

The Memory of Plastic: How Aligner Chemistry Divides the Evidence on Force Delivery, Leachables and Biofilm — A 2026 Narrative Review of Thermoformed and Directly Printed Clear Aligners

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Abstract

Background: Clear aligner therapy is now delivered through two fundamentally different material routes: aligners thermoformed from extruded thermoplastic sheets, mostly glycol-modified polyethylene terephthalate, copolyesters and thermoplastic polyurethanes, and aligners photopolymerised directly from shape-memory thermoset resins. The two routes are frequently discussed as though they differed only in manufacturing convenience, yet they rest on distinct polymer architectures, and the bench evidence published in 2025 and 2026 does not converge on which chemistry delivers orthodontic force more favourably.

Materials and Methods: A narrative review was conducted through structured searches of PubMed and the Consensus academic database covering January 2020 to September 2026, prioritising in vitro comparative studies, systematic and scoping reviews that contrasted thermoformed and directly printed aligner materials

across mechanical, chemical, surface and environmental outcomes. Thirty-two publications were retained for qualitative synthesis.

Results: Directly opposed findings were identified for stress relaxation, the single property most closely tied to sustained force delivery: one investigation reported that glycol-modified polyethylene terephthalate lost 23% of stress while shape-memory resins lost 83% to 99%, whereas another reported that a shape-memory resin relaxed substantially less than a thermoformed polyurethane and retained a higher residual force at 180 minutes. Methodological divergence in conditioning, strain magnitude, test duration and shape-recovery history accounts for much of the discrepancy. Printed aligners generally showed superior dimensional trueness but lower retentive force, higher surface roughness and greater bacterial adhesion than thermoformed counterparts, with wide variation between resins. Leachable compounds were low overall and bisphenol A was not detected, yet cytotoxicity was consistently governed by post-curing adequacy rather than by resin brand, and ageing increased release across all systems.

Conclusion: Aligner chemistry, not manufacturing route alone, is the variable that governs force decay, biological release and surface behaviour. The contradictory bench literature should not be read as evidence that one chemistry is clinically superior, but as evidence that testing protocols are not yet standardised. Clinicians adopting in-office direct printing assume responsibility for post-curing fidelity, which the present evidence identifies as the dominant determinant of biocompatibility.

Key Word: clear aligners; shape-memory polymers; polyethylene terephthalate glycol; stress relaxation; biocompatibility; three-dimensional printing.

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I. Introduction

Clear aligner therapy has moved, in roughly three decades, from a niche adult finishing option to one of the dominant modalities in contemporary orthodontics, and the literature that accompanies it has grown accordingly. Recent syntheses place the global user base above fourteen million patients and estimate that the modality generates more than one thousand tonnes of plastic waste annually, a figure that speaks less to any individual appliance than to the sheer volume of polymer now circulating through orthodontic practice [1,2]. What has not kept pace with that growth is a settled understanding of the materials themselves. The appliance that a patient wears for twenty-two hours a day is, from a materials science perspective, a thin viscoelastic shell whose capacity to store and release elastic energy over a one-to-two-week interval determines everything the clinician is trying to achieve.

For most of the modality's history that shell was produced in a single way: an extruded thermoplastic sheet was heated above its glass transition temperature and drawn over a physical model under pressure or vacuum, then trimmed. The chemistries used for those sheets are themselves heterogeneous and include glycol-modified polyethylene terephthalate, unmodified and modified copolyesters, thermoplastic polyurethanes, polypropylene–polyethylene blends and multilayered laminates that sandwich an elastomeric core between harder outer layers [3]. The clinical community has often treated these as interchangeable, distinguishing them chiefly by nominal sheet thickness, which the evidence increasingly shows to be an inadequate proxy for mechanical behaviour.

