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Comparative Evaluation of 3D-Printed Resins for Single-Tooth Dental Crowns - Provisional and Permanent: A Scoping Review

Keywords

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ABSTRACT

Objective: Collect and synthesize data on 3D-printed resins used for single-tooth dental crowns. Methods: A comprehensive search was conducted across MEDLINE/PubMed, Web of Science, and Scopus databases, covering publications from January 2013 to 18th August 2024. Relevant gray literature was also considered. From a total of 2803 records initially identified, 103 studies met the inclusion criteria and were included in the review. Results: Data were extracted for 47 different 3D-printed resin materials, including information on product names, manufacturers, and chemical compositions. Mechanical properties: flexural strength (124 MPa), load to failure (1397 N), flexural modulus (2818 MPa), and Vickers microhardness (20.94 kgf/ mm^2). Degree of conversion (27-95.2%); Wear loss (vertical loss: 62-257 μm; volumetric loss: 0.08-20 mm^3); Surface roughness (Ra: 2.16 μm); Internal fit (137.26 μm), marginal fit (86.49 μm); Bond strength (16.97-24.75 MPa). Cellular response and bacterial adhesion showed variability in biocompatibility, influenced by post-processing protocols. Conclusions: 3D-printed resins dental crowns demonstrate promising in vitro mechanical performance, including fracture resistance values that withstand typical masticatory forces. Studies report generally favorable bond strength, and acceptable internal and marginal adaptation. However, these materials tend to exhibit lower flexural strength, elastic modulus, and hardness when compared to milled resin counterparts.

INTRODUCTION

Provisionals and final crowns, as well as fixed dental prostheses (FDPs), are essential components in dental restorations, serving both natural teeth and implants. These prostheses play a crucial role in restoring the biomechanics of the masticatory function while also significantly enhancing dental and facial esthetics[1]. The development of dental prostheses manufacturing has closely paralleled advancements in computer-aided design and computer-aided manufacturing (CAD-CAM) technology, driving continuous improvements in both materials and fabrication processes. One of the most significant advancements has been the shift toward producing FDPs through subtractive manufacturing techniques, primarily using milling technologies. This method involves precision cutting of prefabricated blocks to create dental prostheses that not only meet, but often exceed the accuracy, cost efficiency, and production speed of traditional prostheses[2].

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While subtractive manufacturing through milling has set high standards in the production of FDPs[3-5], more recently there has been the emergence of three-dimensional (3D) printing as a promising alternative. This technique offers unique advantages in customization and efficiency, making it an increasingly attractive option for the fabrication of dental prostheses. 3D printing, acknowledged for its potential in both the dental industry and clinical practice, represents a shift from traditional methods. Unlike subtractive manufacturing, 3D printing is an additive manufacturing (AM) process in which objects are produced layer by layer based on 3D virtual models[6].

Among the various AM technologies, Vat Photopolymerization (VPP) has become the most prevalent in dental applications, used technology, for fabricating models, aligners, surgical guides, splints, removable dentures, and FDPs. VPP primarily employs materials such as epoxy resins and methacrylates, which are well-suited to meeting the high demands for accuracy, strength, and biocompatibility in dental applications[7]. VPP technologies are further classified based on the type of light source used, including stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD)-based printers[8]. Among these, SLA and DLP are the most commonly used for producing 3D-printed resin-based specimens[9]. The primary difference between DLP, SLA and LCD 3D printing technologies lies in their light-curing mechanism, which translate into practical implications for dental crown fabrication[10,11]. SLA uses a focused laser to cure resin point by point, offering high precision but slower print times. DLP utilizes a digital projector to cure entire layers simultaneously, resulting in faster production with consistent resolution, which is advantageous in clinical settings requiring higher throughput. LCD technology cures layers using a masked light source displayed on a screen; while generally more cost-effective, it may be associated with lower durability and consistency over time. These differences impact key clinical considerations such as print speed, accuracy, surface quality, and cost-efficiency, guiding material and equipment selection based on the intended use of the crown—whether provisional or permanent.

