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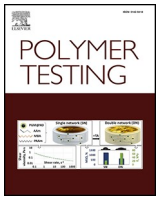

Narrative review of 3D-printed temporary and permanent dental resin restorations

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ABSTRACT

The advent of 3D-printed permanent restorations marks a significant evolution in restorative dentistry, offering potential in terms of customization and production of complex geometries in a time- and cost-effective way by additive manufacturing. The aim was to critically review the literature on the current state of printing technologies, materials, as well as pre- and post-processing. It addresses the challenges and limitations associated with the adoption of printed permanent restoration materials. Vat polymerisations remain the dominant manufacturing process, while first attempts have been made in direct-ink-writing. The group of 3D-printable materials has shown great heterogeneity, significantly different mechanical and physical properties. Fillers enhanced the properties of resins and were added to materials for printable permanent restorations in contrast to those for temporary restorations. While the mechanical properties of 3D-printed resin restorations have significantly improved, the biggest challenges are color stability, water sorption, solubility, and anisotropy. Pre-processing and post-processing of the materials have been found to significantly impact material performance, while a systematic benchmarking of different approaches, needed to guide daily application, is missing. The biological properties and clinical performance, as well as the cost-effectiveness and applicability, remain almost unexplored. At present, 3D-printing of restorations is characterised by a high number of individual manual steps. A higher degree of automation is essential if it is to become a mainstream workflow.

1. Introduction

Additive manufacturing, also known as 3D-printing, has gained significant traction in dentistry, progressing from diagnostic models to functional restorations [1]. Particularly 3D-printed resin restorations have garnered substantial attention.

Early iterations of 3D-printed resins had no or low filler content and were primarily employed for manufacturing temporary restorations due to concerns about their long-term durability, biocompatibility, and mechanical properties. However, advancements in resin formulations, printing technology, and post-processing have addressed many of these issues, enabling the production of restorations that should meet the stringent demands of permanent dental restorations. Today, 3D-printed restorations offer advantages such as digital efficiency, parallel production, and minimal material waste. Thin margins and on-demand manufacturing add further benefits. Despite these improvements, key concerns remain. Issues like long-term wear resistance, color stability, water sorption, and consistent mechanical performance under intraoral conditions continue to limit widespread adoption—particularly for permanent use [1].

Additionally, ensuring consistent quality and safety across different 3D-printing and post-processing strategies is needed, also to obtain regulatory approval. The existing ISO 10477:2020 for polymer-based crown and veneering materials covers indirect resin-based single-tooth restorations such as crowns, onlays, and veneers (but not fixed dental prostheses) and is widely used for regulatory approval of permanent 3D-printed restoration materials worldwide. To approve 3D-printed resin-based permanent fixed dental prostheses, ISO 6872:2019–01 and ISO 22674:2016–09 for ceramic and metal-based restorations, respectively, are employed, whilst the demanded material testing strategies and performance requirements cannot be addressed using resin-based materials. As a result, the regulations around printing resins for permanent

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restorations are still patchy and their application inconsistent, which could lead to uncertainty among dental clinicians. The properties of 3D-printed restorations are influenced by various factors, which can be categorized into pre-printing, printing, and post-printing stages. The performance of printed restorations depends on factors across three main stages: pre-printing (e.g., resin composition), printing (hardware, orientation, layer thickness), and post-processing (curing conditions, rinsing protocols, polishing). These steps significantly impact the degree of conversion, mechanical strength, and biocompatibility of the final restoration.

The use of 3D-printing materials restorations is limited by a variety of factors that have a negative impact on their clinical performance, longevity, and somehow acceptance in mainstream restorative dentistry. The present narrative review will focus on the issues presented by the materials and address them by highlighting the challenges, inconsistencies, and gaps in knowledge in order to move the materials to standardized, clinically reliable applications.

2. Focused question and search strategy

The study addressed the following focused question: "What is the current state of 3D-printed resin materials and technologies for temporary and permanent dental restorations, and what are the challenges, limitations, and knowledge gaps that must be addressed to achieve standardized, clinically reliable applications?"

A comprehensive electronic literature search was conducted in PubMed (Medline), Web of Science, and the Cochrane Library up to July 16, 2025. The search was restricted to studies published in English, without limitations on publication date. To enhance the search sensitivity, a combination of controlled vocabulary (MeSH and Emtree terms) and free-text keywords was employed. In addition, the reference lists of all included and relevant studies were manually screened. To ensure thoroughness, supplementary searches were also performed via Google Scholar. All retrieved records were managed using EndNote (version 21; Clarivate Analytics) to support the screening process. Studies were eligible for inclusion if they were peer-reviewed in vitro or in vivo investigations published in English, comparing temporary and permanent fixed dental restorations fabricated using 3D-printed resin-based materials.

Exclusion criteria comprised studies that focused on printed non-resin materials (e.g., zirconia, glass ceramics), investigated 3D-printed materials for removable denture teeth, investigated conventionally or milled fabricated restorations, reported outcomes not relevant to the review's focus. Furthermore, the following publication types were excluded: case reports, case series, reviews, conference abstracts, book chapters, expert opinions, editorials, and letters to the editor.

The search was conducted with the following keywords: methacrylates, computer-aided design (CAD), additive manufacturing, resin-based composite, SLA, DLP, 3D printed dental restorations, 3D printed temporary restorations, 3D printed permanent restorations, 3D printed restorations in addition to each of the following terms: biological properties, bond strength, preprocessing, postprocessing, mechanical properties, biological properties, color stability, water sorption, solubility, printing orientation, layer size, accuracy.

3. Printing technologies

Additive manufacturing as an umbrella term includes different technologies and can be subdivided into seven process categories [2]: Material jetting, Material extrusion, Vat photopolymerization, Binder jetting, Powder-bed fusion, Directed energy deposition, Sheet lamination.

Material jetting enables multicolor, multi-material prints in one build and can reproduce natural tooth aesthetics. However, filler content is limited, which restricts its mechanical performance. While FDA approval exists for denture applications, no suitable materials are currently marketed for individual restorative units.

Using material extrusion, the first approaches to directly printing commercially available composites through the Direct Ink Writing (DIW) process are already on the market. So highly filled materials can be used for the production of mechanically robust definitive restorations. This approach has the potential to reduce occupational exposure to resin chemicals and minimize the environmental impact by producing no byproducts [3]. The first study was published in dentistry with promising results [4]. However, problems like oozing of the printed material and the stringing phenomenon are still challenging. To fully leverage the potential of DIW technology, ongoing research should focus on using different extruders with different materials and colors simultaneously during the printing process.

Vat photopolymerization (including SLA, DLP, and LCD) is the dominant method in dental restoration printing (Fig. 1). SLA uses a laser to cure resin point-by-point, while DLP projects entire layers at once, accelerating production. LCD systems use LED matrices and are often seen in lower-cost printers. DLP is most prevalent due to its efficiency and resolution balance.

Critical parameters affecting print quality include layer thickness (typically 25–100 μm), resin formulation, and irradiation conditions. These factors influence surface resolution, build time, and mechanical anisotropy. The choice of printer and parameters must align with clinical demands for strength, accuracy, and esthetics.

4. Postprocessing

Post-processing is essential to transforming a 3D-printed object from its initial "green" state to a fully functional dental restoration. Key steps include cleaning, curing, and finishing, all of which impact the mechanical strength, esthetics, and biocompatibility of the final product.