The second route is newer and conceptually different. Rather than deforming a pre-manufactured sheet, direct printing polymerises a liquid photoreactive resin layer by layer into the final appliance geometry. The resins developed for this purpose are not thermoplastics at all but crosslinked thermosets engineered to exhibit shape-memory behaviour, recovering a programmed geometry when warmed towards mouth temperature. This has been framed within the wider concept of four-dimensional printing, in which a printed object changes configuration over time in response to an environmental stimulus [4]. The practical appeal is substantial: no physical model, no thermoforming step, no trimming, region-specific thickness modulation within a single appliance, and the possibility of chairside fabrication.

It would be convenient if the bench literature had resolved which of these two chemistries delivers orthodontic force more favourably. It has not. Within a single year, two comparative in vitro investigations reached conclusions that cannot both be generalised. One reported that glycol-modified polyethylene terephthalate outperformed two shape-memory resins on every strength parameter measured and lost only 23% of its stress over the test interval, while the shape-memory materials lost between 83% and 99% [5]. The other reported that a directly printed shape-memory resin relaxed markedly less than a thermoformed polyurethane, 27.2% against 41.3%, and retained a higher residual force at 180 minutes [6]. These are not marginal disagreements about effect size; they point in opposite directions on the property that matters most.

The present narrative review takes that contradiction as its organising problem rather than as an inconvenience to be averaged away. It examines how the two chemical families differ in architecture, how they behave under force decay, dimensional and retentive testing, what they release into the oral environment, how

their surfaces respond to ageing and microbial colonisation, and what all of this does and does not permit clinicians to conclude. A final section considers the public health and regulatory significance of a modality in which the material and, increasingly, the manufacturing process have migrated into the dental office itself.

II. Materials and Methods

This work is a narrative review and does not claim the systematic reproducibility of a protocol-registered synthesis. Structured searches were conducted in PubMed and the Consensus academic database for publications dated January 2020 to September 2026, combining terms relating to clear aligners, thermoformed and thermoplastic materials, direct three-dimensional printing, shape-memory polymers, polyethylene terephthalate glycol, thermoplastic polyurethane, stress relaxation, leachables, cytotoxicity, surface roughness, bacterial adhesion and environmental impact. Reference lists of retrieved reviews were screened manually.

Priority was given to comparative in vitro investigations that tested thermoformed and directly printed materials under a common protocol, to systematic and scoping reviews, and to studies reporting quantitative outcomes rather than descriptive impressions. Case reports, manufacturer white papers and studies that did not identify the chemistry of the materials tested were excluded. Thirty-two publications were retained. Because the included studies differ substantially in specimen geometry, conditioning medium, ageing interval and loading protocol, no attempt at quantitative pooling was made; the synthesis is qualitative and, where findings conflict, the conflict is reported as such.

III. Two Chemistries, Not Two Factories

A. Thermoformed thermoplastics

Thermoformed aligner materials are linear or lightly branched polymers whose chains are held together by physical entanglement and secondary interactions rather than by covalent crosslinks. Glycol modification of polyethylene terephthalate suppresses crystallisation and yields an amorphous, optically clear sheet with favourable drawability; copolyesters and polypropylene–polyethylene blends occupy adjacent positions in the same design space; thermoplastic polyurethanes introduce soft-segment and hard-segment microphase separation that produces markedly different elastic recovery. A comparative investigation of five commercial sheets spanning three distinct chemical compositions demonstrated that these differences are not academic: raising the test temperature from ambient to 37 °C increased stress relaxation rates by between 0.7% and 18.11% depending on the material, and at 55 °C the spread widened to between 20.54% and 88.31% [7]. The same study found that two weeks of immersion in deionised water and artificial saliva did not accelerate relaxation in any material, and significantly decelerated it in one copolyester, a result that complicates the common assumption that the wet oral environment uniformly degrades force delivery.