3D printing can offer multiple advantages in the production of FDPs, including increased productivity, easy customization of dental products, cost-effectiveness, the ability to manufacture complex geometries in a single fabrication step, and minimal material waste[11,12]. However, the process also has more stringent manufacturing requirements compared to milling. These include the selection of resin type and printer technology, the necessity for appropriate building supports during printing, precise control of printing angulation, the use of specialized washing solutions, and the need for specific curing equipment to ensure proper polymerization. Furthermore, achieving optimal results requires managing of curing time and temperature, which are critical factors in ensuring the durability and biocompatibility of the final product[13-19].

3D printing technology, particularly in Dentistry, is revolutionizing manufacturing processes, significantly enhancing the precision and efficiency of fabricating dental restorations and devices, leading to a potential improved clinical outcome and higher patient satisfaction. This seamless integration of 3D printing into dental practices marks a pivotal shift toward more innovative, rapid and potentially chair-side solutions.

However, despite the promising advancements and the increasing number of resin-based materials introduced to the dental market, there remains a notable lack of consistency and transparency in the scientific literature concerning their biomechanical and biological properties, particularly for their use in FDPs. While manufacturers often provide technical specifications, these data are not always independently verified or peer-reviewed, and the level of detail can vary considerably. As a result, dental professionals and researchers face challenges in critically assessing the reliability, safety, and clinical applicability of these materials.

Given the accelerated integration of 3D printing into dental practice, there is a pressing need for systematically collected, peer-reviewed evidence that consolidates current knowledge and identifies areas requiring further investigation. A scoping review is especially suitable for this purpose, as it enables a broad, exploratory analysis of the literature, mapping existing evidence without the restrictive criteria of a systematic review.

In response to this need, the present review aims to methodically identify and assess the current evidence on 3D-printed resin materials used for the fabrication of single-tooth dental crowns, including both provisional and final restorations. Specifically, it seeks to catalog the resins currently in use, their chemical composition, mechanical properties, dimensional accuracy, surface characteristics, adhesion performance and biological behavior.

MATERIALS AND METHODS

This scoping review was designed using a five-stage framework, following Arskey and O'Malleys' methodological design, and the recommendations provided by Levae, Colquhoun and O'Brien[20].

STAGE I: IDENTIFICATION OF THE RESEARCH QUESTION

The primary research question guiding this review was: "What are the key features of 3D-printed resins used for the fabrication of single-tooth dental crowns?". To ensure a well-defined and researchable question, the PICO (Population, Interventions, Comparisons, and Outcomes) framework was employed, as presented in Table 1.

The review protocol was developed to provide an overview of the studies addressing this question. Secondary research questions (SRQ) included:

SRQ1: What are the types and compositions of 3D-printed resins described in the literature?

SRQ2: What are the mechanical, surface, accuracy and biological properties of these 3D-printed resins?

SRQ3: What protocol considerations are detailed in the literature for the fabrication of a 3D-printed FDP? (e.g., layer thickness, building direction, washing protocol)

SRQ4: Are there clinical studies that evaluate these novel materials?

Table 1. Research question with PICO framework.

Component	Description
Population	3D-printed resins for the fabrication of single dental crowns
Intervention	The use of provisional and permanent 3D-printed resins to fabricate single tooth dental crowns
Comparison	Milling resin-based materials used for the fabrication of single tooth dental crowns
Outcome	Resins (name, manufacturer, composition and type of restoration); Mechanical properties (flexural strength, fracture resistance, flexural modulus, hardness); Chemical properties (degree of conversion); Surface characteristics (wear loss and roughness), Level of accuracy (internal and marginal fit), Adhesion (bond strength); Biological properties (Cytotoxicity and cytocompatibility).

STAGE II: IDENTIFICATION OF RELEVANT STUDIES

Given the variation in terminology across dental materials and the limited MeSH indexing for emerging topics like 3D printing, a keyword-based search strategy was deemed more effective for capturing relevant literature across databases. Comprehensive searches were conducted across three databases: Pubmed, Scopus, and Web of Science. The following search strategy was used to ensure a comprehensive retrieval of relevant studies:

Table 2. Search terms and strategy for the electronic databases.

