



3D-printed definitive dental restorations: permanent resins, mechanical performance and clinical evidence

Restauraciones dentales definitivas impresas en 3D: resinas permanentes, comportamiento mecánico y evidencia clínica

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ABSTRACT

Additive manufacturing has moved from diagnostic models and provisional prostheses toward the fabrication of definitive dental restorations with printable resins marketed as permanent. This narrative review synthesizes the evidence on these permanent resins, their mechanical performance and their clinical outcomes. Searches of OpenAlex, PubMed and Crossref, restricted to 2015 through 2023, were organized into four thematic axes: materials and technologies, mechanical performance, aging and biological properties, and clinical evidence. Forty-five studies informed the synthesis. Vat photopolymerization with filled resin composites is the dominant route, and printed permanent resins approach, without reaching, the strength of milled resin composites and ceramics; layer thickness, build orientation and post-curing modify these properties. Thermocycling and water storage degrade strength, wear and color stability more in printed than in milled materials, and residual monomer release depends on adequate washing and post-curing. Marginal and internal fit are clinically acceptable, but clinical evidence is scarce: randomized data exist for primary-tooth crowns and complete dentures, whereas long-term survival data for printed permanent resin single crowns in adults are absent. Printed definitive resins are promising for single-unit and implant-supported restorations, yet clinical adoption outpaces the evidence. Standardized material classification, fatigue testing under common protocols and prospective clinical studies with survival endpoints are required before these resins can be recommended without reservation.

Keywords: printing, three-dimensional; dental materials; dental restoration, permanent; resins, synthetic; flexural strength.

RESUMEN

La fabricación aditiva ha pasado de los modelos diagnósticos y las prótesis provisionales a la elaboración de restauraciones dentales definitivas con resinas imprimibles comercializadas como permanentes. Esta revisión narrativa sintetiza la evidencia sobre estas resinas, su comportamiento mecánico y sus resultados clínicos. Las búsquedas en OpenAlex, PubMed y Crossref, restringidas a 2015 a 2023, se organizaron en cuatro ejes: materiales y tecnologías, comportamiento mecánico, envejecimiento y propiedades biológicas, y evidencia clínica. Cuarenta y cinco estudios sustentaron la síntesis. La fotopolimerización en cuba con composites cargados es la vía dominante, y las resinas permanentes impresas se acercan sin alcanzar los valores de resistencia de los composites fresados y las cerámicas; el espesor de capa, la orientación y el poscurado modifican esas propiedades. El termociclado y el agua degradan la resistencia, el desgaste y la estabilidad de color más en los materiales impresos que en los fresados, y la liberación de monómero residual depende de un lavado y poscurado adecuados. El ajuste marginal e interno es clínicamente aceptable, pero la evidencia clínica es escasa: existen datos aleatorizados en coronas de dientes temporales y prótesis completas, mientras faltan datos de supervivencia a largo plazo en coronas unitarias de resina en adultos. Las resinas definitivas impresas son prometedoras para restauraciones unitarias e implantosoportadas, pero su adopción clínica supera a la evidencia. Se requieren una clasificación normalizada, ensayos de fatiga con protocolos comunes y estudios clínicos prospectivos con desenlaces de supervivencia antes de recomendarlas.

Palabras clave: impresión tridimensional; materiales dentales; restauración dental permanente; resinas sintéticas; resistencia a la flexión.

INTRODUCTION

Fixed prosthodontics has been reorganized around digital workflows during the past two decades. Intraoral scanners and computer-aided design and computer-aided manufacturing (CAD/CAM) now support most steps from impression to delivery, and systematic reviews describe these digital chains as accurate and efficient for single crowns and fixed partial dentures.(1,2) The spread of intraoral scanning reduced chair time and improved patient-reported comfort relative to conventional impressions, which accelerated the adoption of digital methods in daily practice.(3) Within this sequence, milled ceramics remain the reference for definitive single-unit restorations because lithium disilicate and zirconia combine high strength with well-documented clinical survival, and because their failure modes are known and accepted.(4) Updated syntheses indicate that the complete digital workflow has become reproducible in routine practice and now extends beyond the fabrication of single crowns to multi-unit and implant-supported prostheses.(5)

Additive manufacturing entered this workflow through models, splints and surgical guides and then advanced to provisional and, more recently, definitive restorations.(6,7) Vat photopolymerization, which groups stereolithography and digital light processing, is the technology most used for dental polymers because it offers the resolution, speed and surface quality required for fixed prostheses.(8,9) A specific product category, the printable resins marketed as permanent, has consolidated since about 2018. These are photopolymerizable resin composites with ceramic or glass fillers, formulated to reproduce the behavior of milled resin composites while retaining the geometric freedom of printing and avoiding the material waste of subtractive machining.(10) Manufacturers position them for single crowns, inlays, onlays and implant-supported restorations, and several systems are promoted for the same clinical indications that milled resin composites and, in some cases, ceramics occupy.(11) The label permanent, however, is not tied to a standardized material class, and the same term covers formulations with different filler contents, monomer chemistries and processing requirements.

The distinction between provisional and definitive matters for how the evidence should be read. Provisional resins are used for weeks or months and tolerate limited strength and wear, whereas a definitive restoration must withstand years of occlusal function, thermal cycling and biofilm exposure. The same printing hardware can produce both, which is convenient for laboratories but also blurs the boundary between material categories in the literature: publications labelled as permanent evaluate products whose composition is close to that of long-term provisional resins, and this overlap can inflate the apparent strength of the definitive category. Cost and speed are the main drivers of adoption, because a printed crown requires no block, no milling bur and less manual finishing than a milled restoration, and a printer can produce several restorations in one build. These practical advantages, rather than mature survival data, explain why printed definitive resins have spread through laboratories while the clinical evidence remains thin.

The mechanical and clinical evidence for these resins is dispersed and partly contradictory. Individual in vitro studies apply different printing parameters, post-processing cycles and testing standards, which complicates direct comparison between products, and the clinical literature is dominated by short-term reports on primary teeth, removable prostheses and printed ceramics rather than by data on permanent resin single crowns in adults. A clinician deciding whether to prescribe a printed definitive crown therefore faces a market that moves faster than its supporting evidence. This review aimed to synthesize the available evidence on 3D-printed definitive restorations fabricated with permanent resins. Four guiding questions correspond to the four axes of the synthesis: which materials and technologies are used, how the restorations perform mechanically, how they age and interact with the oral environment, and what clinical evidence supports their use.