Thickness interacts with chemistry rather than substituting for it. Tensile testing of glycol-modified polyethylene terephthalate and thermoplastic polyurethane aligners at 0.6 mm and 0.9 mm under simulated intraoral conditions showed that at the greater thickness the two materials did not differ significantly in stiffness except at the canine, where the polyurethane was significantly stiffer, and that increasing thickness raised stiffness consistently for the polyester but not uniformly across tooth positions [8]. Mechanical behaviour, in other words, is a function of material, thickness and anatomical site simultaneously. Direct comparison of two widely used commercial sheets found the stiffer product retained 96% of its original mechanical properties after a thousand loading cycles against 93% for the more flexible alternative, with the authors noting that the more compliant material may nonetheless carry specific clinical advantages [9]. A recent narrative synthesis of aligner materials and biomechanics adds a further complication to any static ranking: when a glycol-modified polycyclohexylenedimethylene terephthalate product was compared against polyurethane and polyester sheets over time, the ordering of materials by mechanical performance reversed, the polyurethane being initially the stiffest and hardest while decaying fastest, and the polycyclohexylenedimethylene terephthalate glycol delivering a lighter but more sustained force across the wear interval [10]. A material ranked first at time zero is therefore not necessarily the material ranked first at day seven, which is precisely the property that a single-timepoint comparison cannot capture.

B. Photopolymerised shape-memory thermosets

Direct-print resins are covalently crosslinked networks formed in situ by photoinitiated polymerisation. Their shape-memory behaviour derives from a network architecture in which a fixed phase preserves the permanent geometry while a reversible phase, typically governed by a glass transition near oral temperature, allows a temporary shape to be stored and subsequently recovered. This is a fundamentally different mechanism of force generation from the elastic rebound of a deformed thermoplastic shell, and it is the reason that conventional test protocols designed for thermoplastics may not characterise these materials fairly. Comparative characterisation of three commercial printing resins under a standardised printer and post-polymerisation protocol

found significant differences between resins in release kinetics, surface morphology and thermomechanical behaviour, and further differences attributable to post-polymerisation time alone [11].

The printed route also permits something thermoforming cannot: continuous, region-specific modulation of wall thickness within a single appliance. An investigation that printed discs from 0.5 mm to 6 mm and assessed human gingival fibroblast viability found that printed specimens closely matched nominal dimensions and that viability remained above the ISO 10993-5 threshold at every thickness, with no significant difference between the standard 0.5 mm and the thicker groups [12]. That finding matters less as a safety reassurance than as a demonstration that the design freedom is real and dimensionally trustworthy. The thermal signature of this material class is what distinguishes it most sharply from the thermoplastics: characterisation summarised in a recent materials-and-biomechanics review places the glass transition of the leading printed shape-memory resin at approximately 42 °C against roughly 80 °C to 107 °C for thermoformed sheets, with shape recovery reaching up to 86% within ten minutes at oral temperature compared with under 3% for the thermoformed comparators [10]. A transition temperature sitting just above mouth temperature is the mechanism by which these resins are intended to reactivate in service, and it is also the reason their behaviour is acutely sensitive to the thermal protocol under which they are tested.

C. Why the comparison is rarely like for like

A thermoformed aligner and a printed aligner of nominally similar geometry differ in polymer architecture, in fabrication thermal history, in residual stress state, in surface finish, in the presence or absence of unreacted monomer and photoinitiator, and frequently in nominal thickness. A systematic review of aligner retention characteristics concluded that retention is governed principally by modulus of elasticity, fatigue resistance and structural behaviour rather than by thickness alone, and identified high-modulus materials as offering the most consistent force control for complex movements [13]. When investigations comparing the two routes differ in which of these variables they control, discordant results are the expected outcome rather than an anomaly.

IV. Force Delivery and Stress Relaxation: The Central Contradiction

Stress relaxation is the decay of stress in a material held at constant strain. In an aligner it is the physical correlate of the clinical observation that the appliance feels tight on insertion and loose after several days, and it therefore bears directly on the proportion of the wear interval during which biologically useful force is actually delivered. Two 2026 investigations addressed this comparison and reached opposite conclusions.