Cleaning typically involves rinsing with isopropyl alcohol (IPA) to remove unpolymerized resin. IPA is flammable and may pose health risks like ethanol, which presents similar safety concerns. Moreover, exposure to alcohol may cause surface discoloration, especially in filled materials, by dissolving surface monomers. Some manufacturers now advocate for centrifugal cleaning, which has been shown to improve degree of conversion (DC) and reduce surface roughness without relying on solvents [5]. Extended washing times and also higher concentrations have been shown to reduce residual monomers, which in turn improves both the degree of conversion and flexural strength of printed objects [6,7]. Post-curing is the crucial step in improving the mechanical strength and biocompatibility of 3D-printed parts. This process is influenced by factors, such as the type of curing chamber, UV light wavelength, intensity, temperature, exposure duration, and the chemical composition of the resin [8,9].

DC typically improves by approximately 20–30 % from the uncured to cured state, which significantly enhances the mechanical properties of the object and reduces layer anisotropy [10,11]. The implementation of a nitrogen gas atmosphere or vacuum during the post-curing process enables the creation of an inert environment, which effectively reduces the negative impact of the oxygen inhibition layer and its negative effect on the final properties of the material. Furthermore, dry post-processing methods have demonstrated superior performance in terms of flexural strength and fracture resistance compared to wet post-processing conditions [7].

In conclusion, post-processing is of paramount importance for optimizing the final physical, chemical, and mechanical properties.

5. Temporary and permanent restoration materials

An overview of currently available materials is listed in Table 1 for the temporary and in Table 2 for the permanent restoration materials. The evidence supporting temporary and permanent materials is as heterogeneous as the materials and their application themselves. Due to the numerous variations in parameters, comparing studies and isolating the

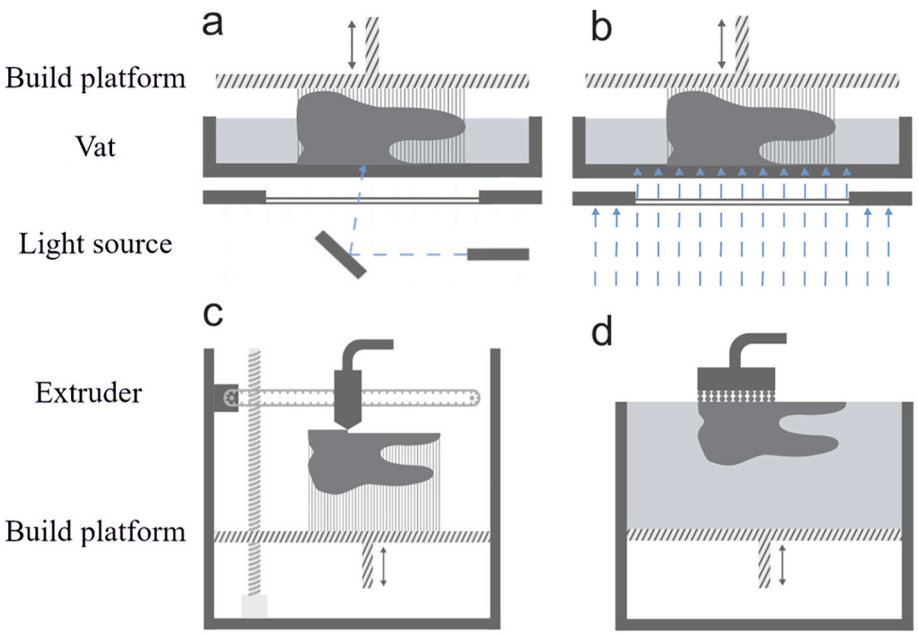

Fig. 1. Schemes for SLA (a) DLP (b) printer with top-down building platform, vat filled with liquid monomer, light source as a laser for the SLA-Printer and structured light by a projector and DMD for the DLP-Printer; 3-axis Direct-Ink-Writing printer (c) and Polyjet printer with build platform and Extruder (d).

impact of individual variables is nearly impossible. Permanent materials have different requirements compared to temporary materials, as they demand higher material properties for long-term use (see Fig. 1).

A comparison of the ingredients constituting printable temporary and permanent materials reveals a significant disparity in their filler content and size. Fillers enhance strength, stiffness, and dimensional stability, but their inclusion complicates the printing process. Filler type, size, shape, and distribution all affect resin viscosity and light scattering. Printable composites typically contain 10–30 vol% or 30–50 wt% fillers - much less than CAD/CAM milled materials (up to 85 wt%) [12]. This difference in content is evident in the material properties exhibited by the respective resins (Fig. 2). Printable materials with higher filler content demonstrate superior mechanical properties, including flexural strength [13–22]. While adding fillers into printable materials improves mechanical properties, it also introduces air entrapment risk, increases anisotropy, and may impair accuracy if dispersion is uneven [23]. Light scattering by fillers influences curing depth, described by the Beer-Lambert law. Mismatches in refractive index between fillers and resin can impair polymerization and weaken interlayer bonding. Therefore, consistent mixing and storage practices are essential. SEM images showed homogeneously distributed irregular glass fillers in bimodal distribution (Fig. 3). The average size of the larger fillers is 1.5 μm while smaller filler are about 0.5 μm. The irregular of the mostly silanized fillers prevent rapid sedimentation and enable a high curing depth. The type of filler and the density of the packing is therefore different to the conventional microhybrid oder nanohybrid resin based composites.

Viscosity remains a bottleneck in printable resin development. SLA and DLP printing require a viscosity below ~5 Pa s to ensure smooth layer recoating and surface quality [24]. Highly filled formulations with small fillers like known from traditional direct composites risk becoming too viscous to print reliably, leading to voids, reduced accuracy, or build failure. As such, a balance between mechanical performance and printability must be maintained [13,15]. A clinical study showed a success rate of 76.2 % for 3D-printed single-crown provisionals compared to a success rate of 85.7 % for conventional PMMA single-crown provisionals [25].

3D-printed materials intended for permanent applications present inadequate mechanical performance in comparison to nanohybrid composite resin and polymer-infiltrated ceramic network [23]. This phenomenon can be attributed to the presence of nonhomogeneous microstructural features that emerge during the process of material mixing [23], as well as variations in polymerization modes and filler composition [26]. Adding nanofillers can improve the flexural strength but decreases aesthetics [27]. Marginal adaptation of 3D-printed restorations has been shown to be superior to milled restorations. Moreover, 3D-printed abutment crowns have demonstrated adequate internal fit [28]. Wear and volume loss are also important properties for evaluating the suitability of 3D-printed materials for permanent use. Not all materials perform equally well and some are rather recommended for medium-term restorations [29,30].

The flexural strength of certain 3D-printed materials is generally acceptable for single crowns but too low for more extended or specifically loaded restorations [31]. The majority of extant studies make reference to in vitro data. A paucity of clinical trials pertaining to this topic was identified, and furthermore, all of them pertained to a short period of observation [32–35]. Two clinical studies showed survival rates of 82.1 % and 84.4 % for 3D-printed restorations in prosthetic rehabilitation at 12 months [32,33], thereby suggesting them as alternative treatment options in initial phases of complex prosthetic cases [32]. Another clinical study showed considerable material wear after two years of clinical function, thereby suggesting the material appears only for interim restorations [36]. Two other clinical studies of 3D-printed 3-unit fixed dental prostheses found lower survival rates of 71.6 % after one year and 61 % after two years [34,35].

