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REVIEW

MECHANICAL, PHYSICAL AND OPTICAL PROPERTIES COMPARISON BETWEEN DIRECT PRINTED AND THERMOFORMED ALIGNERS - A SYSTEMATIC REVIEW

Comparación de las propiedades mecánicas, físicas y ópticas entre alineadores impresos directamente y termoformados: una revisión sistemática

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ABSTRACT

Background: Clear aligners are a popular choice for orthodontic treatment due to their aesthetic appeal, comfort, and the ability to be easily taken on and off, unlike fixed appliances, which cannot be removed once treatment begins. Two common fabrication methods for aligners are direct 3D printing and thermoforming. This systematic review aims to compare the mechanical, physical, and optical properties of 3D-printed aligners (DPAs) and thermoformed aligners (TFAs) to provide evidence-based insights for clinicians and researchers.

Material and Methods: A comprehensive literature search was conducted in electronic data-bases, including *PubMed, Scopus, Web of Science and Google Scholar*, to identify studies evaluating and comparing DPAs and TFAs. Studies were selected based on predefined inclusion and exclusion criteria, focusing on outcomes such as load-deflection behavior, dimensional accuracy, tensile strength, force decay, thickness, and transparency. The quality of the included studies was assessed using the RoBDEMAT tool for *in vitro* studies and the ROBINS-I tool for *in vivo* studies. Data synthesis involved narrative and qualitative approaches to summarize the findings.

Results: A total of ten studies were included, comprising eight *in vitro* studies and two *in vivo* studies. The included studies exhibited moderate risk of bias due to insufficient reporting of randomization and operator blinding. DPAs demonstrated superior dimensional accuracy, thickness uniformity, and optical properties compared toTFAs. However, TFAs exhibited better force retention and consistent load. While the mechanical strength of DPAs was higher, TFAs showed greater stability in long-term force delivery.

Conclusions: DPAs provide superior precision and aesthetics, while TFAs offer better durability and sustained force retention, highlighting the need for case-specific aligner selection.

Keywords: *Orthodontic appliances, removable; Materials testing; Tensile strength; Mechanical phenomena; Optical phenomena; Three dimensional printing*

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RESUMEN

Antecedentes: Los alineadores transparentes son una opción popular para el tratamiento de ortodoncia debido a su atractivo estético, comodidad y facilidad de colocación y extracción, a diferencia de los aparatos fijos, que no se pueden retirar una vez iniciado el tratamiento. Dos métodos comunes de fabricación de alineadores son la impresión 3D directa y el termoformado. Esta revisión sistemática tiene como objetivo comparar las propiedades mecánicas, físicas y ópticas de los alineadores impresos en 3D (APD) y los alineadores termoformados (ATF) para proporcionar información basada en la evidencia a clínicos e investigadores.

Materiales y métodos: Se realizó una búsqueda bibliográfica exhaustiva en bases de datos electrónicas, incluyendo *PubMed, Scopus, Web of Science y Google Scholar*, para identificar estudios que evalúan y comparan los APD y los ATF. Los estudios se seleccionaron según criterios de inclusión y exclusión predefinidos, centrándose en resultados como el comportamiento carga-deformación, la precisión dimensional, la resistencia a la tracción, la disminución de la fuerza, el grosor y la transparencia. La calidad de los estudios incluidos se evaluó utilizando la herramienta RoBDEMAT para estudios *in vitro* y la herramienta ROBINS-I para estudios *in vivo*. La síntesis

Resultados: Se incluyeron un total de diez estudios, ocho in vitro y dos in vivo. Los estudios incluidos presentaron un riesgo moderado de sesgo debido a la información insuficiente sobre la aleatorización y el enmascaramiento del operador. Los alineadores DPA demostraron una precisión dimensional, uniformidad de espesor y propiedades ópticas superiores en comparación con los TFA. Sin embargo, los TFA mostraron una mejor retención de fuerza y una carga más consistente. Si bien la resistencia mecánica de los DPA fue mayor, los TFA mostraron mayor estabilidad en la aplicación de fuerza a largo plazo.

Conclusión: Los alineadores DPA ofrecen una precisión y estética superiores, mientras que los TFA brindan mayor durabilidad y una retención de fuerza más sostenida, lo que subraya la necesidad de seleccionar el alineador adecuado para cada caso.