	Pubmed	Scopus	Web of Science
• **3D AND printing AND crown;** • **“additive manufacturing” AND crown** • **“additive manufacturing” AND restoration** • **“additive manufacturing” AND resin-ceramic** • **(additive manufacturing) AND (ceramic-reinforced polymers)** • **“additive manufacturing” AND partial AND fixed AND denture**	1,129	307	1,367

STAGE III: STUDY SELECTION

In order to be included in this review, studies had to meet specific inclusion criteria: articles published between January 2013 and 18th August 2024, written in English, French, Portuguese or Spanish, and related to the use of 3D-printed resins for single-tooth dental crowns. Exclusion criteria included studies focusing on non-single-unit restorations (e.g., dental bridges or full-arches), partial coverage single-tooth indirect restorations (e.g., inlays, onlays, and/or overlays), other 3D-printed materials (e.g., zirconia, ceramics, or metals), or non-relevant 3D printing applications (e.g., casts, removable dentures bases, surgical guides, aligners, or splints). Additionally, review articles, editorials, book chapters, conference proceedings, letters, and clinical case reports were excluded.

The initial selection process involved screening titles and abstracts for relevance, followed by a full-text review of the selected articles. Subsequently, a secondary search was performed by examining the references of the selected papers to identify additional relevant articles not found in the initial database searches.

STAGE IV: DATA CHARTING AND EXTRACTION

For qualitative and descriptive analysis, data extraction was performed for the included studies using standardized charts. These captured essential information such as the authors and year of publication, details about the resin used (including name, manufacturer, composition, and type of restoration), and a range of physical and mechanical properties (including flexural strength, fracture resistance, flexural modulus, wear loss, hardness; degree of polymerization), surface roughness, level of accuracy (internal fit/gap, marginal fit/gap), adhesion (bond strength) as well as biological properties (including Cell viability and cytotoxicity).

Disperse or non-numerical findings were analysed and presented in the discussion section. Excel spreadsheets were employed for systematic data organization and summary. In cases of ambiguity or missing information, corresponding authors of the articles of interest were contacted by email. If no response was received, the study was excluded from the review. Endnote software was used to build a reference library.

STAGE V. COLLECTING, SUMMARIZING, AND REPORTING RESULTS

A systematic search was conducted following the PRISMA-ScR guidelines. The initial electronic search yielded 2,803 records across MEDLINE/PubMed (n=1,129), Scopus (n=307), and Web of Science (n=1,367). After removing duplicates, 1,613 unique records remained. Following title/abstract screening, and exclusion of reports not retrieved, 120 articles were selected for full-text review, of which 75 met the inclusion criteria. An additional 28 articles were identified through reference list screening, resulting in a total of 103 articles included in the final review. Figure 1 shows a flowchart outlining the procedure for selecting studies in accordance with the PRISMA statement.

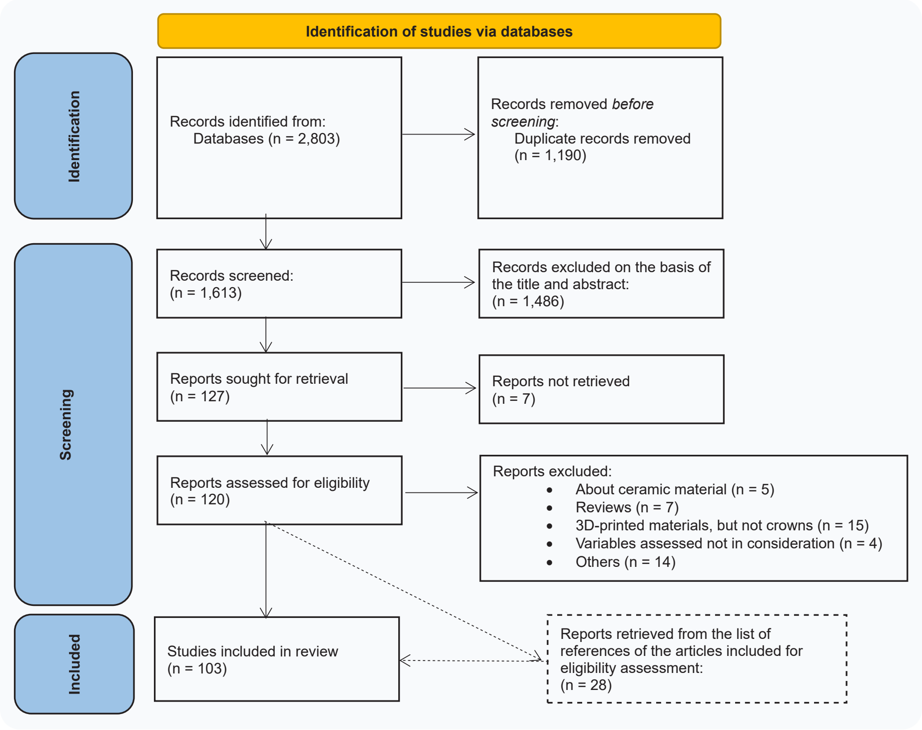

Figure 1: PRISMA flowchart detailing the study selection process.