The layer-by-layer printing process has been found to be limited by anisotropy in its fundamental design. Studies have evaluated the influence of different layer thicknesses on mechanical properties and anisotropy of temporary materials, underscoring the importance of optimizing these parameters [13,37,38]. It is important to note that the bond between each printed layer and the adjacent layers may not be optimal, resulting in mechanical properties that vary depending on the print orientation [13,15,21,39].

This can result in inconsistent performance and may lead to premature failure, especially in restorations that experience multidirectional stress. Printing orientation significantly affects the anisotropy of 3D-printed restorations, but results vary due to differences in resin types and printing parameters also for permanent restoration materials

Table 1
Overview of materials for the additive manufacturing of temporary restorations (acc. instructions of use/safety data sheets).

Material	Manufacturer	Print technique	Chemical composition	Indication
3Delta Etemp	DeltaMed GmbH	DLP	contains acrylates, fillers (50 wt%), initiators, pigments	Temporary crowns, bridges, inlays, onlays, veneers
FREEPRINT temp	DETAX GmbH	DLP	contains (meth)acrylates and phosphine oxides (e.g. Isopropylidenediphenol peg-2 dimethacrylate (45 - < 60 %), 1,6-Hexandiol dimethacrylate (1 - < 5 %), 2-Hydroxyethylmethacrylate (HEMA) (1 - < 5 %), Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (1 - < 5 %), Hydroxypropyl methacrylate (1 - < 5 %), Phenyl-bis(2,4,6-trimethylbenzoyl)-phosphine oxide (<1 %))	Temporary crowns, bridges
IMPRIMO LC Temp lt	SCHEU-DENTAL GmbH	DLP	a.o. 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3, 14-dioxa-5,12-diazahexadecane-1, 16-diyl bismethacrylate (<40 %), Esterification products of 4,4′-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (<20 %), Esterification products of 4,4′-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (<20 %), 3,6,9-trioxaundecamethylene dimethacrylate (<10 %), Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (<2 %)	Temporary crowns, bridges and mock ups
NextDent C&B Micro Filled Hybrid	NextDent B.V.	DLP	a.o. 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo- 3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate; ethylene dimethacrylate; 2-hydroxyethyl methacrylate; diphenyl(2,4,6- trimethylbenzoyl)phosphine oxide	Temporary crowns, bridges
optiprint lumina	dentona AG	DLP	contains methacrylate blend, inorganic fillers, photoinitiators, dye (residual monomer <2,2 %)	Temporary crowns, bridges
P pro Crown & Bridge	Straumann GmbH	DLP	N/A	Temporary crowns, bridges, inlays, onlays, veneers
printodent GR-17.1 temporary lt	pro3dure medical GmbH	DLP	contains functional methacrylic resins and inorganic fillers (0.4–3 μm), e.g. (Esterification products of 4,4′-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (25–45 %), 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3, 14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate (24–45 %), 3,6,9-trioxaundecamethylenedimethacrylate (7–10 %), 2-Propenoic acid, reaction products with pentaerythritol (<2 %), Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (<2 %))	Denture teeth, temporary crowns, bridges
SprintRay EU Temporary Crown & Teeth	SprintRay Europe GmbH	DLP	consists of functional (meth)acrylic resins (e.g. 7,7,9(or 7,9,9)- trimethyl-4,13-dioxo- 3,14-dioxa-5,12- diazahexadecane-1,16- diyl bismethacrylate (<98 %), Phenyl bis(2,4,6- trimethylbenzoyl)- phosphine oxide (<2 %)), Siliciumdioxid and inorganic fillers (size 0,4 - 3 μm)	Temporary crowns, bridges
Temp PRINT	GC Germany GmbH	DLP	o.a. 7,7,9(or 7,9,9)- trimethyl-4,13-dioxo- 3,14-dioxa-5,12- diazahexadecane-1,16- diyl bismethacrylate (50 - < 75 %), 2,2′-Ethylenedioxydiethyl dimethacrylate (10 - < 25 %), silica glass (10 - < 25 %), Silanamines, 1,1,1-trimethyl-N-(trimethylsilyl)-, hydrolysis products with silica (5 - < 10 %), products of 4,4′-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (2,5 - < 5 %), Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (1 - < 2,5 %), 2-(2H-Benzotriazol-2-yl)-p-cresol (0,5 - < 1 %), formaldehyde polymer with 1,3,5-triazine-2,4,6-triamine (0,5 - < 1 %), 2,6-di-tert-butyl-p-cresol (0,5 - < 1 %), iron (III) oxide (0,5 - < 1 %), titanium dioxide (0,5 - < 1 %)	Temporary crowns, bridges, inlays, onlays, veneers
Temporary CB Resin	Formlabs GmbH	SLA	o.a. esterification products of 4,4′-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (50 - < 75 %), dipheny|(2,4,6-trimethylbenzoyl) phosphine oxide (<2,5 %), silanized dental glass, methyl benzoylformate (inorganic filler content 30–50 % by weight and size of 0,7 μm)	Temporary crowns, bridges, inlays, onlays, veneers
V-Print c&b temp	VOCO GmbH	DLP	contains inorganic fillers (26 wt%), (meth)acrylates and phosphine oxide (e.g. aliphatic urethane dimethacrylate (10–25 %), aliphatic acrylate (5–10 %), triethylenglycoldimethacrylate (2,5–5 %), diphenyl(2,4,6,-trimethylbenzoyl) phosphine oxide (1–2,5 %)	Temporary crowns, bridges and mock ups
Varseo Smile Temp	BEGO Bremer Goldschlägerei Wilh. Herbst GmbH & Co. KG	DLP	contains inorganic fillers (size 0.7 μm, 30–50 wt%), esterification products of 4,4'-isopropylidiphenol, ethoxylated and 2-methylprop-2eno-ic acid (50 - <75 %), diphenyl(2,4,6-trimethyl-benzoyl) phosphine oxide (<2,5 %), silanized dental glass, methyl benzoylformate	Temporary crowns, bridges, inlays, onlays, veneers

[26]. The layer thickness exerts a significant influence on the mechanical behavior of materials [40]. The anisotropy can be considered higher for permanent materials due to the quantity of their filler and the resulting inhomogeneity. The literature on mechanical properties is limited and heterogeneous, with inconsistencies largely arising from variations in experimental setups, evaluated parameters, and material compositions [12,23,26,41,42]. Perpendicular builds involve more layers and greater interfacial areas, where polymer chains are less densely crosslinked. This increases dimensional instability and anisotropy, making restorations vulnerable to layer separation and distortion. Adhesion between printed layers is a mechanical weak point and frequently the origin of fracture or delamination [43,44] (Fig. 4). A higher layer thickness can reduce anisotropy but is not consistent with the surface resolution of the object. Inhomogeneity due to filler sedimentation during storage or printing must be strictly controlled. No universal optimal printing angle can be recommended for all materials in the literature [13,37]. Furthermore, the printing orientation and artificial ageing influence the mechanical properties and lead to their deterioration so that 3D-printed resins should rather be considered for temporary restorations [39]. In addition to print orientation, factors such as material composition, print layer thickness, cleaning protocols, type of post-curing device, and post-curing duration also significantly influence the mechanical properties [5,17,37,45–54].