Palabras clave: *Aparatos ortodóncicos removibles; Ensayo de materiales; Resistencia a la tracción; Fenómenos mecánicos; Fenómenos ópticos; Impresión tridimensional*

INTRODUCTION

The rise in demand for aesthetic, and patient-friendly orthodontic treatment has fueled advancements in the development of clear aligner technologies.[1] Clear aligners offer numerous benefits over traditional fixed appliances, including improved aesthetics, comfort, reduced chair time, and better patient compliance.[2]

Traditionally, clear aligners have been fabricated using a thermoforming process, which involves creating a series of physical dental models over which thermoplastic sheets are vacuum-formed.[3] However, this method can introduce geometric inaccuracies and material inconsistencies, potentially affecting clinical outcomes.[4]

The advent of 3D printing technologies has enabled the direct fabrication of aligners, bypassing intermediate steps like thermoforming and model creation.[5] This innovation promises to enhance precision, and improve mechanical properties by allowing greater control over material composition and design parameters. Studies have demonstrated that 3D-printed aligners exhibit improved geometric accuracy, mechanical strength, and consistent force application compared to their thermoformed counterparts.[6]

Despite these advancements, a systematic evaluation comparing the various properties of direct-printed aligners (DPA) and thermoformed aligners (TFA) is lacking. Properties such as elasticity, strength, and durability are critical for ensuring an aligner's clinical efficacy and longevity.[7] Elasticity ensures consistent force application by allowing the material to return to its original shape after deformation, while tensile and flexural strength determine its ability to withstand stretching and bending without damage.[8] Stiffness, quantified by Young's modulus, governs resistance to deformation and influences force delivery.

Durability, including resistance to wear and fracture, ensures the aligner maintains its integrity throughout use. Additionally, properties like stress relaxation and creep behavior affect the aligner's ability to sustain effective forces over time, making these factors essential for optimizing treatment outcomes and patient satisfaction.[8]

This review aims to systematically analyze and compare the mechanical, physical, and optical properties of direct-printed aligners (DPAs) and thermoformed aligners (TFAs) based on existing literature. By evaluating studies that report on these properties across both aligner types, this review seeks to provide valuable insights for orthodontists and researchers, aiding in the selection of materials and techniques to achieve optimal clinical and aesthetic outcomes for patients.

MATERIALS AND METHODS

Protocol Registration

The reporting of this study complies with the PRISMA 2020 statement reporting guidelines for systematic reviews was registered in the PROSPERO database (CRD42024629435).

The research question for this systematic review was: What are the differences in the mechanical, physical, and optical properties of 3D-printed aligners compared to thermoformed aligners? The included studies were presented in the PICO format, consisting of *in vitro* and *in vivo* studies that evaluated the mechanical, physical, and optical properties of DPAs and TFAs, as well as comparisons of these properties between the two types of aligners.

Search Strategy

To identify all peer-reviewed articles pertainning to the research question, an electronic search of literature published after January 2000 was conducted in the following databases: *PubMed, Scopus, Google scholar, Web of Science*. The manual search included reviewing the reference lists of included studies and related reviews to identify additional relevant publications. Only articles published until November 2024 were included. Duplicates were removed using *Rayyan.ai software*. Table 1 enumerates the search strategy and keywords used in the above mentioned databases. Figure 1 illustrates the PRISMA 2020 flow diagram for the selection of studies from the various databases.

Screening and selection of studies

The PRISMA flow chart illustrates the process of selecting the studies for the review (Figure 1). Two authors, NVP and RKJ, handled the study selection, tabulation, and quality assessment. NVP, and RKJ collaborated on data extraction from the included studies, resolving conflicts through discussion. Table 2 outlines the eligibility criteria for the included studies. Table 3 outlines the study characteristics, including the first author's name, publication year and journal, type of aligner (DPA or TFA), test parameters (mechanical, physical, optical properties), and testing methods and testing equipment.

Outcome measures

The included studies assessed various outcome parameters to compare the mechanical, physical and optical properties of DPAs and TFAs. The outcomes evaluated included dimensional accuracy, tensile strength, elastic modulus, hardness, thickness, gap width, load *versus* displacement behavior, geometric deviations, force application tests, and optical properties such as transparency and clarity.

Geometric deviations were evaluated to determine discrepancies between the intended and actual aligner shapes. Load *versus* displacement behavior was analyzed to measure the aligner's ability to generate and maintain orthodontic forces under applied stress. Dimensional accuracy was assessed using linear measurements to quantify precision in aligner fabrication.