It is important to note that few clinical investigations were found, with only two clinical trials included. Most of the published papers included in this review addressed either mechanical and/or biological tests performed *in vitro* and/or in laboratory conditions. As reported by the guidelines for scoping reviews by Tricco *et al.*[21], a key difference between scoping reviews and systematic reviews is that the former generally provides an overview of the existing evidence regardless of the methodological quality or risk of bias from the primary studies. Therefore, only the information about 3D-printed resins used for single-tooth dental crowns was collected, summarized and presented in the results section of this review.

RESULTS

RESIN NAME, PURPOSE AND COMPOSITION

This review identified a wide array of 3D-printed resins utilized for single-tooth dental crowns. Overall, 36 different resins were identified for use in provisional single-tooth dental crowns, ten resins were specified for long-term dental crowns, and one resin lacked a specified application. The most frequently cited and tested resin was NextDent C&B (provisional) by Nextdent. Table 3 provides an overview of the resins, including their commercial names, manufacturers, chemical compositions, and references to the studies that cited or tested these materials.

MECHANICAL PROPERTIES

Flexural Strength (FS)

Flexural strength reflects a material's ability to withstand deformation under bending forces, measuring the maximum stress experienced at the point of failure, and serving as a key indicator of its mechanical robustness. In dental applications, flexural testing is commonly used to simulate the complex loading conditions encountered intraorally, involving a combination of tensile, compressive, and shear forces. In the present review, all flexural strength data were derived from three-point bending test, as reported in the included studies. A total of 33 studies evaluated the flexural strength of 3D-printed bar-shaped specimens, typically using dimensions of 25 mm x 2 mm x 2 mm[16-19,31,37,39,41,44,48,49,53-57,60,64,70-72,74,77,79,80,82,87,91,96,102-104,109], while one study used a specimen with a reduced thickness of 1.5 mm[109]. From these studies, a total of 101 output values were extracted, exhibiting a mean value of 124.01 MPa, a standard deviation (SD) of 61.13 MPa, with a maximum of 303.81 MPa, a minimum of 19.5 MPa, and a median of 113.60 MPa (*Figure 2* – Appendix). When categorized by the type of restoration, 12 of the 101 FS values corresponded to specimens fabricated from permanent resins, which exhibited a higher mean FS of 142.08 MPa[37,102-104]. In comparison, the remaining 89 values, associated with provisional resin materials, showed a slightly lower mean value of 121.77 MPa.

Load to Failure (LF)

Load to failure, also referred to as fracture resistance, represents the maximum force a material can endure before fracturing – structure failure. It is particularly relevant for brittle

Table 3. Overview of the identified resins: chemical composition, information source, and citing articles.