A multitude of studies have demonstrated that 3D-printed materials exhibit inferior color stability in comparison to milled materials, even when the milled materials are immersed for a more extended duration [55–58]. The optical properties of 3D-printed materials are affected by various factors, including composition, surface treatment, thickness, printing orientation, dietary habits, smoking, and personal hygiene practices [55,59–67]. The underlying reasons for this phenomenon are

Table 2
Overview of materials for the additive manufacturing of permanent restorations (acc. instructions of use/safety data sheets).

Material	Manufacturer	Print technique	Chemical composition	Indication
3Delta Crown	DeltaMed GmbH	DLP	contains crylates, fillers (50 wt%), initiators, pigments	permanent crowns, inlays, onlays, veneers
Flexcera Smile Ultra+	Desktop Metal, Inc.	DLP	contains acrylates, methacrylates, photoinitiators, colorants/dyes, fillers, absorbers (e.g. Methacrylated monomer (10–20 %), Methacrylic oligomer (25–40 %), Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (0,1–1 %), Methacrylated oligomer (25–40 %), Methacrylated monomer (1–10 %)	permanent/temporary denture teeth, permanent crowns, inlays, onlays, veneers, full and partial dentures
FREEPRINT crown	DETAX GmbH	DLP	contains (meth)acrylates and phosphine oxides, inorganic filler	permanent crowns, inlays, onlays, veneers, denture teeth, long-term temporary bridges
Permanent Crown Resin	Formlabs GmbH	SLA	contains esterification products of 4,4′-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (50 - <75 %), dipheny|(2,4,6-trimethylbenzoyl)phosphine oxide (<2,5 %), silanized dental glass, methyl benzoylformate, inorganic fillers (size of 0,7 µm, 50 wt%)	permanent crowns, inlays, onlays, veneers
PRO Resins Crown X	Straumann GmbH	DLP	contains acrylates, fillers and initiators (e.g. acrylic resin (20–40 %), Urethane dimethacrylate (UDMA) (<25 %), Diacrylate (<20 %), Diphenyl (2,4,6-trimethylbenzoyl)phosphine oxide (<1 %), fillers (50 wt%)	permanent crowns, inlays, onlays, veneers
Saremco print CROWNTEC	SAREMCO Dental AG	DLP	contains Bisphenol A Polyethylene Glycol Diether Dimethacrylate (BisEMA) (50 - <75 %), Methyl benzoylformate (1- <5 %), Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (1 - <5 %), dental glass (silanized), pyrogenic, silica, catalysts, inhibitors	denture teeth, permanent/temporary crowns, inlays, onlays, veneers
SprintRay Crown	SprintRay Europe GmbH	DLP	contains esterification products of 4,4'isopropylidiphenol, ethoxylated and 2methyl prop2enoic acid (50 - <75 %), Diphenyl(2,4,6-trimethylbenzoyl) phosphinoxid (<2,5 %), silanized dental glass, methyl benzoylformate, diphenyl(2,4,6trimethyl benzoyl) phosphine oxide, inorganic fillers (size of 0,7 µm, 30–50 wt%)	permanent crowns, inlays, onlays, veneers
VarseoSmile Crown^{plus}	BEGO Bremer Goldschlägerei Wilh. Herbst GmbH & Co. KG	DLP	contains esterification products of 4,4'-isopropylidiphenol, ethoxylated and 2-met- hylprop-2enoic acid (50 - <75 %), silanized dental glass, methyl benzoylformate, diphenyl(2,4,6-trimethyl- benzoyl) phosphine oxide (<2,5 %), inorganic fillers (size of 0,7 µm, 30–50 wt%)	permanent crowns, inlays, onlays, veneers, veneers for metal crowns
VarseoSmile TriniQ	BEGO Bremer Goldschlägerei Wilh. Herbst GmbH & Co. KG	DLP	= ceramic-filled hybrid material (contains ceramic fillers, initiators, additives and pigments, (meth)acrylates e.g. esterification products of 4,4'isopropylidiphenol, ethoxylated and 2methyl prop2enoic acid (55–80 %), Benzeneacetic acid, α-oxo-, methyl ester (<5 %), (2,4,6-trimethylbenzoyl)phosphine oxide (<2,5 %))	permanent crowns, inlays, onlays, veneers, bridges, temporary bridges, denture teeth

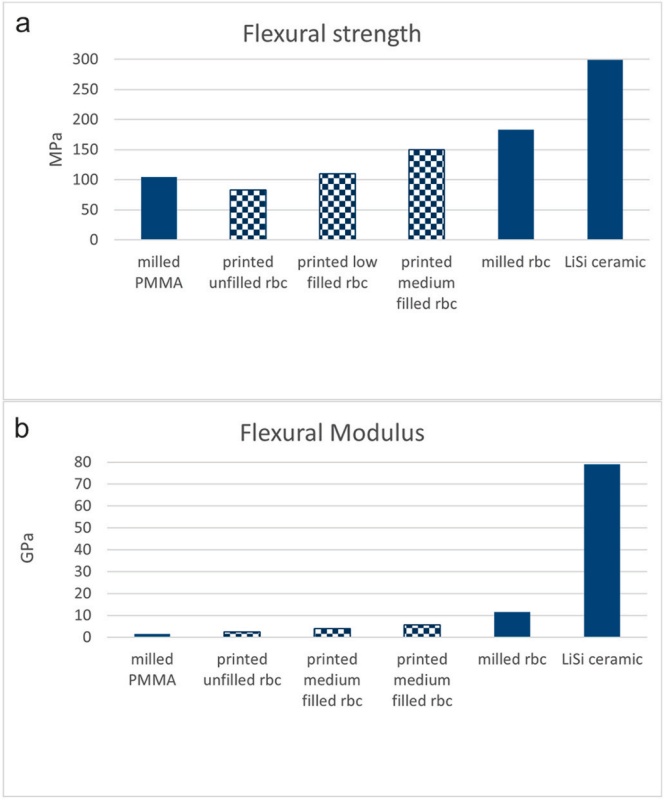

Fig. 2. Flexural strength (a) and flexural modulus (b) of different milled and printed materials (rbc = resin-based composite) [13,21,22].

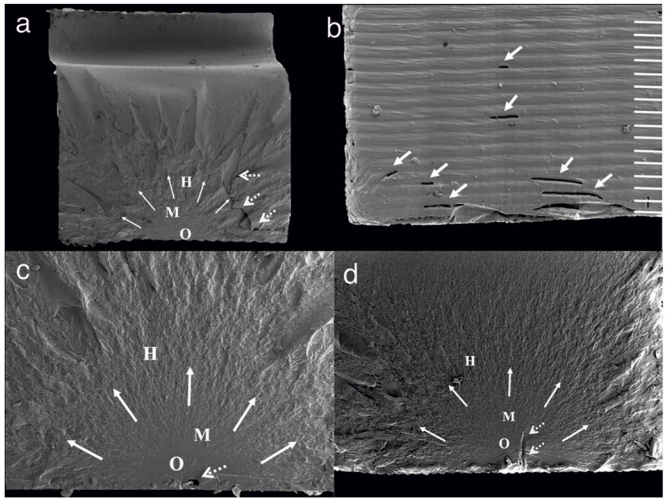

Fig. 3. SEM images displaying a native 3D-printed material with matrix at 5000 × magnification (a) and a 3D-printed material with burnt-out matrix on the surface at 10000 × magnification (b): irregular fillers can be seen, homogenously distributed with bimodal distribution, with smaller (0.5 µm) and larger (1.5 µm) fillers.