Figure 1

PRISMA flow diagram for the included studies in the review

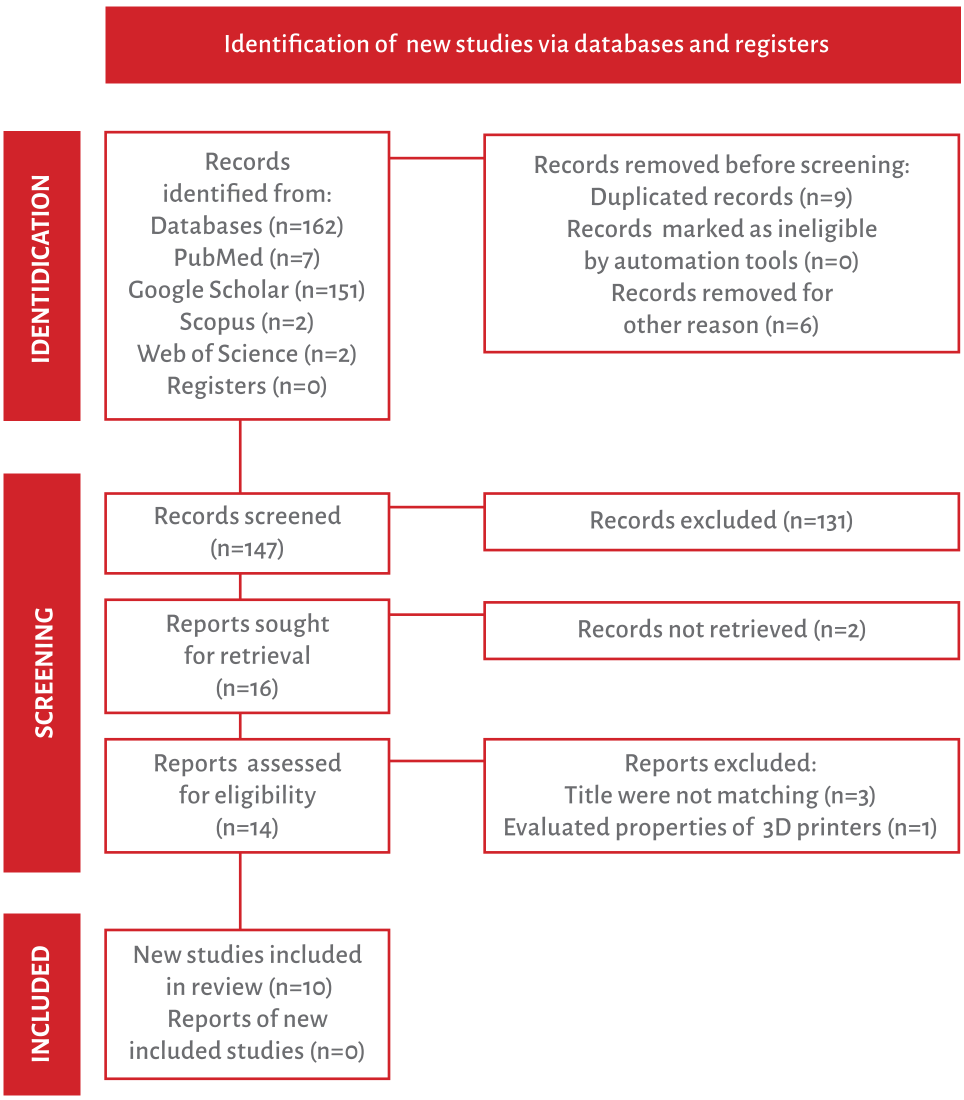

Figure 2

Risk of bias of *in vivo* studies

Low: + ; Moderate: -

Study	Risk of bias domains	D1	D2	D3	D4	D5	D6	D7	Overall
	Sayahpour *et al.*[14] Eur J Orthod, 2024	-	+	-	+	-	-	+	-
	Sayahpour *et al.*[12] Orthod Craniofac Rez, 2024	+	+	-	+	+	-	+	-

Domains:
D1. Bias due to confounding. **D2.** Bias due to selection of participants. **D3.** Bias in classification of interventions. **D4.** Bias due to deviations from intended interventions. **D5.** Bias due to missing data. **D6.** Bias in measurement of outcomes. **D7.** Bias in selection of the reported result.

Tensile strength, hardness, and elastic modulus were examined to determine durability and resistance to wear. Thickness and gap width were measured to evaluate material uniformity and fit, while force application tests determined the consistency and reliability of aligners in delivering the required orthodontic forces. The studies also assessed optical properties, including transparency and clarity, to evaluate the aesthetic appeal of aligners during treatment.

Qualitative assessment of the included studies

The recently developed RoBDEMAT tool was utilized to qualitatively assess the seven included *in vitro* studies,[9] while the ROBINS-I tool was applied for the evaluation of the two *in vivo* studies. Two independent reviewers, NVP and RKJ, meticulously evaluated all ten studies, with any disagreements resolved through consultation with a third author SS.

The RoBDEMAT tool was used to assess key sources of bias across four domains: planning and allocation, specimen preparation, outcome assessment, and data treatment and reporting. Each signaling question was classified as *"sufficiently reported," "insufficiently reported,"* or *"not reported."* Following the recommendations of the RoB-DEMAT developers, the tool was utilized as a detailed checklist to pinpoint specific areas of potential bias, rather than generating an overall summary score. Table 4 highlights areas of methodological strength and potential bias, providing a comprehensive assessment of study quality.

The studies by Sayahpour *et al.*,[14] were assessed for risk of bias using the ROBINS-I tool. Both studies demonstrated a low risk of bias for most domains, including confounding, selection of participants, missing data, and reported results. However, there was a moderate risk of bias in the classification of interventions due to the lack of blinding and in the measurement of outcomes. Overall, both studies were judged to have a moderate risk of bias, suitable for inclusion with minor limitations.

RESULTS

The PRISMA 2020 flow diagram summarizes the study selection process. A total of 162 records were identified through electronic databases, of which 9 duplicates and 6 records for other reasons were removed, leaving 147 unique records for screening. During the screening phase, 131 records were excluded because they did not provide a direct comparison between thermoformed (TFA) and direct printed aligners (DPA), many focused only on treatment outcomes, clinical case reports, or unrelated orthodontic materials, while others examined properties of 3D printers rather than aligners.

Sixteen full-text articles were sought for retrieval, of which two could not be obtained, leaving 14 articles for detailed eligibility assessment. At this stage, four studies were excluded (three did not match the topic and one investigated 3D printers), resulting in 10 studies that fulfilled all criteria and were finally included. These included studies di-rectly compared the mechanical, physical, or optical properties of TFA and DPA, ensuring that the final synthesis was restricted to the most relevant and clinically meaningful evidence.

Study characteristics

The general information of the 10 included studies are enlisted in the characteristic Table 3. The ten included studies, consisting of eight *in vitro* studies and two *in vivo* studies, comprehensively evaluated the mechanical, physical, and optical properties of DPAs and TFAs, focusing on parameters such as geometric deviations, load *versus* displacement behavior, dimensional accuracy, thickness, gap width, force application and optical properties.

The parameters in the included studies were

Table 1

Search Strategies in different databases

Database	Search Strategy	Results
PubMed	*((("direct printed aligners" [All Fields]) OR ("3d printed aligners" [All Fields])) AND ((("thermoformed aligners" [All Fields]) OR ("conventional aligners" [All Fields])) OR ("Vacuum formed aligners" [All Fields]))) AND ((((((("mechanical properties" [All Fields]) OR ("physical properties"[All Fields])) OR ("optical properties" [All Fields])) OR ("elasticity" [All Fields])) OR ("durability" [All Fields])) OR ("hardness" [All Fields])) OR ("thickness" [All Fields])) OR ("flexural strength" [All Fields])) OR ("tensile property" [All Fields])).*	7
Scopus	*"direct printed aligners" OR "3d printed aligners" AND "thermoformed aligners" OR "conventional aligners" OR "Vacuum formed aligners" OR "thermoplastic aligners" AND "mechanical properties" OR "elasticity" OR "durability" OR "hardness" OR "flexural strength" OR "tensile properties" OR "thickness" OR "optical properties"*	*2*
Google scholar	*"direct printed aligners" OR "3d printed aligners" AND "thermoformed aligners" OR "conventional aligners" OR "Vacuum formed aligners" OR "thermoplastic aligners" AND "mechanical properties" OR "physical properties" OR "optical properties" OR "elasticity" OR "durability" OR "hardness" OR "flexural strength" OR " tensile properties" OR "thickness" OR "optical properties".*	*150*
Web of Science	*((((((ALL = (direct printed aligners)) OR ALL = (3d printed aligners)) AND ALL = (thermoformed aligners)) OR ALL = (conventional aligners)) AND ALL = (mechanical properties)) AND ALL = (Physical properties)) AND ALL = (Optical properties).*	2

Table 2

Eligibility criteria for the included studies in format PICOS

	Inclusion Criteria	Exclusion Criteria
Population	*In vitro* and *in vivo* studies on materials used in aligner fabrication.	
Intervention	Direct printed aligners.	Exclude studies that involve aligners made using hybrid or any other alternative manufacturing methods.
Control/Comparator	Thermoformed aligners.	
Outcome Assessed	Mechanical, physical properties, optical properties.	Exclude studies that do not report mechanical properties.
Study Design	*In vitro* and *in vivo* studies.	

assessed using different experimental methods and equipment. Thickness and gap width were reported in three studies,[10-15] with measurements taken using profilometers and micro-CT to assess material uniformity and dimensional consistency. Force decay and relaxation properties were analyzed in four studies[12-14,15] using customized intraoral simulation setups to evaluate sustained force delivery over time. Tensile strength and elastic modulus were examined in two studies, using dynamic mechanical analysis (DMA) and Instron systems, highlighting differences in flexibility and durability between DPAs and TFAs.[13,15] Hardness properties were assessed in two studies[13,14] using nano-indentation and Vickers micro-hardness testing, while optical properties, including transparency and visual appearance, were evaluated in one study.[13] The diverse range of testing methods and outcome parameters provided a comprehensive comparison of DPAs and TAs, emphasizing their respective advantages and limitations in clinical applications.

Risk of bias in the included studies

The risk of bias in the included studies was assessed using the RoBDEMAT tool across four domains. Overall, the included studies exhibited a moderate risk of bias, with sufficient reporting in aspects such as control groups, testing procedures, and outcome measurements, but consistent deficiencies in randomization, sample size justification, and operator blinding.

While all studies adequately reported control groups and identical experimental conditions, randomization of samples and sample size justification were insufficiently reported in 4 studies,[10,16-18] but sufficiently reported by 2 studies.[6,12] Standardization of samples and materials was well-documented except in *et al.*,[10] which lacked material sourcing details.

Testing procedures and outcome measures were sufficiently reported across all studies. However, none reported operator blinding, introducing potential bias. Statistical analysis methods were detailed only in Koenig *et al.*,[6] and Sayahpour *et al.*,[14] though all studies sufficiently reported outcomes. Randomization of samples, sample size justification, operator blinding, and material sourcing details were not sufficiently reported in several studies, while statistical analysis methods were inadequately detailed in most studies except for Koenig *et al.*,[6] and Sayahpour *et al.*[14]

The studies by Sayahpour *et al.*,[14] were assessed for risk of bias using the ROBINS-I tool.

Table 3

Characteristics of the included studies

	Study	Material Used	Properties Evaluated	Testing Methods	Results
Jindal *et al.*[16] 2019	Am J Orthod Dentofacial Orthop *(In vitro)*	TFA- DURAN DPA - Dental LT resin	Geometric deviations. Compressive strength	Instron 3367 universal testting machine	DPA showed higher compressive resistance (662 N *versus* 105 N) and better geometric accuracy than TFA
Koenig *et al.*[6] 2022	Korean J Orthod *(In vitro)*	TFA - Zendura FLX™ (n = 12) (n = 12) DPA-Tera Harz™ TC-85 DAP 3D Printer UV Resin (n = 12)	Dimensional accuracy	3D scanner. Geomagic® Control X™ metrology software	DPA had greater trueness and precision thanTFA
Bandic *et al.*[10] 2024	Acta Stomatol Croat *(In vitro)*	Six different TFA materials. (Biostar, SCHEU-DENTAL GmbH, Iserlohn, Germany). DPA - IZZI Direct printer (3D tech, Zagreb, Croatia).	Thickness	Electronic Universal Micrometer	DPA showed increased thickness compared to initial dimensions; TFA exhibited greater variation.
Park *et al.*[11] 2023	Scie Rep *(In vitro)*	3D print of reference model (n=40). TFA groups: PETG (n=10) Copolyester - elastomer combination(n=10). DPA groups: 1.Tera Harz TC-85 Cleaned with alcohol(n=10). 2. Tera Harz TC-85 cleaned with centrifuge(n=10)	Thickness and the gap width, Translucency	Thickness and gap width using micro-CT. Translucency using spectrophotometer.	DPAs showed lower gap width (0.08 mm vs 0.15 mm) and better dimensional precision than TFAs
Hertan *et al.*[18] 2022	Prog Orthod *(In vitro)*	PET-G (ATMOS 0.030′′American Orthodontics) - TFA TC- 85DAC resin (Graphy Inc) - DPA	Resultant force from displacement	A force measuring appliance	DPA demonstrated consistent, lower forces compared to TFA
Shirey *et al.*[15] 2023	Am J Orthod Dentofacial Orthop	2 TFAs (EX30 and LD30) 2 DPA printing resins (material X and OD -Clear TF)	Elastic modulus, Ultimate tensile strength, Stress relaxation,thickness	Instron Universal testing system. RSA3 Dynamic Mechanical analyser	DPAs showed reduced tensile strength and stress relaxation under wet conditions while TFAs maintained mechanical properties better in simulated oral environments.

The Table 3 continues on the next page →

Table 3

Characteristics of the included studies

	Study	Material Used	Properties Evaluated	Testing Methods	Results
Sayahpour *et al.*[14] 2024	Eur J Orthod (*In vivo*), prospective experimental	DPA-Tera Harz TC-85 DAC resin (Graphy, Korea) TFA-(INV)-Polyurethane (PU) based polymer (Smart Track, Align Technology, USA);TFA (CA)-- PET- G based polymer (CA-Pro foils, Scheu-Dental, Germany)	Martens Hardness (HM) Indentation modulus (EIT) elastic index (ηIT) In dentation relaxation (RIT)	Vickers indenter (UTM) Tetragonal indentation depth pulse	Group DUR showed generally more favorable mechanical properties compared to DPA and INV
Sayahpour *et al.*[12] 2024	Orthod Craniofac Res (*In vivo*), prospective experimental	DPA - (DP)Tera Harz TC-85 DAC resin (Graphy TFA - (INV)-Polyurethane (PU) based polymer (SmartTrack, Align Technology,USA); TFA (CA)-PET-G based polymer (CA-Pro foils,Scheu-Dental, Germany)	Thickness changes (pre- and post-intraoral ageing)	CLSM with refractive index measurements	DPA had the highest thickness pre- and post-intraoral ageing. INV and CA aligners showed thinning post-thermoforming Intraoral ageing did not significantly affect thickness in any group
Atta *et al.*[13] 2024	J Mech Behav Biomed Mate (*In vitro*) experimental study	DPA (Tera Harz TC-85) TFA (CA Pro, Zendura A, Zendura FLX)	Glass transition temperature (Tg) via DSC analysis Shape memory behavior flexural strength surface microhardness	DSC DMA Three-point bending test (3 PB) Surface microhardness test	3D-printed aligners with shape memory characteristics are more adaptable and efficient, while TFA exhibits superior mechanical rigidity
Jindal *et al.*[17] 2020	J Mech Behav Biomed Mater	DPAs (Graphy TC-85 DAC resin) TFA (Duran material)	Non-linear, compressive strength, Load-bearing capacity. Deformation behavior	FEM, UTM	DPAs exhibited higher compressive strength (peak load: 662 N) compared to TFAs (540 N). However,DPAs showed non-linear deformation with higher stress concentration at specific regions