METHODS

This narrative review followed the SANRA guidance for transparent reporting of non-systematic syntheses. Searches were run in OpenAlex, PubMed and Crossref, three sources that cover the dental materials and prosthodontics literature through independent indexes, which reduced the risk of relying on a single database. The core corpus was restricted to publications from 2015 through 2023, the period in which printable resins for definitive restorations became commercially available and in which most of the relevant evidence was published. No lower date limit was applied to contextual references on digital workflows and established restorative materials, which were drawn from any year when they clarified a comparison.

Search terms combined variants of three-dimensional printing, additive manufacturing,

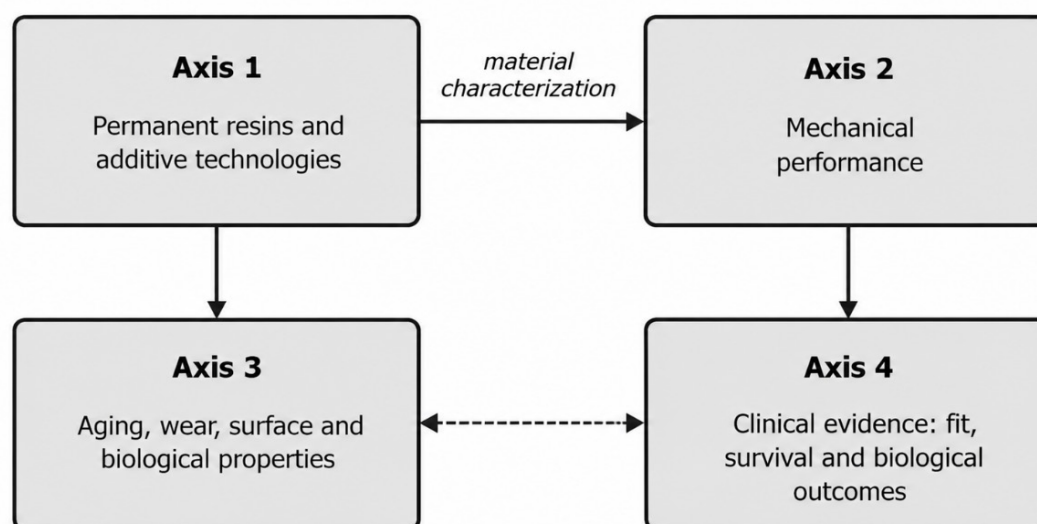
permanent resin, definitive restoration, dental crown, flexural strength, fatigue, wear, marginal fit, biocompatibility and clinical outcomes, in English with the corresponding terms of art used in the indexed literature. Records were screened by title and abstract and selected when they reported original data, or synthesized such data, on printable resins used for definitive or long-term restorations and addressed at least one of the four axes. Studies limited to provisional materials were retained only when they supplied comparative benchmarks or when evidence for definitive resins was absent for a given outcome. Reviews of ceramic additive manufacturing were included when they informed the clinical axis, because printed zirconia is the only printed material with a clinical series in adults. Teaching models, orthodontic aligners, surgical guides and non-dental applications were excluded, as were case reports that did not report measurable outcomes.

Selected studies were organized in an evidence matrix that linked each thematic axis to its main claims and to the studies supporting or contradicting each claim, together with an assessment of design and limitations. The synthesis was written around four axes: materials and technologies, mechanical performance, aging and biological properties, and clinical evidence. Study counts per axis derive from this matrix, and a study could inform more than one axis when it reported both mechanical and biological outcomes, for example. The design of each study was classified as narrative or systematic review, in vitro study, randomized trial or observational study. This classification supported the quality judgment attached to each claim, so that a finding replicated across several designs carries more weight than a single study of one design. Because the review is narrative, no PRISMA flow diagram was produced and no claim of exhaustiveness is made; the selection aimed to capture the converging and diverging findings within each axis rather than to enumerate every publication.

Where studies disagreed, the matrix recorded the direction of each finding and the factors that could explain the difference, such as resin composition, printing parameters, aging protocol or measurement method. This procedure prevented the synthesis from averaging conflicting results and instead preserved them as divergences to be interpreted in the Discussion. It also made explicit that the counts of studies per axis refer to the studies informing that axis, not to independent effect estimates.

DEVELOPMENT

Figure 1. Conceptual map of the four thematic axes of the review.



Note: Material characterization and mechanical testing inform the evaluation of aging and the interpretation of clinical evidence.

Forty-five studies informed the synthesis across four axes, with 10 studies informing the materials and technologies axis, 14 the mechanical performance axis, 12 the aging and biological properties axis, and 10 the clinical evidence axis; two studies informed more than one axis. The main findings per axis are summarized (Table 1) and the relationships among the axes are depicted (Figure 1). The text that follows integrates convergent and divergent evidence within each axis and indicates the type and quality of the underlying studies. Axis order follows the logic of the material pathway: what is printed determines how it performs, how it performs determines how it ages, and how it ages determines what clinical evidence can be expected. For each axis the text first states the dominant finding and then the qualifications that the diverging studies impose, so that the synthesis does not present a single value where the literature offers a range.

Permanent resins and additive technologies for definitive restorations

Vat photopolymerization is the additive route that dominates resin-based definitive restorations. Technical reviews converge in describing stereolithography and digital light processing as the processes with the resolution, speed and surface quality required for fixed prostheses, whereas material extrusion and material jetting occupy secondary positions in this application because they yield rougher surfaces and lower mechanical isotropy.^(6,7) The two vat processes share the same chemistry but differ in how they cure each layer, which has practical consequences for the laboratory: stereolithography traces the layer with a laser, while digital light processing projects a full image of the layer at once, so the choice between them trades resolution against build speed and affects how the manufacturer calibrates exposure and shrinkage compensation.⁽⁸⁾ The same sources distinguish the printable resins marketed as permanent from those used for models and provisionals: the permanent products are photopolymerizable composites formulated with methacrylate matrices and inorganic fillers, and they require washing and post-curing steps that complete conversion before the restoration can be delivered.⁽⁹⁾

The printed part is therefore an incomplete material until it is finished. A crown leaves the printer attached to supports and covered in uncured resin; it must be detached, washed to remove residual monomer, and post-cured with light or heat to reach its final conversion. Each of these steps has variables that laboratories set independently: the orientation and number of supports, the solvent and duration of washing, and the dose, wavelength and temperature of the post-curing cycle. Because the manufacturer specifies a protocol rather than a fixed property, the same resin can yield restorations with different degrees of conversion and different mechanical behavior, a dependence documented repeatedly in the studies reviewed below. This workflow dependence is the clearest difference between printed and milled materials: a milled block arrives fully polymerized, whereas a printed restoration is finished in the laboratory, where quality control is less standardized.