rooted in the printing process itself. Most 3D-printed dental resins are based on acrylate monomers that require photoinitiators to polymerize under light exposure. Common initiators include TPO and BAPO, which cleave to produce free radicals, enabling rapid curing by a concentration of 3–5 % in comparison to conventional direct composites which contain 0.1–1 wt% [1,68]. Notably, TPO was recently classified as toxic for reproduction category 1B from the European Chemicals Agency in 2023

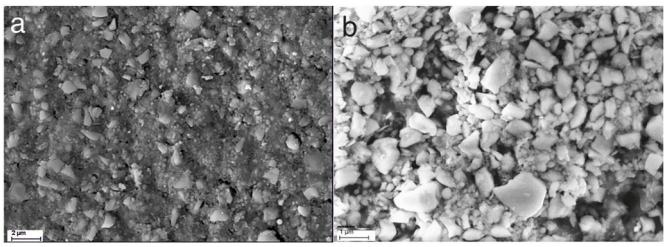

Fig. 4. Fracture surface SEM analysis: fracture origin (O), fracture mirror (M), and hackle lines (H). White bolt arrows indicate delamination (magnification 40 ×) (a); horizontally printed specimen; white lines indicate different printing layers; arrows indicate void inclusions between layers (magnification 150 ×) (b); horizontally parallel printed specimen shows the fracture origin (O) at a surface void (dotted arrow), fracture mirror (M), hackle lines (H) (magnification 250 ×) (c); horizontally parallel printed specimen shows the fracture origin (O) between two layers (dotted arrow), fracture mirror (M), hackle lines (H) (magnification 250 ×) (d).

[69], prompting the search for safer alternatives. BAPO is a common replacement but may exacerbate discoloration [70]. Furthermore, the liquid form of TPO is used, in which a phenyl group is replaced by an ethoxy group, with the aim of reducing its carcinogenicity. Because most 3D printers operate at 385 or 405 nm wavelengths, initiator selection must match the light source for optimal curing.

Unlike conventional composites, printable resins avoid metal oxide pigments to prevent sedimentation, instead using organic pigments that are less color-stable. These pigments are susceptible to chemical degradation, resulting in discoloration and a compromised aesthetic outcome over time [71]. Combined with high monomer content and potential residuals, these contribute to discoloration and water uptake over time. A clinical study revealed a statistically significant difference regarding marginal discoloration between baseline and 24 months [72]. Compared to millable materials, their limited polishability may promote greater plaque accumulation [61,65]. Prolonged polymerization times can significantly reduce residual monomer content, thereby enhancing shade stability [65]. The diminished aesthetic longevity of 3D-printed permanent restorations may necessitate premature replacement.

Polymerization in 3D-printed resins occurs in two stages: initial gelation during printing, followed by post-curing. Conversion rates exceed 50 % after printing but may rise to 90 % post-cure with adequate UV exposure [45]. In the second stage, small monomers like HDMA, HEMA, and TEGDMA are often used; they are hydrophilic in nature and can contribute to poor color stability given their higher polarity [15,71, 73–75]. While these monomers are advantageous during the polymerization and handling stages, they also enhance water uptake, which can result in hydrolytic degradation of the polymer matrix, increased solubility, and dimensional instability [76]. The eluates of 3D-printed provisional materials have therefore been shown to reduce human cell viability and alter the expression of proinflammatory mediators [77–79].

Elevated water absorption can increase the material's susceptibility to staining [71]. Surface treatments such as sealing, glazing, and polishing effectively reduce surface roughness, thereby enhancing the color stability of 3D-printed temporaries [80–83]. Consensus exists in the inferior properties of the 3D-printed restorations in terms of color stability, water sorption, and solubility compared to milled resin-based materials [11,80,84–86]. Such degradation not only reduces the mechanical performance of the restoration but also raises concerns regarding microbial colonization and secondary caries. Limitations in curing depth, particularly in larger structures (e.g., pontics), leave residual monomers that affect performance and biocompatibility. These unreacted compounds may elute in vivo, potentially provoking biological responses. Water sorption is influenced by resin composition, printing orientation, and the number of layers [87,88].

Only few studies have investigated the biological properties of permanent 3D-printing materials. The higher water sorption and solubility promote hydrolytic degradation of the polymer network. In combination with residual monomers from incomplete polymerization, the eluted organic pigments, these components are associated with cytotoxic effects and elevated expression of proinflammatory mediators in surrounding tissues, raising concerns about long-term biocompatibility [14,79]. While in vitro studies have reported no significant differences in cytotoxicity among various 3D-printed materials [14], biocompatibility appears to be highly dependent on post-processing protocols. Procedures such as alcohol washing, thorough polishing, and extended post-curing significantly reduce residual monomer content and improve cellular responses. Resin eluates affect the cell viability and inflammatory responses on human gingival fibroblasts. The post-processing procedures have the potential to enhance the biocompatibility of 3D-printed materials [79].

Moreover, surface roughness, which is influenced by the manufacturing method and material composition, affects bacterial adhesion, which may contribute to plaque accumulation and secondary caries risk [89]. Notably, cytotoxic effects are most prominent shortly after placement and tend to diminish over time. Subtractive materials generally exhibit lower cytotoxicity, likely due to their higher degree of conversion achieved through industrial polymerization under elevated temperature and pressure. Additionally, the type and concentration of photoinitiators may influence cellular toxicity. Therefore, it can be concluded that biocompatibility is closely linked to post-processing protocols. Strategies such as extended post-curing, additional cleaning, and pre-soaking restorations prior to placement may mitigate these effects and enhance the biocompatibility of 3D-printed restorations [79].

For permanent materials, factors such as fixation and repair become particularly important. However, similar to direct composites, printed materials have favorable conditions for these applications, as their conversion rate is not as high as that of CAD/CAM-milled composites.

To evaluate the bond strength, various treatments such as post-washing in alcohol, airborne-particle abrasion, bur cutting, etching, different primers, and different luting cements have been assessed [90–102]. Others revealed that bond strength does not depend on the conditioning or type of luting cement [90,91]. Airborne-particle abrasion and silanization yielded high bond strength values, whereas etching resulted in lower bond strength values [92]. 3D-printed materials can be repaired satisfactorily by applying a primer and bond [103]. Bonding to dentin [96,102,104], PEEK [105], titanium [104,105], and direct composite resin [95] has been investigated. Most studies investigated the shear bond strength [92,94–100,104–107]. Some studies reported predominantly adhesive failure, while others reported primarily cohesive failure or mixed failure modes [95,96,98,101,102,104,105,107].

The advantage of 3D-printed materials compared to milled materials is the decreased material waste and instrument usage for cutting, decreased costs for purchasing a printer rather than a milling machine, and the prefabricated blocks. Time and cost efficiency when printing restorations can be achieved if several restorations are printed at the same time. In contrast to milling, the printing time does not increase. As post-processing currently takes rather long, this will decrease the cost advantage of printing instead of milling single-tooth restorations. Hence, permanently printed materials are today primarily suitable for larger (full-arch) restorations. Notably, in these cases, often involving the aesthetic zone, the limited color stability will be of importance. The limitations described herein highlight the necessity for substantial advancements in the fields of resin chemistry and printing processes. Such advancements are imperative in order to meet the high demands of clinical dental applications and to ensure the functional longevity of 3D-printed restorations. 3D-printed materials for permanent use have improved mechanical properties that might allow a long-term application. However, the term "permanent use" needs to be more clearly defined and the expected lifetime of 3D-printed materials for permanent use needs to be outlined for a more precise indication.