Resin name and Manufacturer	Chemical composition	Information source	Citing articles
PROVISIONAL RESINS			
ZMD-1000B Temporary; Dentis (Daegu, Korea)	Urethane methacrylate oligomer, oxide, acrylate monomer, methacrylate monomer, phosphine oxide, cerium oxide, titanium oxide, acrylate photopolymer (*)	(22)	(18, 22-27)
Temporis DD-1000, DWS (Warsaw, Poland)	Mixture of multi-functional acrylic monomers, esters of acrylic acid (*)	(28)	(29-32)
Prusa White Tough; Prusa 3D (Czech Republic)	Epoxy resin, monomer, color pigments, photoinitiator, dyes (*)	(33)	(33)
Temp PRINT; GC Europe (Leuven, Belgium)	Urethane dimethacrylate (UDMA) 50<75%; Quartz 10<25%; 2,2'-ethylenedioxydiethyl dimethacrylate 10<25%; esterification products of 4,4'-isopropylidenediphenol, ethoxylated and 2-methylprop2-enoic acid., 2.5<5%; diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide <2.5%; 2-(2H-benzotriazol-2-yl)-p-cresol 0.1<0.2%	Manufacturer information	(33-37)
FreeprintTemp®; DETAX GmbH (Germany)	Isopropylidenediphenol peg dimethacrylate 10 <60 %; 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate 20-<40 %; 1,6-hexanediol dimethacrylate 0,1-<5 %; 2-hydroxyethyl methacrylate 0,1-<5 %; diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide 0,1-<5 %; Hydroxy propyl methacrylate 0,1-<5 %; phenyl bis(2,4,6-trimethylbenzoyl)-phosphine oxide 0,1-<5%	Manufacturer information	(22, 26, 36-45)
Temporary CB; FormLabs Inc. (Somerville, USA)	Esterification products of 4,4' - isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid >= 50<75%; diphenyl (2,4,6-trimethylbenzoyl)phosphine oxide <2.50%	(46)	(37, 47-49)
E-Dent 400 C&B; EnvisionTec (Germany)	Microfilled hybrid material, monomer based on acrylic esters (*)	Manufacturer Information	(14, 15, 50, 51)
3Delta Etemp; Deltamed GmbH (Germany)	Methacrylate (matrix), silicon dioxide (50wt%), dental glass (30vol%)	(38)	(36, 38, 44)
Mazic® D Temp; Vericom CO (Malaysia)	Monomers of methacrylic oligomers, crosslinked by phosphine oxide (*)	(52)	(52, 53)
NextDent C&B Micro Filled Hybrid (MFH) Bleach; NextDent B.V.(Soesterburg, Netherlands)	Mequinol; 4-methoxyphenol, hydroquinone monomethyl ether, silicon dioxide, titanium dioxide, 2-hydroxyethyl methacrylate, ethylene dimethacrylate, ethylene dimethacrylate, ethoxylated bisphenol A dimethacrylate, 7,7,9 (or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate, 7,7,9 (or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate. (methacrylic oligomer >60%; Glycol methacrylate 15-25% & posphine oxide <2.50)	(46, 52)	(9, 17, 18, 25, 36, 38, 39, 43, 44, 46, 51, 52, 54-77)
Cosmos Temp; YLLER (Pelotas, Brazil)	Methacrylate oligomers, diphenyl-2,4,6-trimethyl benzoyl phosphine oxide (TPO), titanium dioxide, carbon black (*)	(78)	(19, 78-82)
DIOnavi C&B; DIO Inc. (Busan, Korea)	Methacrylic oligomeres >90%, phosphine oxides <10%, pigment	(18)	(18)
Denture Teeth; FormLabs Inc. (Somerville, USA)	Methacrylate monomer, urethane dimethacrylate, propylidynetrimethyl trimethacrylate, diphenyl (2,46-trimethylbenzoyl) posphine oxide (*)	(56)	(16, 49, 56)
VeroGlaze MED620; Stratasys (USA)	Acrylic monomer <30%, 2-propenoic aacid, exo-1,7,7,-trimethylbicyclo[2.2.1]hept-2-yl ester <25%, acrylic oligomer <15%, ahoto-initiator <3%, titanium dioxide <0.8%, acrylic acid ester <0.3%, carbon black 0.1-1.0%, xylenes (o-, m-, p- isomers) 0.01-0.1, n-butyl acetate 0.01-0.1%, ethylbenzene 0.01-0.1%, propylene glycol monomethyl ether acetate 0.01-0.1%, phosphoric acid 0.00005-0.002%	(83)	(25, 43, 83)