The material base has evolved in three directions. Early printable systems adapted polymethyl methacrylate (PMMA) to stereolithography; Hata et al.⁽¹²⁾ developed such a system to reduce brittleness and improve printability, an adaptation that shows how difficult it is to transfer a well-known dental polymer to a photopolymerization process. Later formulations introduced printable and machinable resin composites in which filler loading and monomer chemistry were adjusted so that the printed part approached the properties of machinable blocks, a comparison that established the milled composite as the natural benchmark for printed permanent resins.⁽¹⁰⁾ Two further directions illustrate the search for stronger materials: printable polymer-infiltrated ceramic networks that mimic the mechanical behavior of enamel and could narrow the gap with glass ceramics,⁽¹³⁾ and resins reinforced with modified zirconia nanoparticles intended for long-term service in the oral environment.⁽¹⁴⁾ Low-shrinkage formulations addressed the dimensional change that accompanies polymerization and can compromise fit, particularly in large restorations.⁽¹⁵⁾

Across these products there is no harmonized definition of what makes a resin permanent. The label reflects the intended use declared by the manufacturer more than a regulated material category, and guidance on biocompatibility certification and post-processing remains product-specific.^(9,11) This heterogeneity conditions the interpretation of the mechanical data reviewed in the next axis, because products sold under the same name differ in filler content, matrix chemistry and processing requirements, and because the post-processing protocol is part of the material system rather than an optional step. In practice, the term permanent should be read as a statement of intended service rather than a guarantee of performance, and any laboratory evaluation must name the exact product, its layer settings and its post-curing regimen before the result can be compared with another study.

Mechanical performance of printed resins

Comparative in vitro studies place printed permanent resins below milled ceramics and roughly within, or slightly below, the range of milled resin composites. Grzebieluch et al.(10) measured printable restorative composites that approached the flexural strength of machinable composites, and Sahin et al.(16) found additive and subtractive composite resins within a comparable strength interval, which supports the claim that printing itself does not impose an insurmountable penalty when the formulation is designed for it. When the comparison extends to hybrid or ceramic restorations, printed resins fracture at lower loads: Suksuphan et al.(17) documented lower fracture resistance for printed hybrid crowns than for milled hybrid materials at reduced occlusal thickness, and Khosravani et al.(18) described the fracture of printed dental resin as brittle and dependent on the layer interfaces, which points to the interlayer boundary as a weak plane. Abad-Coronel et al.(19) reported, in the opposite direction, that a printed CAD/CAM material reached fracture resistance comparable to milled PMMA for single units, which indicates that the gap depends on the specific resin rather than on the printing principle itself.

Failure modes reinforce the same conclusion. Printed resins tend to fail through the layer plane, producing fractures that split the restoration rather than chip it, whereas milled composites and ceramics fail predominantly by crack propagation from the surface or from the margins.(18,20) A single load-to-fracture value cannot express this behavior, because it says little about the weak plane that will dominate in a connector or a thin margin. The dispersion of results across parameter studies(21,22) further complicates the comparison, since the same nominal strength can carry different failure risks depending on how the part was oriented and cured. This situation recalls the early literature on milled resin composites, which also relied on monotonic tests before standardized fatigue protocols were adopted.

Printing parameters modify these values materially. Layer thickness, printing orientation and post-curing time and temperature change flexural strength and hardness, sometimes by a magnitude larger than the difference between competing resins.(21,22) This finding matters for clinical reproducibility, because two laboratories using the same commercial resin but different post-curing units can produce parts with different strength and surface properties, a source of variability that does not exist for prefabricated milled blocks. Park et al.(23) found that crown thickness and post-curing influenced strength and surface characteristics of printed resin crowns for primary molars, and Kim et al.(24) showed that resin composition determined biaxial flexural strength and fracture resistance in the same application, which suggests that pediatric restorations, where loads are lower, tolerate printed resins more easily than adult posterior crowns.

None of these comparisons settles whether printed permanent resins meet the minimum requirements expected of polymer-based crowns. Standards for polymer restorative materials define threshold values for flexural strength, and the values reported for printed permanent resins tend to cluster near that threshold rather than comfortably above it, which leaves little reserve for fatigue, aging and processing variation. The practical consequence is that a printed crown may pass a single-load requirement in ideal conditions and still be marginal under the combined effect of water, load cycling and a suboptimal post-curing protocol, the very combination that defines clinical service. This is why monotonic strength alone is an insufficient basis for recommending a material as permanent, and why the aging data reviewed next carry more weight than the strength data reviewed here.

The ordering of materials follows filler content and matrix type. Ceramics are fully inorganic and reach flexural strengths several times higher than polymer-based materials, which is why printed resins, however well filled, cannot be expected to replace ceramics in high-load posterior sites, a gap documented when printed hybrids were tested against milled ceramic-containing materials.(17) Within the polymer family, the difference between printed and milled composites is smaller because both are methacrylate-based systems with comparable filler fractions; the residual difference comes from the layer structure of the printed part and from the conversion that the post-curing cycle achieves.(16,25) This framing explains most of the apparent contradictions in the literature: studies that compare printed resins with ceramics report large gaps, whereas studies that compare them with milled composites report small or no gaps, and the two conclusions are not in conflict.