The first tested two shape-memory resins and a glycol-modified polyethylene terephthalate sheet after wet conditioning, measuring yield strength, ultimate tensile strength, stress and strain at failure, and both stress and modulus relaxation, with the shape-memory specimens tested twice so that a second run followed shape recovery. The thermoplastic exhibited the highest values for yield strength, ultimate tensile strength and strength and strain at failure, and the lowest relaxation, losing 23% of stress and 38% of modulus. The shape-memory materials lost between 83% and 99% of stress and between 89% and 99% of modulus, and both degraded further on the second run after shape recovery [5].

The second compared a thermoformed polyurethane with a directly printed shape-memory resin using differential scanning calorimetry, gas chromatography–mass spectrometry and shape-recovery testing, adding time-dependent stress relaxation at 2% tensile strain over 180 minutes at 37 °C as a viscoelastic proxy for force decay. Here the printed resin relaxed significantly less than the thermoformed polyurethane, 27.2% against 41.3%, retained 72.8% of residual force at 180 minutes against 58.7%, showed lower cumulative extractables and superior shape recovery after seven days of artificial saliva ageing [6]. The authors were careful to state that these bench differences should not be read as direct evidence of superior clinical force delivery.

Several methodological differences plausibly generate the divergence. The comparator thermoplastic differs between the two studies, a polyester in the first and a polyurethane in the second, and the chemistries are not equivalent. The strain magnitude, test duration and conditioning protocols differ. Most importantly, the first study deliberately interrogated shape-memory materials after a recovery cycle and found degradation, while the second characterised recovery capacity itself as an outcome and found it preserved. A material whose force delivery depends on a thermally triggered recovery mechanism may perform well when that mechanism is intact and poorly once it has been exercised; whether a clinical wear interval exercises it in the way either protocol simulates is unknown.

The temperature sensitivity documented across conventional thermoplastics compounds this [7]. If relaxation rates in thermoplastics vary by an order of magnitude between ambient and 55 °C, and if printed shape-memory resins have glass transitions deliberately positioned near oral temperature, then any protocol that does not tightly control thermal history is measuring something other than the intended comparison. The honest reading of the current literature is not that one chemistry is superior but that the field lacks a standardised force-decay protocol capable of testing both architectures fairly.

A third set of figures, drawn from a narrative synthesis of the materials and biomechanics literature, occupies a position between the two: conventional thermoformed polyester and polyurethane sheets have been reported to lose approximately 30% to 60% of their initial force within the first 24 hours of intraoral wear, whereas printed shape-memory resins lose roughly 10% to 20% over the same interval while delivering lighter sustained forces in the range of 0.73 to 1.69 N [10]. These values derive from a different measurement tradition again, closer to clinical wear than to a constant-strain bench protocol, and the fact that three bodies of evidence on the same question produce three incompatible orderings is the clearest available demonstration that the discrepancy is methodological rather than material. That same synthesis reaches the conclusion this review endorses: the *in vitro* advantages attributed to the printed materials have not yet been confirmed by long-term clinical trials capable of translating them into superior achieved tooth movement [10].

V. Geometric Fidelity, Retention and Fit

If force delivery is contested, dimensional accuracy is comparatively settled, and it favours printing. Aligners produced from an identical reference file by thermoforming and by three different printing resins were scanned before and after artificial saliva ageing at 24 hours, 7 days and 14 days. The thermoformed group showed significantly lower trueness and precision than all three printed groups, and ageing reduced trueness and precision in both routes [14]. The result is mechanistically unsurprising, since thermoforming introduces error at the model-printing, drawing and trimming stages that direct printing bypasses entirely. The two routes also deviate from nominal specification in opposite directions rather than by different magnitudes: thermoformed appliances tend to thin out, most markedly in the maxillary arch, while printed appliances tend to gain thickness, most markedly in the mandibular arch [10]. Since thickness and stiffness are coupled, a systematic error of opposite sign in the two routes means that a nominal thickness printed on a specification sheet describes the delivered appliance less reliably in one route than in the other.