6. Conclusions

The increasing regulatory approval of printing materials and processes for permanent restorations underscores improvements in both material properties and printing processes. However, there is still great heterogeneity in materials. The biggest challenges are the filler content, color stability, water sorption, solubility, and anisotropy. Clinicians need clear instructions from manufacturers on pre-printing, printing, and post-printing factors as well as oral usage, comparable to recommendations that already exist for subtractively manufactured materials. At present, 3D-printing is characterised by a high number of individual manual steps. A higher degree of automation is essential if 3D-printing is to become a mainstream technology. Then the low cost and higher efficiency of 3D-printing make it a viable alternative with high potential to milling dental restorations.

CRediT authorship contribution statement

Andreas Keßler: Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **Lukas Montenbruck:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Falk Schwendicke:** Writing – review & editing, Conceptualization. **Jörg Lüchtenborg:** Writing – review & editing, Writing – original draft, Methodology. **Dalia Kaisarly:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] J.W. Stansbury, M.J. Idacavage, 3D printing with polymers: challenges among expanding options and opportunities, Dent. Mater. 32 (1) (2016) 54–64.
[2] ISO17296-2:, *Additive manufacturing—General Principles—Part 2: Overview of Process Categories and Feedstock*, International Organization for Standardization Geneva, Switzerland, 2015.
[3] V.G. Rocha, et al., Direct ink writing advances in multi-material structures for a sustainable future, J. Mater. Chem. A 8 (31) (2020) 15646–15657.
[4] P.C. Tseng, et al., Direct ink writing with dental composites: a paradigm shift toward sustainable chair-side production, Dent. Mater. (2024).
[5] J. Mayer, et al., Temporary 3D printed fixed dental prosthesis materials: impact of post printing cleaning methods on degree of conversion as well as surface and mechanical properties, Int J Prosthodont 34 (6) (2021) 784–795.
[6] W. Jang, et al., Effect of washing condition on the fracture strength, and the degree of conversion of 3D printing resin, Appl. Sci. 11 (24) (2021) 11676.
[7] M.D. Scherer, et al., Influence of postprocessing rinsing solutions and duration on flexural strength of aged and nonaged additively manufactured interim dental material, J. Prosthet. Dent 131 (5) (2024) 959–968.
[8] D. Kim, et al., Effects of post-curing time on the mechanical and color properties of three-dimensional printed crown and bridge materials, Polymers (Basel) 12 (11) (2020).
[9] E. Bayarsaikhan, et al., Effects of postcuring temperature on the mechanical properties and biocompatibility of three-dimensional printed dental resin material, Polymers (Basel) 13 (8) (2021).
[10] M. Monzon, et al., Anisotropy of photopolymer parts made by digital light processing, Materials (Basel) 10 (1) (2017).
[11] S. Aati, et al., Effect of post-curing light exposure time on the physico-mechanical properties and cytotoxicity of 3D-printed denture base material, Dent. Mater. 38 (1) (2022) 57–67.
[12] D. Balestra, et al., 3D printed materials for permanent restorations in indirect restorative and prosthetic dentistry: a critical review of the literature, Materials (Basel) 17 (6) (2024) 1380.
[13] A. KeßLer, R. Hickel, N. Ilie, In vitro investigation of the influence of printing direction on the flexural strength, flexural modulus and fractographic analysis of 3D-printed temporary materials, Dent. Mater. J. 40 (3) (2021) 641–649.
[14] P.J. Atria, et al., 3D-printed resins for provisional dental restorations: comparison of mechanical and biological properties, J. Esthetic Restor. Dent. 34 (5) (2022) 804–815.
[15] A. Kessler, et al., Three-body wear of 3D printed temporary materials, Dent. Mater. 35 (12) (2019) 1805–1812.
[16] R.S. Saini, et al., The flexural strength of 3D-printed provisional restorations fabricated with different resins: a systematic review and meta-analysis, BMC Oral Health 24 (1) (2024) 66.
[17] J. Mayer, et al., Influence of cleaning methods after 3D printing on two-body wear and fracture load of resin-based temporary crown and bridge material, Clin. Oral Invest. 25 (10) (2021) 5987–5996.
[18] G. Myagmar, et al., Wear of 3D printed and CAD/CAM milled interim resin materials after chewing simulation, J. Adv. Prosthodont. 13 (3) (2021) 144–151.
[19] K.M. Suralik, et al., Effect of fabrication method on fracture strength of provisional implant-supported fixed dental prostheses, Prosthesis 2 (4) (2020) 325–332.
[20] M. Reymus, et al., Fracture load of 3D-printed fixed dental prostheses compared with milled and conventionally fabricated ones: the impact of resin material, build direction, post-curing, and artificial aging-an in vitro study, Clin. Oral Invest. 24 (2) (2020) 701–710.
[21] S. Mudhaffer, et al., Effects of print orientation and artificial aging on the flexural strength and flexural modulus of 3D printed restorative resin materials, J. Prosthet. Dent (2024).
[22] P.V. Bora, et al., Characterization of materials used for 3D printing dental crowns and hybrid prostheses, J. Esthetic Restor. Dent. 36 (1) (2024) 220–230.
[23] E. Prause, et al., Mechanical properties of 3D-printed and milled composite resins for definitive restorations: an in vitro comparison of initial strength and fatigue behavior, J. Esthetic Restor. Dent. 36 (2) (2024) 391–401.
[24] G. Taormina, et al., 3D printing processes for photocurable polymeric materials: technologies, materials, and future trends, J. Appl. Biomater. Funct. Mater. 16 (3) (2018) 151–160.
[25] F.A. de Souza, et al., 3D-printed and conventional provisional single crown fabrication on anterior implants: a randomized clinical trial, Dent. Mater. 40 (2) (2024) 340–347.
[26] M. Mandurino, et al., Mechanical properties of 3D printed vs. subtractively manufactured composite resins for permanent restorations: a systematic review, Materials (Basel) 18 (5) (2025) 985.
[27] N.S. ElMalah, et al., Effect of nanomodified 3D printed photopolymerizable resin on flexural strength, color, and antimicrobial efficacy: an in vitro study, J. Prosthet. Dent 132 (1) (2024) 268.e1–268.e8.
[28] M. Demirel, A.A. Diken Türksayar, M.B. Donmez, Fabrication trueness and internal fit of hybrid abutment crowns fabricated by using additively and subtractively manufactured resins, J. Dent. 136 (2023) 104621.
[29] N. Güntekin, A.R. Tunçdemir, Comparison of volumetric loss and surface roughness of composite dental restorations obtained by additive and subtractive manufacturing methods, Heliyon 10 (4) (2024) e26269.
[30] A.A. Diken Türksayar, et al., Comparison of wear and fracture resistance of additively and subtractively manufactured screw-retained, implant-supported crowns, J. Prosthet. Dent 132 (1) (2024) 154–164.
[31] Z. Sahin, et al., Mechanical characteristics of composite resins produced by additive and subtractive manufacturing, Eur. J. Prosthodont. Restor. Dent. 31 (3) (2023) 278–285.
[32] E. Prause, et al., Survival and complications of 3D-printed, noninvasive restorations for prosthetic rehabilitations: a 12-month preliminary observational study, Int. J. Comput. Dent. 27 (4) (2024) 379–388.
[33] K.E. Lee, et al., Comparison of three-dimensional printed resin crowns and preformed stainless steel crowns for primary molar restorations: a randomized controlled trial, J. Clin. Pediatr. Dent 48 (3) (2024) 59–67.
[34] P. Hobbi, et al., 3D-printed resin composite posterior fixed dental prosthesis: a prospective clinical trial up to 1 year, Front. Dent. Med. 5 (2024) 1390600.
[35] P. Hobbi, et al., Clinical performance of 3D printed resin composite posterior fixed dental prosthesis: a permanent solution? Eur. J. Prosthodont. Restor. Dent. 33 (1) (2025) 1–10.
[36] M. Doumit, et al., Wear behavior of 3D printed, minimally invasive restorations: clinical data after 24 months in function, J. Prosthet. Dent (2025).
[37] J.S. Shim, et al., Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations, J. Prosthet. Dent 124 (4) (2020) 468–475.
[38] P. Derban, et al., Influence of the printing angle and load direction on flexure strength in 3D printed materials for provisional dental restorations, Materials (Basel) 14 (12) (2021).
[39] S. Mudhaffer, et al., Effects of printing orientation and artificial ageing on martens hardness and indentation modulus of 3D printed restorative resin materials, Dent. Mater. 40 (7) (2024) 1003–1014.
[40] P.S. Borella, et al., Physical and mechanical properties of four 3D-printed resins at two different thick layers: an in vitro comparative study, Dent. Mater. 39 (8) (2023) 686.
[41] C. Abad-Coronel, et al., Flexural strength, fatigue behavior, and microhardness of three-dimensional (3D)-Printed resin material for indirect restorations: a systematic review, Materials (Basel) 18 (3) (2025) 556.

[42] G.J. Pot, et al., Mechanical properties of additive-manufactured composite-based resins for permanent indirect restorations: a scoping review, Materials (Basel) 17 (16) (2024) 3951.
[43] N. Alharbi, R. Osman, D. Wismeijer, Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations, J. Prosthet. Dent 115 (6) (2016) 760–767.
[44] A. Kessler, R. Hickel, N. Ilie, In vitro investigation of the influence of printing direction on the flexural strength, flexural modulus and fractographic analysis of 3D-printed temporary materials, Dent. Mater. J (2021).
[45] M. Reymus, N. Lumkemann, B. Stawarczyk, 3D-printed material for temporary restorations: impact of print layer thickness and post-curing method on degree of conversion, Int. J. Comput. Dent. 22 (3) (2019) 231–237.
[46] D. Kim, et al., Effects of post-curing time on the mechanical and color properties of three-dimensional printed crown and bridge materials, Polymers (Basel) 12 (11) (2020) 2762.
[47] A.A. Alshamrani, R. Raju, A. Ellakwa, Effect of printing layer thickness and postprinting conditions on the flexural strength and hardness of a 3D-Printed resin, BioMed Res. Int. 2022 (2022) 8353137.
[48] E. Bayarsaikhan, et al., Influence of different postcuring parameters on mechanical properties and biocompatibility of 3D printed crown and bridge resin for temporary restorations, J. Mech. Behav. Biomed. Mater. 128 (2022) 105127.
[49] N. Alharbi, R. Osman, D. Wismeijer, Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations, J. Prosthet. Dent 115 (6) (2016) 760–767.
[50] A. Kessler, R. Hickel, N. Ilie, In vitro investigation of the influence of printing direction on the flexural strength, flexural modulus and fractographic analysis of 3D-printed temporary materials, Dent. Mater. J. 40 (3) (2021) 641–649.
[51] J.R.C.D.S. Siqueira, et al., Characterization of microstructure, optical properties, and mechanical behavior of a temporary 3D printing resin: impact of post-curing time, Materials (Basel) 17 (7) (2024).
[52] P. Derban, et al., Influence of the printing angle and load direction on flexure strength in 3D printed materials for provisional dental restorations, Materials (Basel) 14 (12) (2021) 3376.
[53] M.A. Alghauli, et al., Properties and behavior of additively manufactured provisional fixed dental prostheses: a systematic review on 3D printing orientations relative to applied materials and postprocessing, J. Esthetic Restor. Dent. (2025). **Online ahead of print**.
[54] M.M. Gad, S.M. Fouda, Factors affecting flexural strength of 3D-printed resins: a systematic review, J. Prosthodont. 32 (S1) (2023) 96–110.
[55] N. Krajangta, et al., Color alteration of CAD/CAM 3D-printed, milled resin-ceramic hybrid material compared to enamel, Dent. Mater. J. 43 (3) (2024) 386–393.
[56] S. Karaoğlanoğlu, et al., Comparison of the surface properties of 3D-printed permanent restorative resins and resin-based CAD/CAM blocks, Operat. Dent. 48 (5) (2023) 588–598.
[57] G. Çakmak, et al., Influence of polishing technique and coffee thermal cycling on the surface roughness and color stability of additively and subtractively manufactured resins used for definitive restorations, J. Prosthodont. 33 (5) (2024) 467–474.
[58] S. Taşın, A. Ismatullaev, Effect of coffee thermocycling on the color and translucency of milled and 3D printed definitive restoration materials, J. Prosthet. Dent 131 (5) (2024) 969.e1–969.e7.
[59] C. Espinar, et al., The influence of printing angle on color and translucency of 3D printed resins for dental restorations, Dent. Mater. 39 (4) (2023) 410–417.
[60] S. Tasin, A. Ismatullaev, Effect of coffee thermocycling on the color and translucency of milled and 3D printed definitive restoration materials, J. Prosthet. Dent 131 (5) (2024) 969.e1–969.e7.
[61] G. Cakmak, et al., Surface roughness, optical properties, and microhardness of additively and subtractively manufactured CAD-CAM materials after brushing and coffee thermal cycling, J. Prosthodont. 34 (1) (2025) 68–77.
[62] N. Intralawan, et al., Surface discoloration of 3D printed resin-ceramic hybrid materials against various stain beverages, J. Int. Dent. Med. Res. 15 (4) (2022) 1465–1471.
[63] A. Vichi, et al., Translucency of CAD/CAM and 3D printable composite materials for permanent dental restorations, Polymers (Basel) 15 (6) (2023) 1443.
[64] M. Lask, et al., Impact of glazing, coating, and polishing on the color stability and surface properties of a 3D printed resin and two veneering composite resins, J. Esthetic Restor. Dent. (2025). **Online ahead of print**.
[65] G. Cakmak, et al., Influence of polishing technique and coffee thermal cycling on the surface roughness and color stability of additively and subtractively manufactured resins used for definitive restorations, J. Prosthodont. 33 (5) (2024) 467–474.
[66] C. Espinar, et al., Optical behavior of 3D-printed dental restorative resins: influence of thickness and printing angle, Dent. Mater. 39 (10) (2023) 894–902.
[67] C. Espinar, et al., The influence of printing angle on color and translucency of 3D printed resins for dental restorations, Dent. Mater. 39 (4) (2023) 410–417.
[68] K.L. Van Landuyt, et al., Systematic review of the chemical composition of contemporary dental adhesives, Biomaterials 28 (26) (2007) 3757–3785.
[69] M. Rasenberg, Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide as a substance of very high concern beacuse of its toxic for reproduction (article 57C) properties, in: D(2023)3788-DC, European Chemicals Agency, Helsinki, 2023.
[70] G.T. Kim, et al., Cytotoxicity, colour stability and dimensional accuracy of 3D printing resin with three different photoinitiators, Polymers (Basel) 14 (5) (2022) 979.
[71] G. Paolone, et al., Color stability of polymer-based composite CAD/CAM blocks: a systematic review, Polymers (Basel) 15 (2) (2023).
[72] E. Sonkaya, G. Zeliha Bek Kurklu, Additively manufactured definitive crown resins on premolar and molar teeth: 2-year results of a prospective clinical study, Int J Prosthodont 38 (3) (2025) 279–289.
[73] D. Sarac, et al., The effect of polishing techniques on the surface roughness and color change of composite resins, J. Prosthet. Dent 96 (1) (2006) 33–40.
[74] N. Hersek, et al., Color stability of denture base acrylic resins in three food colorants, J. Prosthet. Dent 81 (4) (1999) 375–379.
[75] G. Iazzetti, et al., Color stability of fluoride-containing restorative materials, Operat. Dent. 25 (6) (2000) 520–525.
[76] S. Jain, 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 (Basel) 14 (13) (2022).
[77] M. Folwaczny, et al., Cytotoxicity of 3D printed resin materials for temporary restorations on human periodontal ligament (PDL-hTERT) cells, Dent. Mater. 39 (5) (2023) 529–537.
[78] I. Frasheri, et al., Effects of resin materials dedicated for additive manufacturing of temporary dental restorations on human gingival keratinocytes, J. Esthetic Restor. Dent. 34 (7) (2022) 1105–1112.
[79] S.N. Wuersching, et al., Initial biocompatibility of novel resins for 3D printed fixed dental prostheses, Dent. Mater. 38 (10) (2022) 1587–1597.
[80] Q. Yao, et al., The effect of surface treatments on the color stability of CAD-CAM interim fixed dental prostheses, J. Prosthet. Dent 126 (2) (2021) 248–253.
[81] S. Tasin, A. Ismatullaev, A. Usumez, Comparison of surface roughness and color stainability of 3-dimensionally printed interim prosthodontic material with conventionally fabricated and CAD-CAM milled materials, J. Prosthet. Dent 128 (5) (2022) 1094–1101.
[82] T. Temizci, T. Kölüş, T. Servi, Comparison of color stability and surface roughness of 3D printed and conventionally produced temporary materials, J. Stomatol. 76 (3) (2023) 161–166.
[83] S. Jain, 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 (Basel) 14 (13) (2022) 2691.
[84] S.Y. Song, et al., Color stability of provisional restorative materials with different fabrication methods, J. Adv. Prosthodont. 12 (5) (2020) 259–264.
[85] J. Shin, et al., Evaluation of the color stability of 3D-printed crown and bridge materials against various sources of discoloration: an in vitro study, Materials (Basel) 13 (2020) 5359, 2020.
[86] A. Daghrery, Color stability, gloss retention, and surface roughness of 3D-Printed versus indirect prefabricated veneers, J. Funct. Biomater. 14 (10) (2023).
[87] C. Berli, et al., Comparing the mechanical properties of pressed, milled, and 3D-printed resins for occlusal devices, J. Prosthet. Dent 124 (6) (2020) 780–786.
[88] L. Perea-Lowery, et al., 3D-Printed vs. heat-polymerizing and autopolymerizing denture base acrylic resins, Materials (Basel) 14 (19) (2021).
[89] N.E. Ozer, et al., Bacterial adhesion to composite resins produced by additive and subtractive manufacturing, Odontology 112 (2) (2024) 460–471.
[90] M.B. Donmez, et al., Bond strength of additively manufactured composite resins to dentin and titanium when bonded with dual-polymerizing resin cements, J. Prosthet. Dent (2023).
[91] Y.J. Kang, et al., Effect of adhesion conditions on the shear bond strength of 3D printing resins after thermocycling used for definitive prosthesis, Polymers (Basel) 15 (6) (2023).
[92] Z. Mao, et al., Effect of surface treatment strategies on bond strength of additively and subtractively manufactured hybrid materials for permanent crowns, Clin. Oral Invest. 28 (7) (2024) 371.
[93] T. Graf, et al., Influence of pre-treatment and artificial aging on the retention of 3D-Printed permanent composite crowns, Biomedicines 10 (9) (2022).
[94] Z. Kagaoan, et al., Prolonged post-washing in ethanol decreases bond strength of additively manufactured crown materials, J. Dent. 144 (2024) 104873.
[95] E. Kariper, A. Cilingir, Bond strength of different resin-based cements to 3D-printed permanent restorations, Am. J. Dent. 38 (1) (2025) 39–45.
[96] N. Aydin, H.N. Uguz, Shear bond strength of permanent 3D-printed resin and milled zirconia to primary teeth using different luting agents, Am. J. Dent. 36 (5) (2023) 239–245.
[97] M. Kim, et al., Evaluation of shear bond strengths of 3D printed materials for permanent restorations with different surface treatments, Polymers (Basel) 16 (13) (2024) 1838.
[98] B. Ersoz, et al., Effect of surface treatments applied to 3D printed permanent resins on shear bond strength, J. Clin. Exp. Dent. 16 (9) (2024) e1059–e1066.
[99] L.E.B. Tanaka, et al., Characterization of 3D printed composite for final dental restorations, Clin. Oral Invest. 28 (11) (2024) 617.
[100] M. Dederichs, et al., Effect of surface conditioning on the adhesive bond strength of 3D-printed resins used in permanent fixed dental prostheses, J. Dent. 155 (2025) 105621.
[101] E.O. Sutuven, N.C. Yildirim, Bond strength of self-adhesive resin cement to definitive resin crown materials manufactured by additive and subtractive methods, Dent. Mater. J. 44 (1) (2025) 41–51.
[102] L. Montenbruck, et al., Influence of pretreatment strategies on the tensile bond strength of 3D printed composite resins for definitive cementation to dentin, J. Prosthet. Dent (2025).
[103] E. Sonkaya, G.B. Kürklü, The effect of different surface treatments on the repair of 3D permanent resin restorations by composite resin different surface treatments and repair of 3D permanent resin, Res. Square (2022).

[104] M.B. Donmez, et al., Bond strength of additively manufactured composite resins to dentin and titanium when bonded with dual-polymerizing resin cements, J. Prosthet. Dent 132 (5) (2023) 1067.e1–1067.e8.
[105] A.S. Kucukekenci, et al., Bond strength of recently introduced computer-aided design and computer-aided manufacturing resin-based crown materials to polyetheretherketone and titanium, J. Prosthet. Dent 132 (5) (2024) 1066.e1–1066.e8.
[106] Y.J. Kang, et al., Effect of adhesion conditions on the shear bond strength of 3D printing resins after thermocycling used for definitive prosthesis, Polymers (Basel) 15 (6) (2023) 1390.
[107] N. Aydin, et al., A comparison of the shear bond strength between a luting composite resin and both machinable and printable ceramic-glass polymer materials, Materials (Basel) 17 (19) (2024) 4697.