Evidence for multi-unit and implant restorations is thinner and less favorable. Skienhe et al.(20) reported lower fracture resistance for printed three-unit fixed dental prostheses than for milled composite equivalents, and Bein et al.(26) documented lower fatigue and fracture values for printed than for milled interim implant-supported crowns, a comparison that warns against transferring the single-unit results to connectors and cantilevered spans. Fatigue data for defini-

tive printed resins remain scarce; most studies apply monotonic loading, which does not capture the slow degradation expected under intraoral function, and the few available fatigue reports use different numbers of cycles and loads.(17) Reinforcement with glass silica or zirconia nanoparticles raises strength and hardness, but the benefit depends on dispersion and interfacial adhesion and has been demonstrated mostly in experimental formulations rather than in commercial permanent resins.(14,27) Two systematic syntheses of provisional printed materials(28,29) show that the provisional literature is larger and more homogeneous than the definitive one, and their estimates should not be transferred to permanent resins, which are exposed to longer service and higher demands.

Aging, wear, surface and biological properties

Artificial aging widens the gap between printed and milled or ceramic materials. Güven et al.(30) found that additively manufactured resin crowns showed greater dimensional change and occlusal wear than subtractive ones after thermomechanical aging, and Cha et al.(31) reported that 3D-printed denture tooth resin wore more than zirconia and metal antagonists under simulated function, which has implications for the maintenance of the opposing dentition. Surface studies agree that printed permanent resins are more sensitive to thermocycling and brushing than resin-based CAD/CAM blocks, with roughness and microhardness deteriorating faster.(32,33) The consistency across these studies is notable because they use different resins, aging regimens and measurement methods, yet they converge on the same ordering: printed resins degrade more, and the degradation is visible in wear, roughness and hardness rather than in color alone.

The chemical basis of this sensitivity lies in incomplete polymerization. Berghaus et al.(25) measured a lower degree of conversion and higher residual monomer elution for printed composites than for milled or self-cured materials, and Hwangbo et al.(34) showed that washing time and washing solution modify both biocompatibility and mechanical properties. Kim et al.(35) linked the choice of photoinitiator to cytotoxicity, color stability and dimensional accuracy, which connects processing chemistry to clinical tolerability. These findings indicate that the properties of a printed restoration are not fixed at printing but are determined by the entire post-processing chain, from the solvent used for washing to the dose and wavelength of the post-curing light.

Biocompatibility assessments give a generally acceptable but product-dependent picture. Aydin et al.(36) found that printed permanent resins, resin-based CAD/CAM blocks and conventional composites elicited comparable cytotoxic responses on gingival and fibroblast cell lines when processing was complete. Wuerschling et al.(37) reported, by contrast, that some novel resins for printed fixed prostheses failed initial biocompatibility screening, a divergence that reflects the influence of formulation and post-processing and that cautions against assuming all permanent resins are interchangeable. Optical properties follow the same logic: translucency of printable permanent composites is lower than that of ceramics and varies with shade and thickness,(38) and color stability under coffee staining and aging is material-specific.(33) Water sorption and solubility of printed denture resins also exceed those of heat-polymerized acrylic,(39) which matters for the dimensional stability of large prostheses. Retention of printed permanent crowns to prepared teeth is adequate after artificial aging when surfaces are pre-treated, but the evidence rests on a single material comparison.(40)

Surface finish adds a further dimension. Printed restorations carry the layered texture of the build and, unless polished, retain roughness that is higher and less stable than that of milled blocks.(32) Polishing restores a smoother surface, but the degree of recovery varies with the resin and the finishing protocol, and the roughness returns under thermocycling and brushing faster than in subtractive materials.(33) Because roughness conditions biofilm accumulation and stain retention, the surface behavior of printed permanent resins is inseparable from their aging behavior, and the two should be evaluated together rather than as separate properties. This coupling between surface and bulk degradation is a recurring feature of the axis and one of the strongest arguments for standardized aging protocols.

The aesthetic record follows the same pattern. Printed permanent resins offer a narrower shade range than ceramics and lower translucency, which limits their use in the anterior region where color matching is decisive.(38) Staining under coffee and repeated thermocycling changes color in a product-dependent way, and the change is larger than that of resin-based CAD/CAM blocks in most comparisons.(33) Together with the surface and sorption data, these optical limitations suggest that the natural indication for printed permanent resins is the posterior single unit or the implant-supported crown where strength and fit dominate and where aesthetic demand is moderate, rather than the anterior restoration where optical fidelity is the primary requirement.

Clinical evidence on fit, survival and biological outcomes

Laboratory fit data support clinical feasibility. Kakinuma et al.(41) and Dönmez et al.(42) reported marginal and internal gaps for printed resin crowns within clinically accepted thresholds, with implant-supported printed definitive composite crowns performing similarly to milled equivalents. Build angle and the number of supports modify internal fit, so accuracy is controllable but protocol-dependent, and a laboratory that does not control these variables can produce restorations that fall outside the acceptable range even with a validated resin.(43) For endocrowns, Arafa et al.(44) found printed and milled restorations comparable in marginal adaptation before and after thermomechanical loading. The picture for printed ceramics is less uniform: Refaie et al.(45) observed larger marginal gaps for printed than for milled monolithic zirconia crowns, a divergence explained by the additional sintering steps required for ceramic green bodies rather than by any limitation of the resin systems.

Direct clinical evidence on printed permanent resins is limited. A randomized trial in primary molars by Al-Halabi et al.(46) compared printed resin crowns with CAD/CAM crowns and reported acceptable short-term clinical performance, which remains the principal *in vivo* datum for resin definitive crowns. For adults, clinical series concentrate on printed zirconia rather than resin: Kao et al.(47) described favorable short-term outcomes of selective laser melted zirconia crowns, and a systematic review with meta-analysis concluded that printed and milled zirconia prostheses have comparable clinical effectiveness over short observation periods.(48) In removable prosthodontics, randomized and follow-up studies document that printed complete dentures perform acceptably over up to 18 months,(49,50) but these findings concern denture base resins and cannot be transferred to fixed single crowns, where the loads and the cement interface differ.

No prospective study with survival endpoints exists for printed permanent resin single crowns in adults, and no comparative trial has followed such restorations beyond short observation periods. The clinical axis therefore rests on laboratory fit data and on evidence borrowed from neighboring applications, a limitation developed in the Discussion. This absence is itself a finding: the market adoption of permanent resins has run ahead of the evidence that would normally precede the routine use of a new definitive material. The consequence for practice is that the clinician who prescribes such a restoration accepts an evidentiary position closer to that of a provisional material than to that of a milled ceramic, even though the restoration is intended to be definitive.