TFA: Thermoformed Aligner. DPA: Direct-Printed Aligner. DSC: Differential Scanning Calorimetry. DMA: Dynamic Mechanical Analysis. CLSM: Confocal Laser Scanning Microscopy. Micro-CT: Micro-computed tomography. PET-G: Polyethylene terephthalate glycol. UTM: Universal testing machine. DUR: DURAN. 3 PB: Three-point bending test. INV: Invisalign™. FEM: Finite Element Method.

Table 4

Risk of Bias assessment of the included studies (RoBDEMAT Tool)

Author		Jindal *et al.*[16] Am J Orthod Dentofacial Orthop 2019	Koenig *et al.*[6] Korean J Orthod 2022	Bandic *et al.*[10] Acta Stomatol Croat 2024	Hertan *et al.*[18] Prog Orthod 2022	Park *et al.*[11] Sci Rep 2023	Shirey *et al.*[15] Am J Orthod Dentofacial Orthop 2023	Atta *et al.*[13] J Mech Behav Biomed Mate 2024	Jindal *et al.*[17] J Mech Behav Biomed Mater 2020
D1 (Bias in planning and allocation)	(1.1) (1.2) (1.3)	SR IR IR	SR SR SR	SR IR IR	SR SR IR	SR SR SR	SR IR SR	SR SR SR	SR IR IR
D2 (Bias in sample/ specimen preparation)	(2.1) (2.2)	SR SR	SR SR	SR SR	IR SR	SR SR	SR SR	SR SR	SR SR
D3 (Bias in outcome assessment)	(3.1) (3.2)	SR NR	SR NR	SR NR	SR NR	SR NR	SR NR	SR NR	SR NR
D4 (Bias in data treatment and outcome reporting)	(4.1) (4.2)	IR SR	SR SR	IR SR	IR SR	SR SR	SR SR	SR SR	SR SR

SR: Sufficiently Reported. IR: Insufficiently reported. NR: Not Reported.

Both studies demonstrated a low risk of bias for most domains. However, there was a moderate risk of bias in the classification of interventions due to the lack of blinding and in the measurement of outcomes. Overall, both studies were judged to have a moderate risk of bias, suitable for inclusion with minor limitations. The Table 4 highlights areas of methodological strength and potential bias, providing a comprehensive assessment of study quality.

Dimensional Accuracy and Geometric Deviations

DPAs demonstrated superior dimensional accuracy and stability compared to TFAs, with smaller geometric deviations and narrower gap widths. The precision of additive manufacturing minimizes distortions, whereas the thermoforming process in TFAs introduces variability. Dimensional accuracy and geometric deviations were assessed in three studies.[6,11,16] Koenig *et al.*,[6] demonstrated superior precision in DPAs, with trueness values of ± 0.08 mm compared to ± 0.15 mm for TFAs. Jindal *et al.*,[17] reported smaller geometric deviations in DPAs (0.12 mm) compared to TFAs (0.20 mm), indicating better dimensional stability.[16] Park *et al.*,[11] found that DPAs exhibited narrower gap widths of 0.08 mm, whereas TFAs showed greater deviations with gap widths of 0.15 mm. These findings suggest that DPAs may provide better aligner fit, which could contribute to their potential suitability for precision driven orthodontic treatments, although further comparative studies with TFAs are warranted.

Thickness

Thickness variation, a critical physical property, was evaluated in three studies Bandic *et al.*,[10] and Park *et al.*,[11] Sayahpour *et al.*,[12] and Shirey *et al.*,[15] using micrometers, profilometers and micro-CT.

Sayahpour *et al.*,[14] reported that DPAs maintained an average thickness of 0.85 mm during intraoral use, while TFAs exhibited slight reductions, with average thicknesses of 0.56 mm and 0.42 mm for two thermoformed groups.[12] Bandic *et al.*[10] reported that DPAs demonstrated minimal thickness deviations of ±0.05 mm, while TFAs exhibited greater variability at ±0.12 mm under mechanical stress. Park *et al.*,[11] observed that DPAs had a median thickness of 687.53 µm, compared to 509.54 µm for TFAs.

In addition, Shirey *et al.*,[15] directly measured aligner thickness in the facial aspects of all the samples (maxillary left: canine, first premolar, second premolar, and first molar) using Miltex Ilwanson Caliper and reported that DPAs had a significantly greater and more consistent thickness (0.76 ± 0.02 mm) than TFAs (0.72 ± 0.04 mm), with the difference being statistically significant ($p < 0.05$). These results indicate that DPAs maintain superior thickness uniformity during the fabrication process, ensuring material consistency.

Load *versus* Displacement Behavior

The load *versus* displacement behavior, reflecting mechanical performance, was examined in three studies.[16,12,18] Two out of the three studies concluded that TFAs exhibited better and more stable load-deflection behavior, with consistent force profiles observed during incremental loading and simulated intraoral conditions.[18,12] In contrast, one study reported that DPAs demonstrated a higher load-bearing capacity (662 N compared to 540 N for TFAs) but exhibited less predictable load-deflection behavior.[16]

These findings suggest that while DPAs exhibit superior strength, TFAs offer more predictable and stable mechanical performance.

Force Decay and Relaxation

Four studies evaluated and compared the force decay and relaxation properties of DPAs and TFAs.[12-15] Two studies reported that TFAs retained 94.2% of their initial force after one week, compared to 87.7% for DPAs, indicating higher force decay in DPAs.[12]

Atta *et al.*,[13] demonstrated that DPAs exhibited significant force decay at room temperature but achieved excellent shape recovery of 86.1% at 45°C, compared to minimal recovery of 1.5-2.9% in TFAs. These findings suggest that while TFAs offer better force retention over time, DPAs excel in shape recovery under elevated temperatures.

Tensile Strength and Elastic Modulus

Two studies by Shirey *et al.*,[15] Atta *et al.*,[13] assessed tensile strength and elastic modulus. Shirey *et al.*,[15] reported that DPAs exhibited reduced tensile strength and greater stress relaxation under wet conditions, while TFAs maintained superior mechanical stability. The study found that direct-printed aligners (DPAs) exhibited significantly greater stress relaxation under wet conditions than thermoformed aligners (TFAs).[15] Within 60 minutes, DPAs lost 40-50% of their initial stress, while TFAs relaxed by only 20-30%. This suggests TFAs provide more consistent force retention over time ($p < 0.05$). Atta *et al.*,[13] found that DPAs demonstrated greater flexibility but slightly lower tensile strength compared to TFAs. These findings indicate that while DPAs offer enhanced flexibility, TFAs exhibit superior durability and stability, particularly under simulated oral conditions.

Hardness

Hardness, which determines material resistance to wear, was evaluated in two studies by Sayahpour *et al.*,[14] and Atta *et al.*,[13] observed a 15% reduction in hardness for DPAs after intraoral wear, whereas TFAs retained their hardness with minimal changes. Atta *et al.*,[13] reported higher hardness values for TAs at room temperature compared to DPAs, suggesting greater resistance to mechanical wear over time. These findings highlight the superior mechanical stability of TFAs during prolonged clinical use.

Optical Properties

Although optical properties were not widely evaluated, one study reported on material transparency and visual appearance.[13] TFAs demonstrated better optical clarity at room temperature compared to DPAs, which exhibited slight cloudiness under mechanical stress. This suggests that TFAs may offer superior aesthetic outcomes in clinical applications.

DISCUSSION

The increasing demand for precise, comfortable, and aesthetic orthodontic solutions has brought 3D-printed aligners (DPAs) and thermoformed aligners (TFAs) to the forefront of orthodontics. This systematic review included ten studies (eight *in vitro* and two *in vivo*) to compare the mechanical, physical, and optical properties of these two aligner types. Based on a qualitative synthesis, DPAs exhibited superior dimensional accuracy and thickness uniformity, making them ideal for cases requiring high precision. In contrast, TFAs exhibited better durability, force retention, hardness, and optical properties, making them preferable for long-term clinical applications.

A systematic review by Srinivasan *et al.*,[19] examined the physical and mechanical properties of clear aligners, identifying variations in hardness, stif-fness, stress relaxation, and creep behavior. Their findings emphasized that properties like hardness and stiffness deteriorate after thermoforming and intraoral aging, supporting the observed variability in TFAs.

Additionally, polyurethane-based aligners were found to have superior mechanical properties but greater stress relaxation, consistent with this review's findings that TFAs retain orthodontic forces more effectively over time.[20] Srinivasan *et al.*,[19] conducted a systematic review exclusively on TFAs, identifying mechanical limitations that align with this study's findings. Although DPAs were not included in their analysis, their results suggest that TFAs require further refinement to improve long-term clinical performance.

Dimensional accuracy, a key determinant of aligner fit and treatment precision, was significantly better in DPAs compared to TFAs. The studies reviewed here, including Koenig *et al.*,[6] and Park *et al.*,[11] supported these findings, reporting narrower gap widths and minimal geometric deviations for DPAs compared to TFAs. This precision makes DPAs particularly effective for complex orthodontic cases requiring highly accurate aligner fit. Thermoforming process in TFAs can result in reduced flexural strength.[21]

Thickness variation, another critical factor influencing force application and aligner durability, was more consistent in DPAs.[10,15] The consistent thickness in DPAs enhances the uniformity of force delivery across the aligner surface, reducing the risk of deformation or uneven force application. In contrast, the thermoforming process often introduces thickness inconsistencies, particularly at aligner edges, due to uneven heating and material stretching. Similar findings have been reported in previous systematic reviews on TFAs, which noted thickness inconsistencies as a primary limitation of the thermoforming process.

Interestingly, TFAs outperformed DPAs in several mechanical and physical properties critical for long-term orthodontic applications. For example, Sayahpour *et al.*,[12] and Atta *et al.*,[13] showed that TFAs retained a higher percentage of their initial force over time, maintaining 94.2% compared to DPA's 87.7%. This superior force retention highlights their reliability for sustained orthodontic treatments. Additionally, TFAs demonstrated greater tensile strength and hardness, making them more durable under clinical conditions. Also TFAs subjected to surface coatings have reported improved antibacterial properties.[22,23] Previous systematic reviews on TFAs, such as the one by Padmanabhan *et al.*,[19] have similarly noted that force retention varies significantly among different thermoformed materials, further confirming the current findings.

Optical clarity and transparency significantly impact patient satisfaction with clear aligners. The findings of this review indicate that TFAs exhibited superior transparency and visual clarity compared to DPAs, as reported by Atta *et al*.[13] The layer-based additive manufacturing process of DPAs may contribute to minor surface irregularities, which could reduce optical clarity, making TFAs the preferred choice for patients prioritizing aesthetics. Prior systematic reviews on aligners have emphasized the importance of optical properties, confirming that TFAs generally maintain better clarity due to their uniform surface characteristics.[19]

In vivo studies offer scientifically valid insights and more accurately reflect the real-world performance of aligners, as they account for biological factors such as saliva, temperature fluctuations, and patient compliance. Therefore, to provide a comprehensive evaluation, the present review includes both *in vivo* and *in vitro* studies.

Across the ten studies reviewed, there was some overlap in the materials tested for both direct printed aligners (DPAs) and thermoformed aligners (TFAs). The TFA groups mainly used PETG-based materials such as Duran, Essix ACE, and Biostar foils, along with polyurethane-based sheets like INV/SmartTrack and Zendura. On the other hand, the DPA groups largely focused on the TC-85 resin family from Graphy Inc., which was examined in seven of the studies. The TC-85-based DPAs consistently showed better dimensional accuracy, maintained their thickness more reliably, and preserved their shape more than others.

However, they generally produced lower force that decreased more slowly over time when compared to TFA materials, especially those made from polyurethane. While some studies also looked at other proprietary resins like Dental LT, IZZI, and Material X, the repeated evaluation of TC-85 gives us a clearer picture: DPAs made with TC-85 tend to be more precise and resist aging better, but they may not deliver as strong or as resilient a force, particularly in moist environments. Although the variety of materials tested means we can't make broad generalizations, the consistent focus on TC-85 helps confirm these trends with more confidence.

Limitations

The quality of the systematic review is limited by the quality of included studies. Most of the included studies have moderate risk of bias, there were notable gaps in randomization, sample size justification, and operator blinding. Most of the included studies were based on *in vitro* setups, which cannot fully replicate the biological factors like saliva,masticatory forces, patient compliance or intraoral ageing.

These methodological inconsistencies highlight the need for standardized study protocols and rigorous experimental designs in future research. Future research should focus on high-quality clinical trials with standardized evaluation methods to further validate these findings and explore hybrid approaches that integrate the advantages of both DPAs and TFAs. Additionally, future systematic reviews should aim to incorporate more *in vivo* studies to assess long-term clinical performance and patient-reported outcomes. The studies included in this SR had compared different types of TFAs and DPA except for TC85 which was mostly uniformly included, hence drawing definite conclusions will be misleading for most of them except for TC 85.

CONCLUSIONS

It can be concluded that DPAs offer superior precision and thickness uniformity; they are found to exhibit greater force decay and stress relaxation compared to TFAs. These mechanical limitations may affect their ability to deliver sustained, controlled forces over time, an essential factor in predictable orthodontic treatment. From a clinical perspective, TFAs may currently provide more stable biomechanical behavior, particularly in cases where prolonged force application is needed. The moderate risk of bias across studies underscores the need for more rigorous methodologies in future research. Therefore, well-designed longitudinal clinical studies are essential to confirm whether the observed mechanical differences translate into meaningful treatment outcomes.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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Najiya VP: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Writing – Original Draft.
Ravindra Kumar Jain: Project Administration, Resources, Supervision, Validation, Visualization, Writing – Review & Editing.

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