VarseoSmile Temp; BEGO (Bremen, Germany)	Esterification products of 4,4'-isopropylidenediphenol, ethoxylated and 2-meethylprop-2-enoic acid >= 50<75%, diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide, <2.5%,	Manufacturer information	(34, 84-86)
P Pro Crown and Bridge, Straumann (Basel, Switzerland)	Methacrylic acid ester-based resin; 20-40% wt acrylic resin, 25%wt UDMA, <10%wt acrylic resin, <1%wt TMPTA	(34)	(34)
Stratasys; Stratasys Direct (USA)	Nylon 12 PA2201 (PA2201; Stratasys Direct; manufacturing) SLS resin (*)	(87)	(87)
TFD-23-5; Graphy (Seoul, Korea)	α,α'-[(1-methylethylidene)di-4,1-phenylene]bis[ω-[(2-methyl-1-oxo-2-propenyl)oxy]poly(oxy-1,2-ethanediyl) 0-20%, 1,4-butanediol polymer with α-hydro-ω-hydroxypoly(oxy-1,4-butanediyl) and 1,1'-methylendbis[4-isocyanatobenzene] 20-60%, 2-hydroxyethyl methacrylate 30-80%, phenylbis(2,4,6- trimethylbenzoyl)phosphine oxide 0-10%, titanium dioxide 0-1%, pigment 0-1%	(88)	(88)
Dima Print Denture Teeth; Kulzer (Tokyo)	Methyl methacrylate (MMA) (*)	(22)	(22)
DT-1 Temporary Teeth; Hephzibah (South Korea)	Urethane acrylate, silicon oxides, pigments (*)	(22)	(22)
DENTCA Crown & Bridge (Torrance, CA, USA)	Methacrylate monomer 40-60%, diurethane dimethacrylate 30-50%, trimethylolpropane trimethacrylate 3-10%, initiator proprietary <3, stabilizer proprietary <1, pigment <0.7	(50)	(50)
DentaTooth; Asiga (Alexandria, Australia)	7,7,9(or 7,9,9)-trimethyl-4,13-dioxo3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate 10-25%, Tetrahydrofurfuryl methacrylate 10-20%, Diphenyl(2,4,6-trimethylbenzoyl) phosphine oxid <1%	Manufacturer information	(89)
Resilab 3D Temp; Wilcos (Petrópolis, Brazil)	Not found	-	(19, 54, 78, 90)
Nanolab 3D, Wilcos (Petrópolis, Brazil)	Nanohybrid resin	(54)	(54, 81, 82)
Everes Temporary; SISMA (Italy)	Aliphatic difunctional methacrylate <50%, 2,2'-ethylenedioxydiethyl dimeethacrylate <40%, aliphatic urethane acrylate <20%, prosphine oxide <2,5%	(91)	(91)
Smart Print Bio Temp; RLB (Petrópolis, Brazil)	Methacrylic ester monomers, stabilizer, fillers, pigments, photoinitiators, acelerators (*)	(78)	(19, 78)
Printodent Generative Resin GR-17.1 temporary; Pro3dure medical (Iserlohn, Germany)	,7,9(or 7,9,9)- trimethyl-4,13-dioxo3,14-dioxa-5,12- diazahexadecane-1,16- diyl bismethacrylate 20-50%, 3,6,9-trioxaundecamethylene dimethacrylate 10-25%, Silicon dioxide <50%, phenyl bis(2,4,6-trimethylbenzoyl)-phosphine oxide <2%	Manufacturer information	(92)
els-3D; Harz labs (Russia)	Urethane acrylate oligomer 50-70%, polyethyleneglycol dimethacrylate 30-50%, 2-hydroxyethyl methacrylate 1-5%, Diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide 1-3%	Manufacturer information	(93)
PriZma Bioprov; Markertech (Tatuí, Brazil)	Acrylic monomers (20-40%), acrylic oligomers (>50%), pigment (<2%) and photoinitiators (<1%).	Manufacturer information	(19, 81, 82, 90)
Enlighten AA temp; Enlighten Materials (Taiwan)	Aromatic methacrylic oligomers, aliphatic methacrylic oligomers, phosphine oxides (*)	(55)	(55)
SHERAprint-cb; SHERA Werkstoff (Germany)	Flowable, light-curing acrylic-based composite (matrix: methacrylate oligomers, phosphine oxide) (*)	(94)	(95)
E-dent 100; EnvisionTec (Germany)	Acrylic resin 20-40%, tethahydrofurfuryl methacrylate 10-30%, 7,7,9-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diaza-hexadecan-1,16-diol dimethacrylate 10-30%, diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide <1%, phosphine oxide <1%	Manufacturer information	(51, 96)