Despite this thin evidence, printed definitive resins are adopted for practical reasons. A single printer can produce crowns, provisionals, splints and surgical guides, which amortizes equipment costs, and the workflow removes the milling bur, the block inventory and much of the manual finishing that subtractive methods require. These advantages are real and explain why laboratories and clinicians have moved toward printed definitive restorations before survival data are available. They do not, however, substitute for evidence on longevity, and they should be weighed against the lower mechanical margins and the higher aging sensitivity documented in the previous axes when a posterior load-bearing site is planned. The same logic applies to the minimal evidence that would be needed: a prospective series of printed permanent resin single crowns with at least two or three years of follow-up, survival and marginal integrity would begin to answer the question that the current literature leaves open.

Table 1. Synthesis of the evidence by thematic axis.

Axis	Main finding	Predominant evidence	Representative studies
Materials and technologies	Vat photopolymerization with filled resin composites is the dominant AM route; the permanent label is market-driven	Narrative and technical reviews; <i>in vitro</i> materials development	(6,7,10,11)
Mechanical performance	Printed resins approach milled composites but fall below ceramics; parameters and fatigue dominate differences	<i>In vitro</i> comparative and parameter studies	(16,17,20,21)
Aging and biological properties	Printed resins degrade more under aging; biocompatibility is product- and post-processing-dependent	<i>In vitro</i> aging, wear, elution and cytotoxicity studies	(25,30,31,36)
Clinical evidence	Fit is acceptable but clinical data are short-term and mostly borrowed from neighboring applications	<i>In vitro</i> fit studies; randomized trials in primary teeth and dentures	(41,46,48,49)

Note: The number of studies per axis derives from the evidence matrix; two studies informed more than one axis. AM = additive manufacturing. Source: Elaboración propia a partir de la matriz de evidencia.

Laboratory fit data should not be over-read. A marginal gap within laboratory thresholds is a necessary but not sufficient condition for clinical success, because cement wear, biofilm ingress and occlusal loading act on the margin over time and are not reproduced by a single seating measurement. The favorable in vitro fit of printed resin crowns(41,42) therefore predicts early seating rather than long-term integrity, and cannot compensate for the absence of survival data. The same caveat applies to the fracture values reviewed earlier: they describe the restoration on the day of delivery, whereas the clinical question concerns its behavior years later.

DISCUSSION

The synthesis places printed permanent resins in an intermediate position. They are stronger and more stable than provisional resins, yet below milled ceramics and, in several protocols, below milled resin composites, while their clinical record is much shorter than that of either established material class. This intermediate position, rather than a categorical verdict, is the most defensible reading of a literature in which the direction of differences is consistent but the magnitude varies with the resin and the protocol.

The mechanical findings align with the composition of these materials. Printed permanent resins are highly filled photopolymers, so their flexural strength depends on filler fraction and on the degree of conversion achieved by post-curing; this explains why parameter studies(21,22) change the ranking among products. The lower fatigue and fracture values reported for printed multi-unit and implant restorations(20,26) are consistent with the anisotropy introduced by layer-by-layer polymerization, a feature absent from milled blocks. Where printed and milled composites reached similar single-load strength,(16,19) the equivalence held for monotonic tests rather than for the cyclic loading that better reflects intraoral function. The clinical translation is that single-load flexural strength, the measure most often reported, overstates the serviceability of printed resins because it ignores both fatigue and the interlayer plane that dominates failure in larger restorations.

The degradation pattern is equally coherent. Printed resins absorb more water and elute more residual monomer than milled or heat-cured materials,(25,39) and the resulting plasticization explains the greater wear and surface change observed after aging.(30,31) This behavior contrasts with the dimensional and color stability of zirconia documented over years of clinical service(51)and with the longevity reported for indirect resin composites, which nevertheless remains below that of ceramics.(52,53) Demarco et al.(54) argued that the survival of composite restorations depends as much on operator and patient factors as on the material, a caveat that applies with equal force to printed resins, whose post-processing introduces a new source of operator-dependent variability that does not exist for a milled block delivered with standardized conversion.

The clinical literature is the weakest link. Randomized evidence for printed definitive resins is confined to primary molar crowns(46)and, in the removable domain, to complete dentures followed up to 18 months.(49,50) For adults, the only clinical series of printed crowns concern zirconia fabricated by selective laser melting,(47)whose systematic review reports short-term effectiveness comparable to milling.(48)By comparison, milled CAD/CAM implant crowns have five-year prospective data,(55)and conventional ceramic single crowns carry decades of survival evidence.(4)The absence of survival estimates for printed permanent resin crowns means that clinicians currently extrapolate from laboratory fit data,(41,42) which, although favorable, do not capture fatigue, wear or biological complications. Prior reviews have focused on removable prostheses and on provisional materials,(28,56) leaving the definitive resin crown as a gap that this synthesis addresses but cannot fill with clinical data.

The fit evidence also illustrates a material-specific caution. Printed resin crowns reproduce the digital design with acceptable accuracy,(41,42) but printed zirconia showed larger marginal gaps than milled zirconia in one comparison,(45)a divergence attributable to the sintering shrinkage of ceramic green bodies rather than to the printing principle itself. Accuracy in resin systems is therefore a controllable variable through build angle and supports,(43)whereas accuracy in printed ceramics depends on additional thermal steps.

The trajectory of printed zirconia offers a cautionary parallel for printed resins. Zirconia moved from laboratory studies to short clinical series because its post-processing, although demanding, is centralized in sintering furnaces whose parameters are controlled; the clinical reports that followed were enough to justify limited use while longer data accumulated.(47,48) Printed resins do not yet have that controlled post-processing, because washing and post-curing are distributed across laboratories with variable equipment and protocols. The lesson is that the pathway from a printable material to a clinical indication depends as much on the reproducibility of its finishing as

on its intrinsic strength; this is precisely the step that the current evidence shows to be the least standardized for permanent resins.(25,34) This distinction explains why fit data for resins are more consistent than for ceramics and why the two material families should not be evaluated with the same expectations.

The practical implication is a staged use. Printed permanent resins are defensible where the alternative is a provisional or a restoration with limited survival expectations, and where follow-up is possible; they are harder to justify as a routine substitute for milled ceramics in posterior single crowns until survival data exist. The market term permanent should be interpreted with caution, because biocompatibility screening(37)and monomer elution(25)show that the safety margin depends on how the part is washed and post-cured, steps that vary between laboratories. Clinicians should therefore verify the post-processing protocol of the laboratory rather than rely on the material name, and should inform patients that the long-term behavior of the restoration is not yet documented.

Workflow economics help to explain why adoption has outpaced evidence. A printed definitive crown removes the cost of the block and the bur, reduces finishing time, and allows several restorations to be built in one session, which lowers the marginal cost of each unit. These efficiencies are attractive for the single-unit market and for practices that already own a printer for models and provisionals. The risk is that the economic argument is read as a clinical one: the fact that a restoration is cheaper to produce does not shorten the time required to demonstrate that it survives. Cost and longevity are separate questions and should be kept apart when a material is selected, with the lower cost presented to the patient as a trade-off against a shorter evidentiary record.

This review has limitations. The search was not exhaustive and relied on three databases; selection was narrative, so relevant studies may have been missed and no quantitative pooling was performed. The primary studies are predominantly in vitro and heterogeneous in resins, printing parameters, aging protocols and outcome measures, which limits the strength of the comparisons. Publication bias may inflate favorable results, and the restriction to English and Spanish excluded work published in other languages. Each limitation can be addressed by a protocol-driven systematic review with standardized data extraction and by the registration of future laboratory studies, which would reduce selective reporting and allow the field to distinguish real material differences from differences in testing method.

Three lines of work would close the main gaps. A consensus classification of printable resins according to composition, filler content and intended service life would replace the commercial label with a testable definition. Standardized fatigue, wear and aging protocols, aligned with the existing ISO framework for polymer-based restorations, would make laboratory results comparable across laboratories. Prospective cohort and randomized studies with survival, marginal integrity and biological endpoints, starting with single-unit posterior crowns, would provide the clinical estimates that are currently missing.

CONCLUSIONS

Printed permanent resins form a coherent materials category with promising laboratory performance, but their clinical evidence lags behind the mechanical data. Vat-photopolymerized composites can match milled resin composites in single-load strength, yet they are more sensitive to aging, wear and processing errors, and their long-term survival has not been measured. Until standardized material classification, fatigue protocols and prospective clinical studies are available, printed permanent resins should be reserved for indications in which their advantages outweigh the absence of survival data, with careful washing, post-curing and follow-up.

REFERENCES

1. Joda T, Zarone F, Ferrari M. The complete digital workflow in fixed prosthodontics: a systematic review. *BMC Oral Health*. 2017;17(1):124. doi: 10.1186/s12903-017-0415-0
2. Ahlholm P, Sipilä K, Vallittu P, Jakonen M, Kotiranta U. Digital Versus Conventional Impressions in Fixed Prosthodontics: A Review. *Journal of Prosthodontics*. 2018;27(1):35-41. doi: 10.1111/jopr.12527
3. Mangano F, Gandolfi A, Luongo G, Logozzo S. Intraoral scanners in dentistry: a review of the current literature. *BMC Oral Health*. 2017;17(1):149. doi: 10.1186/s12903-017-0442-x
4. Zarone F, Di Mauro MI, Ausiello P, Ruggiero G, Sorrentino R. Current status on lithium disilicate and zirconia: a narrative review. *BMC Oral Health*. 2019;19(1):134. doi: 10.1186/s12903-019-0838-x
5. Bernauer SA, Zitzmann NU, Joda T. The Complete Digital Workflow in Fixed Prosthodontics Updated: A Systematic Review. *Healthcare*. 2023;11(5):679. doi: 10.3390/healthcare11050679
6. Schweiger J, Edelhoff D, GÜth JF. 3D Printing in Digital Prosthetic Dentistry: An Overview of Recent Developments in Additive Manufacturing. *JCM*. 2021;10(9):2010. doi: 10.3390/jcm10092010
7. JOCKUSCH J, ÖZCAN M. Additive manufacturing of dental polymers: An overview on processes, materials and applications. *Dent Mater J*. 2020;39(3):345-354. doi: 10.4012/dmj.2019-123
8. Jeong M, Radomski K, Lopez D, Liu JT, Lee JD, Lee SJ. Materials and Applications of 3D Printing Technology in Dentistry: An Overview. *Dentistry Journal*. 2023;12(1):1. doi: 10.3390/dj12010001
9. Dimitrova M, Vlahova A, Kalachev Y, Zlatev S, Kazakova R, Capodiferro S. Recent Advances in 3D Printing of Polymers for Application in Prosthodontics. *Polymers*. 2023;15(23):4525. doi: 10.3390/polym15234525
10. Grzebieluch W, Kowalewski P, Grygier D, Rutkowska-Gorczyca M, Kozakiewicz M, Jurczyszyn K. Printable and Machinable Dental Restorative Composites for CAD/CAM Application—Comparison of Mechanical Properties, Fractographic, Texture and Fractal Dimension Analysis. *Materials*. 2021;14(17):4919. doi: 10.3390/ma14174919
11. Guttridge C, Shannon A, O'Sullivan A, O'Sullivan KJ, O'Sullivan LW. Biocompatible 3D printing resins for medical applications: A review of marketed intended use, biocompatibility certification, and post-processing guidance. *Annals of 3D Printed Medicine*. 2022;5:100044. doi: 10.1016/j.stlm.2021.100044
12. Hata K, Ikeda H, Nagamatsu Y, Masaki C, Hosokawa R, Shimizu H. Development of Dental Poly(methyl methacrylate)-Based Resin for Stereolithography Additive Manufacturing. *Polymers*. 2021;13(24):4435. doi: 10.3390/polym13244435
13. Sodeyama MK, Ikeda H, Nagamatsu Y, Masaki C, Hosokawa R, Shimizu H. Printable PICN Composite Mechanically Compatible with Human Teeth. *J Dent Res*. 2021;100(13):1475-1481. doi: 10.1177/00220345211012930
14. Aati S, Akram Z, Ngo H, Fawzy AS. Development of 3D printed resin reinforced with modified ZrO2 nanoparticles for long-term provisional dental restorations. *Dental Materials*. 2021;37(6):e360-e374. doi: 10.1016/j.dental.2021.02.010
15. Ling L, Taremi N, Malyala R. A Novel Low-Shrinkage Resin for 3D Printing. *Journal of Dentistry*. 2022;118:103957. doi: 10.1016/j.jdent.2022.103957
16. Sahin Z. Mechanical Characteristics of Composite Resins Produced by Additive and Subtractive Manufacturing. *Eur J Prosthodont Restor Dent*. 2023;31(3):278. doi: 10.1922/ejprd_2478sahin08
17. Suksuphan P, Krajangta N, Didron PP, Wasanapiarnpong T, Rakmanee T. Marginal adaptation and fracture resistance of milled and 3D-printed CAD/CAM hybrid dental crown materials with various occlusal thicknesses. *J Prosthodont Res*. 2023;68(2):326-335. doi: 10.2186/jpr.jpr_d_23_00089
18. Khosravani MR, Reinicke T. Fracture and mechanical behavior of 3D-printed dental resin. *Procedia Structural Integrity*. 2023;51:81-87. doi: 10.1016/j.prostr.2023.10.071
19. Abad-Coronel C, Bravo M, Tello S, Cornejo E, Paredes Y, Paltan CA, et al. Fracture Resistance Comparative Analysis of Milled-Derived vs. 3D-Printed CAD/CAM Materials for Single-Unit Restorations. *Polymers*. 2023;15(18):3773. doi: 10.3390/polym15183773
20. Skienhe H, Özcan M, Eid R, Hardan L, Alharbi N, Corbani K. Fracture Resistance of Three-unit Fixed Dental Prostheses Fabricated with Milled and 3D Printed Composite-based Materials. *The Journal of Contemporary Dental Practice*. 2021;22(9):985-990. doi: 10.5005/jp-journals-10024-3137
21. Farkas AZ, Galatanu SV, Nagib R. The Influence of Printing Layer Thickness and Orientation on the Mechanical Properties of DLP 3D-Printed Dental Resin. *Polymers*. 2023;15(5):1113. doi: 10.3390/polym15051113
22. Alshamrani AA, Raju R, Ellakwa A. Effect of Printing Layer Thickness and Postprinting Conditions on the Flexural Strength and Hardness of a 3D-Printed Resin. *BioMed Research International*. 2022;2022(1):8353137. doi: 10.1155/2022/8353137
23. Park S, Cho W, Lee H, Bae J, Jeong T, Huh J, et al. Strength and Surface Characteristics of 3D-Printed Resin Crowns for the Primary Molars. *Polymers*. 2023;15(21):4241. doi: 10.3390/polym15214241
24. Kim N, Kim H, Kim IH, Lee J, Lee KE, Lee HS, et al. Novel 3D Printed Resin Crowns for Primary Molars: In Vitro Study of Fracture Resistance, Biaxial Flexural Strength, and Dynamic Mechanical Analysis. *Children*. 2022;9(10):1445. doi: 10.3390/children9101445
25. Berghaus E, Klocke T, Maletz R, Petersen S. Degree of conversion and residual monomer elution of 3D-printed, milled and self-cured resin-based composite materials for temporary dental crowns and bridges. *J Mater Sci: Mater Med*. 2023;34(5):23. doi: 10.1007/s10856-023-06729-z
26. Bein L, Rauch A, Schmidt M, Rosentritt M. In vitro fatigue and fracture testing of temporary materials from different manufacturing processes in implant-supported anterior crowns. *Clin Oral Invest*. 2023;27(8):4215-4224. doi: 10.1007/s00784-023-05038-7

27. Alshamrani A, Alhotan A, Kelly E, Ellakwa A. Mechanical and Biocompatibility Properties of 3D-Printed Dental Resin Reinforced with Glass Silica and Zirconia Nanoparticles: In Vitro Study. *Polymers*. 2023;15(11):2523. doi: 10.3390/polym15112523
28. Jain S, Sayed ME, Shetty M, Alqahtani SM, Al Wadei MHD, Gupta SG, et al. Physical and Mechanical Properties of 3D-Printed Provisional Crowns and Fixed Dental Prosthesis Resins Compared to CAD/CAM Milled and Conventional Provisional Resins: A Systematic Review and Meta-Analysis. *Polymers*. 2022;14(13):2691. doi: 10.3390/polym14132691
29. Alzahrani SJ, Hajjaj MS, Azhari AA, Ahmed WM, Yeslam HE, Carvalho RM. Mechanical Properties of Three-Dimensional Printed Provisional Resin Materials for Crown and Fixed Dental Prosthesis: A Systematic Review. *Bioengineering*. 2023;10(6):663. doi: 10.3390/bioengineering10060663
30. Güven ME, Çakmak G, Dönmez MB, Yilmaz B. Evaluation of Dimensional Stability and Occlusal Wear of Additively and Subtractively Manufactured Resin-Based Crowns after Thermomechanical Aging. *Applied Sciences*. 2023;13(21):11849. doi: 10.3390/app132111849
31. Cha HS, Park JM, Kim TH, Lee JH. Wear resistance of 3D-printed denture tooth resin opposing zirconia and metal antagonists. *The Journal of Prosthetic Dentistry*. 2020;124(3):387-394. doi: 10.1016/j.prosdent.2019.09.004
32. Karaoğluanoğlu S, Aydın N, Oktay E, Ersöz B. Comparison of the Surface Properties of 3D-printed Permanent Restorative Resins and Resin-based CAD/CAM Blocks. *Oper Dent*. 2023;48(5):588-598. doi: 10.2341/23-006-I
33. Bozoğulları HN, Temizci T. Evaluation of the Color Stability, Stainability, and Surface Roughness of Permanent Composite-Based Milled and 3D Printed CAD/CAM Restorative Materials after Thermocycling. *Applied Sciences*. 2023;13(21):11895. doi: 10.3390/app132111895
34. Hwangbo NK, Nam NE, Choi JH, Kim JE. Effects of the Washing Time and Washing Solution on the Biocompatibility and Mechanical Properties of 3D Printed Dental Resin Materials. *Polymers*. 2021;13(24):4410. doi: 10.3390/polym13244410
35. Kim GT, Go HB, Yu JH, Yang SY, Kim KM, Choi SH, et al. Cytotoxicity, Colour Stability and Dimensional Accuracy of 3D Printing Resin with Three Different Photoinitiators. *Polymers*. 2022;14(5):979. doi: 10.3390/polym14050979
36. Aydın N, Karaoğluanoğlu S, Kılıç-Süloğlu A, Öztürk S. Comparison of the Cytotoxic Effect of 3D-Printed Resins, Resin-based CAD/CAM blocks and Composite Resin. *J Clin Exp Dent*. 2023;15(12):e984-e990. doi: 10.4317/jced.60987
37. Wuerschling SN, Hickel R, Edelhoff D, Kollmuss M. Initial biocompatibility of novel resins for 3D printed fixed dental prostheses. *Dental Materials*. 2022;38(10):1587-1597. doi: 10.1016/j.dental.2022.08.001
38. Vichi A, Balestra D, Scotti N, Louca C, Paolone G. Translucency of CAD/CAM and 3D Printable Composite Materials for Permanent Dental Restorations. *Polymers*. 2023;15(6):1443. doi: 10.3390/polym15061443
39. Gad MM, Alshehri SZ, Alhamid SA, Albarrak A, Khan SQ, Alshahrani FA, et al. Water Sorption, Solubility, and Translucency of 3D-Printed Denture Base Resins. *Dentistry Journal*. 2022;10(3):42. doi: 10.3390/dj10030042
40. Graf T, Erdelt KJ, Güth JF, Edelhoff D, Schubert O, Schweiger J. Influence of Pre-Treatment and Artificial Aging on the Retention of 3D-Printed Permanent Composite Crowns. *Biomedicines*. 2022;10(9):2186. doi: 10.3390/biomedicines10092186
41. KAKINUMA H, IZUMITA K, YODA N, EGUSA H, SASAKI K. Comparison of the accuracy of resin-composite crowns fabricated by three-dimensional printing and milling methods. *Dent Mater J*. 2022;41(6):808-815. doi: 10.4012/dmj.2022-074
42. Donmez MB, Okutan Y. Marginal gap and fracture resistance of implant-supported 3D-printed definitive composite crowns: An in vitro study. *Journal of Dentistry*. 2022;124:104216. doi: 10.1016/j.jdent.2022.104216
43. Çakmak G, Agovic D, Donmez MB, Kahveci Ç, de Paula MS, Schimmel M, et al. Effect of number of supports and build angle on the fabrication and internal fit accuracy of additively manufactured definitive resin-ceramic hybrid crowns. *Journal of Dentistry*. 2023;134:104548. doi: 10.1016/j.jdent.2023.104548
44. Arafa A, Ziada A. Marginal Adaptability and Fracture Resistance of Endodontically Treated Premolars Restored with 3D printed and milled Endo-crowns. *Egyptian Dental Journal*. 2023;69(3):2137-2152. doi: 10.21608/edj.2023.204867.2513
45. Refaie A, Fouda A, Bourauel C, Singer L. Marginal gap and internal fit of 3D printed versus milled monolithic zirconia crowns. *BMC Oral Health*. 2023;23(1):448. doi: 10.1186/s12903-023-03184-8
46. Al-Halabi MN, Bshara N, Nassar JA, Comisi JC, Rizk CK. Clinical Performance of Two Types of Primary Molar Indirect Crowns Fabricated by 3D Printer and CAD/CAM for Rehabilitation of Large Carious Primary Molars. *Eur J Dent*. 2021;15(03):463-468. doi: 10.1055/s-0040-1721905
47. Kao CT, Liu SH, Kao CY, Huang TH. Clinical evaluation of 3D-printed zirconia crowns fabricated by selective laser melting (SLM) for posterior teeth restorations: Short-term pilot study. *Journal of Dental Sciences*. 2023;18(2):715-721. doi: 10.1016/j.jds.2022.11.017
48. Dewan H. Clinical Effectiveness of 3D-Milled and 3D-Printed Zirconia Prosthesis—A Systematic Review and Meta-Analysis. *Biomimetics*. 2023;8(5):394. doi: 10.3390/biomimetics8050394
49. Srinivasan M, Kalberer N, Fankhauser N, Naharro M, Maniewicz S, Müller F. CAD-CAM complete removable dental prostheses: A double-blind, randomized, crossover clinical trial evaluating milled and 3D-printed dentures. *Journal of Dentistry*. 2021;115:103842. doi: 10.1016/j.jdent.2021.103842
50. Cristache CM, Totu EE, Iorgulescu G, Pantazi A, Dorobantu D, Nechifor AC, et al. Eighteen Months Follow-Up with Patient-Centered Outcomes Assessment of Complete Dentures Manufactured Using a Hybrid Nanocomposite and Additive CAD/CAM Protocol. *JCM*. 2020;9(2):324. doi: 10.3390/jcm9020324

51. Guncu MB, Aktas C, Turkyilmaz I, Gavras JN. Performance of high-translucent zirconia CAD/CAM fixed dental prostheses using a digital workflow: A clinical study up to 6 years. *Journal of Dental Sciences*. 2023;18(1):44-49. doi: 10.1016/j.jds.2022.07.023
52. Josic U, D'Alessandro C, Miletic V, Maravic T, Mazzitelli C, Jacimovic J, et al. Clinical longevity of direct and indirect posterior resin composite restorations: An updated systematic review and meta-analysis. *Dental Materials*. 2023;39(12):1085-1094. doi: 10.1016/j.dental.2023.10.009
53. Bresser RA, Hofsteenge JW, Wieringa TH, Braun PG, Cune MS, Özcan M, et al. Clinical longevity of intracoronal restorations made of gold, lithium disilicate, leucite, and indirect resin composite: a systematic review and meta-analysis. *Clin Oral Invest*. 2023;27(9):4877-4896. doi: 10.1007/s00784-023-05050-x
54. Demarco FF, Cenci MS, Montagner AF, de Lima VP, Correa MB, Moraes RR, et al. Longevity of composite restorations is definitely not only about materials. *Dental Materials*. 2023;39(1):1-12. doi: 10.1016/j.dental.2022.11.009
55. Joda T, Bragger U, Zitzmann NU. CAD/CAM implant crowns in a digital workflow: Five-year follow-up of a prospective clinical trial. *Clin Implant Dent Rel Res*. 2019;21(1):169-174. doi: 10.1111/cid.12681
56. Alhallak K, Hagi-Pavli E, Nankali A. A review on clinical use of CAD/CAM and 3D printed dentures. *Br Dent J*. 2023. doi: 10.1038/s41415-022-5401-5

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