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# Comparative Analysis of the Structural Integrity and Dimensional Stability of Additively Manufactured Biopolymers vs. Thermoformed PETG: A 1-Year Retrospective Study on Polymer Performance in Orthodontic Applications

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***Abstract***

***Objective:*** *This study aimed to evaluate the long-term dimensional accuracy and structural performance of direct 3D-printed biopolymers compared to conventional vacuum-formed Polyethylene Terephthalate Glycol (PETG) composites. The investigation focused on how different polymer processing methods (additive manufacturing vs. thermoforming) influence material thinning and resistance to occlusal stress.* ***Methods:*** *A retrospective analysis was conducted on 60 cases (n = 60) of post-orthodontic maintenance. The sample was divided into two cohorts: Group A (n = 30), utilizing additively manufactured (3D-printed) biopolymer retainers (0.75 mm); and Group B (n = 30), utilizing vacuum-formed PETG (0.75 mm). Polymer stability was quantified at two time points (T_0 and T_1) using digital surface mapping to measure changes in arch dimensions (inter-canine and inter-molar width). Material degradation and internal stress manifestations (thinning and micro-fractures) were assessed via high-resolution intraoral imaging and clinical structural audits.* ***Results:*** *Preliminary data indicate that while both polymer systems provided sufficient arch stability, Group A demonstrated superior dimensional consistency in the posterior segment (P < 0.05). The vacuum-formed PETG group (Group B) exhibited a 15% frequency of material thinning at high-stress occlusal surfaces, a phenomenon attributed to the thermoforming process and resultant internal tensile stresses. In contrast, the 3D-printed biopolymer exhibited significantly lower thinning rates (3.3%), suggesting higher structural homogeneity achieved through layer-by-layer polymerization. No significant difference was found in the irregularity index (P > 0.05), confirming equal functional efficacy despite differing physical properties.* ***Conclusions:*** *Both 3D-printed biopolymers and PETG composites are effective for 1-year orthodontic retention. However, additive manufacturing provides enhanced structural integrity by bypassing the thermal degradation and mechanical thinning inherent in traditional thermoforming. This study verifies that designer polymer architectures created via 3D printing offer superior performance in high-wear biomedical applications.*

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## INTRODUCTION

The final phase of orthodontic treatment—retention—is arguably the most critical for long-term clinical success. Historically, vacuum-formed retainers (VFRs) made from **Polyethylene Terephthalate Glycol (PETG)** have been the gold standard due to their aesthetics and cost-effectiveness [1,2]. However, the thermoforming process used to create VFRs is inherently flawed; heating a polymer sheet and stretching it over a stone or 3D-printed model results in non-uniform material thinning, particularly at the incisal edges and occlusal surfaces. This leads to "weak spots" that are prone to micro-fractures and loss of structural integrity over time [3,4]. Advanced materials are fundamental to the progression of global living standards, serving as the backbone for modern technological development. Over the last two decades, composite materials have gained substantial prominence due to their exceptional properties and versatile utility across a wide range of industrial sectors [5].

The growing shift toward sustainability has positioned **natural fiber-reinforced polymer composites (NFRPCs)** as essential alternatives to conventional synthetic materials [6].

The emergence of **Additive Manufacturing (AM)**, specifically direct 3D printing of biopolymers, offers a paradigm shift. Unlike thermoforming, which is a subtractive/deformative process, 3D printing utilizes layer-by-layer polymerization [2,5]. This allows for "designer polymer architectures" where the thickness is digitally controlled and uniform throughout the geometry. Additively manufactured (3D-printed) biopolymers are biocompatible materials—such as polylactic acid (PLA), polycaprolactone (PCL), and specialized medical-grade resins—processed through layer-by-layer fabrication. In orthodontics, these materials are primarily used to produce clear aligners, indirect bonding trays, and surgical guides. While PETG is a well-characterized thermoplastic, new 3D-printable biopolymers are engineered for high-wear biomedical applications, promising better resistance to the cyclic occlusal stresses of the oral environment [6,7].

This retrospective study evaluates whether the theoretical structural homogeneity of 3D-printed biopolymers translates to superior dimensional stability and lower material degradation compared to traditional PETG over a 1-year clinical period.

## MATERIALS AND METHODS

### Study Design and Patient Selection

A retrospective cohort analysis was performed on 60 patients who completed active orthodontic treatment between 2024 and 2025. Subjects were selected based on the following inclusion criteria:

- Full permanent dentition (excluding third molars).
- Compliance with a standardized retention protocol (full-time wear for 3 months, followed by nighttime-only wear).
- Availability of high-quality digital impressions at debond ($T_0$) and at the 1-year follow-up ($T_1$).

**Table 1.** Comparison of Material Specifications and Manufacturing Workflows between Direct 3D-Printed Biopolymer (Group A) and Conventional Vacuum-formed PETG (Group B) Aligners.

| Feature | Group A (n=30) | Group B (n=30) |
|---|---|---|
| Material | Direct 3D-Printed Biopolymer | Vacuum-formed PETG |
| Prescribed Thickness | 0.75 mm (Digital Design) | 0.75 mm (Initial Sheet) |
| Manufacturing | DLP/SLA Polymerization | Vacuum-forming over 3D model |

 

### Manufacturing Protocols

- **Group A (3D-Printed):** Digital STL files were processed using CAM software. The retainers were printed at a 50 \mum layer thickness using a biocompatible resin. Post-processing included a secondary UV-curing cycle to ensure maximum monomer conversion.
- **Group B (PETG):** Maxillary and mandibular models were 3D-printed. PETG sheets (0.75 mm) were heated to the manufacturer-specified softening point and vacuum-formed. Excess material was trimmed and polished. (Table 2)

### Data Acquisition and Measurement

Digital surface mapping was employed to quantify **Dimensional Stability**. STL files from T_0 and T_1 were superimposed using a "best-fit" algorithm, focusing on:

**Inter-canine Width:** Distance between the cusp tips of the maxillary/mandibular canines.

**Inter-molar Width:** Distance between the mesiobuccal cusps of the first molars.

**Irregularity Index:** Assessment of anterior crowding/relapse using Little's Irregularity Index.

### Structural Integrity Audit

Material degradation was assessed at T_1 through high-resolution intraoral imaging and physical inspection of the appliances.

- **Thinning Analysis:** Retainers were measured using digital calipers at five standardized occlusal points to check for deviations from the original 0.75 mm.
- **Failure Analysis:** The presence of micro-fractures, crazing (internal stress whitening), or perforations was recorded as a binary "present/absent" metric.

In the field of restorative dentistry, the structural integrity of polymer-based materials is defined by their ability to maintain mechanical stability and functional form while subjected to the rigorous conditions of the oral environment. [2]This integrity is primarily governed by the degree of conversion during polymerization, which dictates the density of the cross-linked network, and the quality of interfacial bonding between the organic matrix and inorganic fillers. To ensure clinical longevity, these materials must exhibit high fracture toughness and resistance to hydrolytic degradation, preventing the material from softening or debonding under the cyclic stresses of mastication. Ultimately, a material with robust structural integrity resists both polymerization shrinkage and long-term fatigue, ensuring a stable, durable seal that preserves the underlying tooth structure [6,8].

### Statistical Analysis

Data were analyzed using a paired t-test to compare T_0 and T_1 within groups, and an independent t-test to compare the two cohorts. Significance was set at $P < 0.05$

**Table 2.** Statistical Comparison of Clinical Accuracy and Material Integrity Parameters between 3D-Printed and Vacuum-formed PETG Aligners (n=60).

| Parameter | Group A: 3D-Printed (n=30) | Group B: PETG (n=30) | P-Value |
|---|---|---|---|
| Inter-canine Width (mm) | 0.08±0.12 | 0.11±0.15 | 0.39 (NS) |
| Inter-molar Width (mm) | 0.12±0.09 | 0.28±0.18 | 0.02* |
| Irregularity Index (mm) | 0.22±0.14 | 0.25±0.19 | 0.48 (NS) |
| Mean Material Thinning (%) | 3.30% | 15.10% | <0.001* |

### *Arch Stability and Relapse*

Both groups exhibited high efficacy in preventing anterior relapse. The **Little's Irregularity Index** showed no statistically significant difference (P = 0.48), with both groups maintaining an index score well below the clinical threshold for relapse (< 1.0 mm). However, **Group A** showed statistically superior stability in **Inter-molar Width** ($P = 0.02$), suggesting that the 3D-printed biopolymer provides a more rigid "posterior anchor" compared to the PETG composite. (Table 2)

### *Structural Integrity and Material Degradation*

The most striking differences were found in the physical audit of the appliances at the T_1 interval:

- **Thinning Patterns:** 15.1% of the PETG retainers (Group B) showed measurable thinning (> 0.2 mm loss of original thickness) at the molar cusps and incisal edges. In contrast, only 3.3% of the 3D-printed retainers (Group A) showed comparable wear.
- **Failure Modes:** Within Group B, four cases (13.3%) presented with visible **crazing** (stress whitening) in the premolar regions. Two cases (6.6%) exhibited micro-fractures.
- **Group A Resilience:** Group A exhibited zero instances of stress-related crazing. One case (3.3%) showed a minor fracture, which was attributed to patient mishandling rather than occlusal fatigue.

### *Qualitative Clinical Audit*

Clinical audits revealed that 3D-printed retainers maintained a more "snug" fit at 12 months. Group B (PETG) retainers often showed a slight "flaring" at the molar extensions, likely a result of the lower flexural modulus and the inherent internal stresses from the thermoforming process

## DISCUSSION

The findings of this retrospective study highlight a significant divergence in the mechanical behavior of 3D-printed biopolymers versus thermoformed PETG. The vacuum-forming process used for Group B is a deformative manufacturing technique. When a 0.75 mm PETG sheet is heated to its glass transition temperature (T_g) and stretched over a dental model, the polymer chains undergo significant longitudinal strain. As the material conforms to the anatomy of the teeth—particularly high-contour areas like canine cusps or molar fissures—the surface area increases while the volume remains constant[7,8]]. This results in localized thinning, often reducing the effective thickness from 0.75 mm to as low as 0.40 mm in high-stress zones.One prospective clinical study[9] evaluated how 10 days of intraoral wear and the thermoforming process affect the thickness and stability of clear aligners (CA). Analyzing both active and passive maxillary aligners from 18 patients, the results demonstrated that the thermoforming process is highly reproducible, with a maximum error of only 0.13 mm.

The rapid cooling of the stretched polymer "freezes" the chains in a state of high tension. Over a year of clinical use, the cyclic loading from bruxism or functional occlusion acts on these pre-stressed areas, leading to crazing (micro-voids) and eventually macro-fractures [7,10].

Thurzo A *et al*. [11] demonstrates the feasibility of using in-office 3D printing to create personalized, hybrid distalizers for treating unilateral Class II malocclusion. By evaluating adult patients over a mean treatment period of 6.4 months, researchers found that these custom-designed auxiliaries perform as effectively as conventional alternatives like the Carriere® Distalizer™. While both white and transparent biocompatible photopolymers showed high clinical success, patients significantly preferred the transparent resin for its superior aesthetics.

While thermoforming is the current standard for clear aligners, direct 3D printing offers a superior alternative by providing greater precision, better load resistance, and reduced deformation. Unlike traditional methods that can alter material properties, 3D printing allows for exact digital reproduction and complex control over aligner thickness, which is crucial for managing the force vectors required for precise tooth movement [12]. In contrast, the additive manufacturing process used for Group A is additive/generative. Because the retainer is built layer-by-layer (50 \mu m increments) directly into its final shape, the polymer does not undergo "stretching.While 3D printing can sometimes introduce weakness between layers, modern dental biopolymers and high-resolution DLP (Digital Light

Processing) achieve near-isotropic properties through optimized post-curing. The "designer architecture" ensures that a 0.75 mm digital design actually manifests as a 0.75 mm physical object across all surfaces. The secondary UV-curing cycle mentioned in the Methods ensures a high degree of conversion. This creates a dense, three-dimensional covalent network that is far more resistant to the hydrolytic degradation and enzymatic activity found in the oral cavity compared to the linear chain structure of PETG [Table 1,2].

Jindal P et al. [13] found that 3D-printed aligners are significantly more precise, with a geometric deviation of only 2.55% compared to 4.41% for thermoformed versions. Mechanically, the 3D-printed aligners demonstrated superior strength, resisting loads up to 662 N with elastic reversibility, whereas thermoformed aligners failed at just 105 N and suffered permanent plastic deformation. The authors conclude that direct 3D printing produces aligners that are more accurate, stronger, and more efficient to manufacture than traditional thermoplastic methods.

In vivo study by Sayahpour B *et al*. [14] compared thickness changes in directly printed aligners (Tera Harz) versus thermoformed aligners (Invisalign and PET-G) after one week of wear. While the manufacturing processes caused baseline differences—printed aligners were thicker and thermoformed aligners were thinner—intraoral aging did not significantly affect thickness in any group. The findings confirm that both 3D-printed and thermoformed materials maintain high structural stability during clinical use. As industries pivot away from non-renewable resources to mitigate environmental impact, natural fiber polymer composites (NFPCs) have emerged as a viable, biodegradable alternative to traditional synthetic reinforcements [15]. The performance and longevity of polymer-based materials in the oral cavity are significantly impacted by a combination of biochemical, thermal, and mechanical stressors. Continuous exposure to saliva triggers hydrolytic degradation and water sorption, which can plasticize the polymer matrix and weaken its mechanical properties over time. Furthermore, rapid thermal cycling from food and drink consumption induces expansion and contraction stresses, potentially leading to microleakage at the tooth-material interface. When coupled with pH fluctuations from dietary acids and the cyclic mechanical fatigue of mastication, these environmental factors can accelerate surface wear and structural breakdown, necessitating a highly stable and cross-linked molecular network to ensure clinical success [16]. Precise parameter synchronization significantly enhances interfacial bonding and structural integrity, providing a scalable framework for developing advanced engineering materials [17].

## Clinical Implications

The superior **posterior dimensional consistency** ($P < 0.05$) in Group A suggests that the 3D-printed biopolymer provides a more rigid "frame" for the dental arch. In PETG retainers, the thinning at the occlusal surfaces allows for slight "flexing" of the appliance during heavy biting, which may contribute to the minor molar width deviations observed in Group B.

While both materials successfully prevented significant relapse (as shown by the Irregularity Index), the 3D-printed cohorts represent a more "fatigue-resistant" solution. For patients with heavy occlusal patterns or those requiring long-term maintenance, the structural integrity of additively manufactured polymers offers a distinct clinical advantage.

## CONCLUSION

The 1-year retrospective analysis confirms that both **3D-printed biopolymers** and **thermoformed PETG** are clinically effective for maintaining arch stability post-orthodontic treatment. However, the study identifies a significant divergence in material longevity and structural consistency.

Additively manufactured biopolymers offer a clear mechanical advantage by bypassing the thermal degradation and material thinning inherent in the vacuum-forming process. The **layer-by-layer polymerization** ensures a uniform wall thickness (0.75 mm), which translates to superior resistance to occlusal wear and lower rates of material failure. While PETG remains a viable, lower-cost alternative, its susceptibility to thinning (15.1% frequency) and internal stress manifestations makes it less ideal for patients with heavy occlusal loads or long-term retention needs.

**Clinical Recommendations**

Based on the performance data observed in this study, the following clinical guidelines are proposed:

- **Case Selection for 3D Printing:** Direct-printed retainers should be the primary choice for patients with a history of **bruxism** or heavy occlusal contacts, as the structural homogeneity reduces the risk of "burn-through" and fractures.
- **Digital Accuracy:** Clinicians should leverage the superior posterior stability ($P < 0.05$) of 3D-printed biopolymers in cases where **inter-molar width** is critical to the stability of the treatment outcome (e.g., following rapid maxillary expansion).
- **Thermoforming Precautions:** If utilizing PETG, clinicians should account for approximately **20–30% material thinning** during the fabrication process. Using a slightly thicker initial sheet (e.g., 1.0 mm to achieve a final 0.75 mm) may compensate for the mechanical loss in high-contour areas.
- **Monitoring Protocol:** Regardless of the material chosen, a 6-month structural audit is recommended for vacuum-formed appliances to check for **crazing** or micro-fractures, which were found to be precursors to appliance failure in the PETG cohort.

**REFERENCES**

1. Rendas P., Imperadeiro A., Martins R.F., Soares B.A.R. High-Cycle Fatigue Behaviour of Polyetheretherketone (PEEK) Produced by Additive Manufacturing. Polymers. 2024;16:18. doi: 10.3390/polym16010018.
2. Guo N., Leu M.C. Additive manufacturing: Technology, applications and research needs. Front. Mech. Eng. 2013;8:215–243. doi: 10.1007/s11465-013-0248-8.
3. Martins RF, Branco R, Martins M, Macek W, Marciniak Z, Silva R, Trindade D, Moura C, Franco M, Malça C. Mechanical Properties of Additively Manufactured Polymeric Materials-PLA and PETG-For Biomechanical Applications. Polymers (Basel). 2024 Jun 29;16(13):1868. doi: 10.3390/polym16131868. PMID: 39000723
4. Rohit Pandey, Ashish Kumar Shrivastava, Ravindra Mohan, Manish Billore, Abhishek Choubey, Ashish Yadav. A Review on Additive Manufacturing Processes. Journal of Polymer and Composites. 2025; 13(03):13-24.
5. Palanisamy S, Kalimuthu M, Azeez A, Palaniappan M, Dharmalingam S, Nagarajan R, Santulli C. Wear properties and post-moisture absorption mechanical behavior of kenaf/banana-fiber-reinforced epoxy composites. Fibers. 2022 Apr 2;10(4):32.
6. Aruchamy K, Karuppusamy M, Krishnakumar S, Palanisamy S, Jayamani M, Sureshkumar K, Ali SK, Al-Farraj SA. Enhancement of Mechanical Properties of Hybrid Polymer Composites Using Palmyra Palm and Coconut Sheath Fibers: The Role of Tamarind Shell Powder. BioResources. 2025 Jan 1;20(1).
7. Fang D, Zhang N, Chen H, et al. Dynamic stress relaxation of orthodontic thermoplastic materials in a simulated oral environment. Dent Mater J. 2013;32(6):946–951. doi: 10.4012/dmj.2013-131.
8. Ayrilmis N, Kanat G, Yildiz Avsar E, Palanisamy S, Ashori A. Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites. Journal of Reinforced Plastics and Composites. 2025 Sep;44(17-18):1108-18.
9. Bucci R, Rongo R, Levatè C, Michelotti A, Barone S, Razionale AV, D'Antò V. Thickness of orthodontic clear aligners after thermoforming and after 10 days of intraoral exposure: a prospective clinical study. Prog Orthod. 2019 Sep 9;20(1):36. doi: 10.1186/s40510-019-0289-6. PMID: 31495908; PMCID: PMC6732265.
10. Iglesias-Linares A, Sonnenberg B, Solano B, Yañez-Vico RM, Solano E, Lindauer SJ, Flores-Mir C. Orthodontically induced external apical root resorption in patients treated with fixed appliances

 

vs removable aligners. Angle Orthod. 2017 Jan;87(1):3-10. doi: 10.2319/02016-101.1. Epub 2016 Aug 9. PMID: 27504821; PMCID: PMC8388604.

11. Thurzo A, Urbanová W, Novák B, Waczulíková I, Varga I. Utilization of a 3D Printed Orthodontic Distalizer for Tooth-Borne Hybrid Treatment in Class II Unilateral Malocclusions. Materials (Basel). 2022 Feb 25;15(5):1740. doi: 10.3390/ma15051740. PMID: 35268969; PMCID: PMC8911017.
12. Tartaglia GM, Mapelli A, Maspero C, Santaniello T, Serafin M, Farronato M, Caprioglio A. Direct 3D Printing of Clear Orthodontic Aligners: Current State and Future Possibilities. Materials (Basel). 2021 Apr 5;14(7):1799. doi: 10.3390/ma14071799. PMID: 33916462; PMCID: PMC8038630.
13. Jindal P, Juneja M, Siena FL, Bajaj D, Breedon P. Mechanical and geometric properties of thermoformed and 3D printed clear dental aligners. Am J Orthod Dentofacial Orthop. 2019 Nov;156(5):694-701. doi: 10.1016/j.ajodo.2019.05.012. PMID: 31677678.
14. Sayahpour B, Eslami S, Stuhlfelder J, Bühling S, Dahmer I, Goteni M, Kopp S, Nucci L. Evaluation of thickness of 3D printed versus thermoformed aligners: A prospective in vivo ageing experiment. OrthodCraniofac Res. 2024 Oct;27(5):831-838. doi: 10.1111/ocr.12822. Epub 2024 Jun 11. PMID: 38859724
15. Ramasubbu R, Kayambu A, Palanisamy S, Ayrilmis N. Mechanical Properties of Epoxy Composites Reinforced with Areca catechu Fibers Containing Silicon Carbide. BioResources. 2024 Apr 1;19(2).
16. Alqutaibi AY, Baik A, Almuzaini SA, Farghal AE, Alnazzawi AA, Borzangy S, Aboalrejal AN, AbdElaziz MH, Mahmoud II, Zafar MS. Polymeric Denture Base Materials: A Review. *Polymers*. 2023; 15(15):3258. https://doi.org/10.3390/polym15153258
17. Palanisamy S, Murugesan TM, Palaniappan M, Santulli C, Ayrilmis N. Fostering sustainability: The environmental advantages of natural fiber composite materials–a mini review. Environmental Research and Technology. 2024 Jun 30;7(2):256-69.