RAYDENT C&B; Ray (Seoul, Korea)	α,α`-[(1-methylethylidene)di-4,1- phenylene]bis[ω-[(2-methyl- 1- oxo-2-propenyl)oxy]poly(oxy- 1,2-ethanediyl) 20-35%, ,7,9(or 7,9,9)-trimethyl-4,13-di oxo-3,14-dioxa-5,12- diazahexadecane-1,16-diyl 2-methyl-2-pro penoate 20-28%, -methyl-2-propenoic acid 1,2- ethanediylbis(oxy-2,1- ethanediyl) ester 20-25%, phenylbis(2,4,6-trimethylbenzoyl)phosphine 1-10%, rutile(TiO2) 0.1-5%	Manufacturer information	(27)
V-print c&b temp; Voco (Germany)	Aliphatic urethane dimethacrylate, acrylate, triethylenglycoldimethacrylat, diphenyl(2,4,6-trimethyl-benzoyl) phosphine oxide (*)	(86)	(86)
DSI 3d Crown & Bridge; Dental Solutions (Israel)	Urethane methacrylate oligomer (50-70%), polyethyleneglycol dimethacrylate (30-50%), 2-hydroxyethyl methacrylate (1-5%), diphenyl (2, 4, 6-trimethylbenzoyl) phosphine oxide (1-3%)	Manufacturer information	130
PrintaX; Odontomega (Brazil)	Methacrylate and acrylate monomers, aromatic methacrylic oligomer, aliphatic methacrylic oligomer, phosphine oxide, pigments, stabilizers (*)	(90)	(90)
DEFINITIVE RESINS			
Saremco print CROWNTEC; NextDent B.V. (Soesterburg, Netherlands)	Esterification products of 4,4'-isopropylidiphenol, ethoxylated and 2-methyl-prop-2noic acid, silanized dental glass, pyrogenic silica, initiators. total content of inorganic fillers (particle size 0.7 µm) is 30-50 wt%	(97)	(13, 46, 76, 97-103)
Permanent Crown Resin; FormLabs Inc. (Somerville, USA)	Esterifcation products of 4,4'-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (50–75%), diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide <2.50%	(77)	(37, 77, 100, 102, 104-107)
Varseo Crown Plus; BEGO, (Bremen, Germany)	Esterification products of 4,4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl)phosphine oxide, 30–50wt%—inorganic fillers (particle size 0.7 µm) (*)	(97)	(25, 54, 75, 76, 86, 97, 99, 100, 103, 108-111)
FlexceraTM Smile Ultra+; EnvisionTEC GmbH (Germany)	Acrylates, methylacrylates, methacrylated oligomers and monomers, photoinitiators, colorants/dyes, fillers and absorbers (*)	Manufacturer information	(49)
TC-80DP; Graphy (South Korea)	α,α'-[(1-methylethylidene)di-4,1-phenylene]bis[ω-[(2-methyl-1-oxo-2-propenyl)oxy]poly(oxy-1,2-ethanediyl) 0-20%, 1,4-butanediol polymer with α-hydro-ω-hydroxypoly(oxy-1,4-butanediyl) and 1,1'-methylendbis [4-isocyanatobenzene] 20-60%, 2-hydroxyethyl methacrylate 30-80%, phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide 0-10%, butylhydroxytoluene 0-1%, titanium dioxide 0-1%, pigment 0-1%	(88)	(104, 112, 113)
3Delta crown; DeltaMed (Germany)	Preparation of acrylates, fillers, initiators and pigments. filler content: 50% by weigh and 30% by volume	Manufacturer information	Author
3D-Accuprint; D-tech (Rendlesham, UK)	Methacrylate monomers & oligomers, inert filler, photoinitiator, pigment (*)	Manufacturer information	48
Freeprint Crown®; DETAX GmbH (Germany)	7,7,9(oder 7,9,9)-Trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecan-1,16-diylbismethacrylat, hydroxypropylmethacrylat, diphenyl(2,4,6-trimethylbenzoyl) phosphinoxid, phenyl-bis(2,4,6-trimethylbenzoyl)-phosphinoxid (*)	Manufacturer information	Author
Dental Sand Pro, Harz labs (Russia)	Urethane methacrylate oligomer (50-70%), reactive diluent (50-70%), 2-hydroxypropyl methacrylate (1-5%), diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (1-3%), filler (10-30%)	Manufacturer information	Author
VarseoSmile®TriniQ®, BEGO (Bremen, