stage. Nevertheless, the technology is promising and could address many of the current issues with conventional aligner systems, such as high material costs, slow and labour-intensive manufacturing processes, limited customisation options, inferior biomechanical properties, lower geometric accuracy, and high plastic consumption.

While direct 3D printing offers a pathway for technological advancement, the available evidence is limited, necessitating further research to validate the use of directly 3D-printed aligners. Until then, the use of thermoplastic materials remains the proven approach for aligner treatment. However, future developments could lead to new standards and expand possibilities for both patients and professionals.

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Ethical approval

No ethical approval was required for this study as it did not involve human participants, animal subjects, or sensitive data. This study falls under the category of data collection without participant identification.

Consent for publication

Not applicable.

Authors' contributions

The author(s) declare that all the criteria for authorship designated by the International Committee of Medical Journal Editors have been met. More specifically, these are: (a) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (b) Drafting the work or revising it critically for important intellectual content; AND (c) Final approval of the version to be published; AND (d) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests

The author(s) declare that there are no competing interests related to this work.

Author notes

Correspondence concerning this article should be addressed to
nikola.sophie.ortner@gmail.com

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