Retention behaves differently. Comparative testing of thermoformed and directly printed aligners across three margin designs with and without attachments found that thermoformed appliances generally produced higher retentive force, with the highest mean value recorded in a thermoformed group with attachments and a straight 2 mm margin at 26.18 N, and the lowest in a thermoformed group without attachments and a scalloped 0 mm margin at 3.25 N [15]. The eightfold spread attributable to margin design alone deserves emphasis: within a single fabrication route, design decisions moved retention further than the choice between routes did.

Printed appliance quality is also protocol-dependent in ways that thermoformed appliances are not. Printing seventy aligners in seven orientations demonstrated that print angulation significantly influenced root mean square deviation and linear, angular and height deviations, with the flat orientation achieving both the lowest deviation and the shortest print time, and all orientations producing negative height deviations [16]. This is an operator-controlled variable with no thermoforming equivalent, and it transfers a quality-control responsibility from manufacturer to clinician. The measurement of aligner thickness itself has proved sufficiently operator-dependent that a standardised protocol using a printed auxiliary device was developed, achieving intraclass correlation coefficients above 0.90 for repeatability where direct measurement fell below 0.75 for interoperator reproducibility at almost all points [17].

Surface engineering offers a route to reconcile retention with aesthetics. Laser surface texturing of a thermoplastic polyurethane substrate in a one-millimetre grid increased roughness and consequently retention and gripping force, while reducing average transmittance by only 2.32%, suggesting a way to reduce attachment size without sacrificing mechanical effect [18]. Attachments remain a material question in their own right: a systematic review of composite resins used for aligner attachments found all tested resins within clinically acceptable shear bond strength ranges but significant performance differences by composition and viscosity, with nanohybrid and high-viscosity resins offering better wear resistance and dimensional stability and flowable resins showing greater susceptibility to surface degradation and discolouration [19]. Printed attachments are now also under investigation, with printing direction and post-curing duration significantly affecting dimensional accuracy, water sorption, yield strength and cytocompatibility [20].

VI. What the Aligner Leaves Behind

Concern over chemical release from aligners has centred historically on bisphenol A, and on this point the recent evidence is reassuring. Characterisation of four appliances spanning conventional thermoformable products, a printed shape-memory resin and a laboratory-produced shape-memory polymer found no bisphenol A in any sample after 72 hours; bisphenol S was detected in one appliance. The greatest quantity of leachable compounds came from the two shape-memory materials, and release was concentrated in the first 24 hours [21]. A systematic review of chemical release concluded that aligners are generally safe while noting persistent concerns regarding leaching from thermoplastic materials, bacterial accumulation associated with reduced salivary flow, and moderate cytotoxicity in some materials [22].

Where the printed route introduces genuinely new risk is in polymerisation completeness. A systematic review of printed aligner cytotoxicity identified five *in vitro* studies, two reporting no cytotoxic effect, one reporting mild cytotoxicity under ultraviolet and heat post-curing, and one reporting increased cytotoxicity with extended ultraviolet and nitrogen curing, concluding that cytotoxicity is influenced by post-curing duration and system type and that strict adherence to manufacturer protocols is essential [23]. Testing of two resins under different post-printing protocols found undiluted extracts producing approximately 75% to 80% cell viability at 24 hours with viability exceeding 90% on dilution, and no significant differences between groups at 48 and 72 hours, consistent with a transient early effect followed by recovery [24]. The thickness study cited above found no cytotoxicity up to 6 mm under the manufacturer's twenty-minute ultraviolet post-cure [12].

Two investigations complicate any simple reassurance. Comparative characterisation of three printing resins found good biocompatibility except in insufficiently post-cured materials, and demonstrated that intraoral ageing degraded thermomechanical and surface properties across all resins while releasing residual resin and degradation products that increased cytotoxicity, leading the authors to warn about cumulative exposure even where individual measurements fell within acceptable limits [11]. A quantitative comparison of eight aligner materials including thermoformed systems, printed resins and a polyamide-12 device, tested on human dental pulp stem cells with micro- and nanoplastic suspensions generated by controlled abrasion, found that thermoformed materials and polyamide-12 generally maintained viability above 70% with preserved morphology, whereas several printed resins showed greater viability reductions approaching moderate cytotoxicity at higher concentrations and longer exposures [25].

The pattern that emerges is coherent. Bisphenol A is not the relevant hazard. The relevant variables are the completeness of photopolymerisation, which is operator-controlled in an office workflow and manufacturer-controlled in a thermoformed one, and the cumulative release that accompanies ageing in every system tested. A clinician who prints aligners chairside has assumed a materials-processing responsibility that was previously not theirs, and the evidence indicates that discharging it correctly is what determines biological safety.

VII. The Surface: Roughness, Biofilm and Colour Stability

Surface properties matter aesthetically, microbiologically and mechanically, and here the thermoformed route currently holds an advantage that is nonetheless narrowing. A comparison of three directly printed materials against two thermoformed materials assessed surface morphology, roughness at baseline and after 45 days in artificial saliva, light transmittance and colour stability after ageing in saliva, black tea and coffee, and *Streptococcus mutans* adhesion. The printed materials showed greater surface irregularity and significantly higher roughness values, and roughness increased across all groups after 45 days. The thermoformed materials maintained stable colour integrity and superior biofilm resistance, while printed material performance varied widely: one printed resin achieved a uniform surface, lower roughness, the highest colour stability of the printed group and bacterial adhesion comparable to the thermoformed materials by day seven, whereas two others discoloured significantly and one showed significantly higher bacterial adhesion [26].

The clinical corollary is that hygiene protocols are themselves material-relevant. Evaluation of six cleaning regimens applied to thermoplastic aligner specimens colonised by *Streptococcus mutans* found that toothbrushing, particularly combined with a chemical cleaning solution, achieved the lowest biofilm retention and the greatest reduction in viable counts. After fourteen days of repeated cleaning, surface roughness increased in the brushed groups, but no significant differences in elastic modulus or ultimate tensile strength were observed across any group, indicating that mechanical brushing does not compromise mechanical integrity [27]. Given that printed surfaces begin rougher and roughen further with ageing, the interaction between hygiene protocol and printed surface state remains an open question that the existing literature has not directly addressed.

VIII. Clinical Translation: What Bench Differences Do and Do Not Predict

It is tempting to assume that a material advantage in stress relaxation or trueness translates into superior tooth movement. The clinical literature on aligner efficacy counsels restraint, because the limiting factors it identifies are largely not material factors. A systematic review of prediction accuracy in digital treatment planning concluded that distalisation and rotation are expressed relatively predictably while transverse expansion, tipping and torque, overbite reduction and particularly intrusion remain less reliable, recommending that planning anticipate under-expression and incorporate overcorrection [28]. A systematic review restricted to rotational movements in adults, evaluated through three-dimensional model superimposition, reported accuracy ranging from 36% to 85% with an average near 65%, lack of correction from 0.7° to 4.5°, and maxillary canines and premolars as the least reliable teeth, with nearly all included investigations carrying moderate to serious risk of bias and certainty of evidence rated low to moderate [29]. A further review of mesiodistal molar movement found upper molar predictability of $61.1 \pm 9.1\%$ for movements from 0.45 to 3.2 mm, with lower molar distalisation less predictable still and very low quality of evidence overall [30].

These figures share a feature worth stating plainly: they are dominated by tooth morphology, root surface area, staging, anchorage and patient wear, and none of the studies was designed to isolate a material contribution. A 15% difference in residual force at 180 minutes on a bench specimen may be entirely absorbed by variation in daily wear hours. Until clinical trials randomise patients to aligners differing only in chemistry, with all else held constant, the correct position is that bench differences are hypotheses about clinical performance rather than evidence of it. The prudent clinical inference from the material literature is narrower and more defensible: that chemistry is a variable worth specifying and recording, that thickness is a poor proxy for it, and that appliance design decisions such as margin geometry and attachment configuration currently exert larger measured effects than the choice of fabrication route.

A comprehensive narrative review of clear aligner therapy makes the same point from the opposite direction, by mapping where the modality's limits actually lie. Its synthesis places aligners on comparable footing with fixed appliances for mild-to-moderate crowding, simple spacing and Class I malocclusions requiring predominantly tipping movements, while identifying root torque and bodily root movement, derotation of the rounded crowns of canines and premolars, vertical control, premolar-extraction cases requiring posterior anchorage and root parallelism, and hyperdivergent open-bite correction as the domains in which fixed appliances retain superiority — with reported lower incisor intrusion of only 0.4 to 1.5 mm at a predictability of 35% to 65% [31]. None of these constraints is a property of the polymer. They follow from crown morphology, from the limited surface available for engagement, and from the fundamental difference between a shell that grips a crown and a bracket-and-wire system that can be given a root-directed moment. The same review finds artificial intelligence increasingly embedded across the aligner workflow, in diagnosis and cephalometric analysis, in root and bone movement prediction, in attachment design and in remote monitoring, narrowing but not eliminating the gap between predicted and achieved movement [31] — which is to say that the most active current effort to improve aligner predictability is not being directed at the chemistry at all.

IX. The Environmental Ledger

Composition carries consequences beyond the mouth. A scoping review of sustainable orthodontic supply chains reported that clear aligner therapy serves more than fourteen million users globally while generating in excess of a thousand tonnes of plastic waste annually alongside microplastic contamination and substantial carbon emissions, with recycling rates ranging from 12% in Asian clinics to 29% in the European Union. The same review found that staged production and digital workflows reduced waste by 30% to 41% and lowered carbon emissions by 58%, and that bioplastics and four-dimensionally printed shape-memory aligners show promise but face cost and scalability constraints [2]. A parallel scoping review reached compatible conclusions, identifying biodegradable materials, direct three-dimensional printing, recycling initiatives and circular economy approaches as mitigation strategies whose implementation remains limited by recycling infrastructure, economic considerations and insufficient high-quality lifecycle evidence [32].

Direct printing is often presented as the environmentally preferable route because it eliminates the physical model and the sheet offcut. That accounting is incomplete. It omits resin waste in the vat and support structures, the energy of post-curing, and the disposal of uncured resin and cleaning solvent, which is a hazardous-waste stream that thermoforming does not generate. It also omits the micro- and nanoplastic release documented under controlled abrasion of both material classes [25]. The environmental comparison between the two chemistries has not been settled by a full lifecycle assessment, and the confidence with which it is asserted in commercial communication exceeds what the published evidence supports.

X. National Interest and Significance

The migration of aligner fabrication into the dental office is not merely a technical development; it redistributes regulatory responsibility in ways that public oral health systems have not yet addressed. In a thermoformed workflow the appliance is manufactured by a regulated producer whose process validation, sheet chemistry and quality control are subject to external oversight. In an in-office printing workflow the clinician selects the resin, controls the printer, determines the post-curing exposure and releases the device to the patient. The evidence reviewed here identifies post-curing adequacy as the dominant determinant of cytotoxicity [11,23,24] and print orientation as a significant determinant of dimensional accuracy [16]. Both are now operator variables. No established mechanism exists in most jurisdictions for auditing them at the point of care.

This has equity dimensions that cut in both directions. Chairside printing could materially reduce per-appliance cost and eliminate laboratory turnaround, which in underserved settings, whether rural counties in the United States or peripheral municipalities served by Brazil's Family Health Strategy, is precisely the friction that keeps orthodontic care out of public systems. A modality that requires no external laboratory is far more portable to a public clinic than one that does. Against this, an unvalidated or under-cured device delivered to a patient with limited capacity to seek redress is a risk borne disproportionately by the same populations. The policy implication

is not to restrict the technology but to accompany its diffusion with practical, enforceable post-curing verification standards and with training that treats photopolymerisation as a clinical procedure rather than a machine setting.

A third dimension is environmental and falls squarely within public health. If aligner therapy is to expand into publicly funded systems at scale, the waste and microplastic burden documented above [2,32] becomes a public expenditure and a public exposure rather than a private one. Procurement decisions in public systems are made in volume and are therefore capable of driving material selection toward recyclable or lower-impact chemistries in a way that individual private purchasing cannot. The absence of complete lifecycle data for both fabrication routes is, from this perspective, not an academic gap but an obstacle to responsible public procurement.

XI. Discussion and Limitations

The principal finding of this review is negative in form and useful in substance: the current bench literature does not support a verdict on which aligner chemistry delivers force more favourably, and the appearance of such a verdict in any individual study is an artefact of protocol choice. The two investigations at the centre of this review are both competently executed and reach opposite conclusions because they tested different comparator thermoplastics under different strain magnitudes, durations, conditioning regimes and recovery histories [5,6]. Recognising this is more valuable than picking a side, because it identifies what the field actually needs: a standardised force-decay protocol validated for both linear thermoplastic and crosslinked shape-memory architectures, with explicit control of thermal history, and reported alongside the shape-recovery state of the specimen. Two recent narrative syntheses converge independently on the same verdict from different starting points: one, working from the materials and biomechanics literature, concludes that bench advantages in dimensional control and stress relaxation remain unconfirmed by long-term clinical trials [10]; the other, working from the clinical evidence, concludes that the modality's limits are set by anchorage, crown morphology and the movements a shell can transmit rather than by the polymer it is made from [31]. Read together, they bound the claim this review is willing to make about chemistry: it is measurable, it is worth recording, and it is not currently the binding constraint on clinical outcome.

Several limitations constrain the present synthesis. It is narrative rather than systematic, without protocol registration, duplicate screening or formal risk-of-bias appraisal, and selection of sources therefore reflects author judgement. The great majority of the included evidence is *in vitro*; artificial saliva ageing over seven to forty-five days is a crude analogue of the intraoral environment, and no included study followed materials through a complete clinical treatment. Commercial materials evolve faster than the literature that evaluates them, and several resins characterised here may be superseded before this review is read. Manufacturer involvement in materials research is common in this field and was not systematically appraised. Finally, the clinical efficacy literature drawn upon in Section VIII was not designed to detect material effects, so its use here is illustrative of the limits of translation rather than evidence of material equivalence.

Future work should prioritise three things. First, protocol standardisation, without which the comparative literature will continue to accumulate contradictions. Second, randomised clinical comparison of aligners differing only in chemistry, which no included study provided. Third, full lifecycle assessment of both fabrication routes, including resin, solvent and post-curing energy, so that environmental claims can be evaluated rather than asserted.

XII. Conclusion

Aligner chemistry is a clinically meaningful variable that the field has tended to treat as a manufacturing detail. Thermoformed thermoplastics and directly printed shape-memory thermosets generate force through different physical mechanisms, and they differ measurably in dimensional trueness, which favours printing; in retentive force and surface behaviour, which currently favour thermoforming; and in the locus of biological risk, which shifts from manufacturer to clinician when printing moves chairside. On stress relaxation, the property most directly tied to sustained force delivery, the 2026 evidence is contradictory, and that contradiction is best explained by the absence of a test protocol fair to both architectures rather than by the superiority of either. Clinicians should specify and record the chemistry they use, recognise that nominal thickness does not characterise it, attend to margin design and attachment configuration as levers with larger measured effects than fabrication route, and treat post-curing fidelity as a clinical responsibility with direct biological consequences.

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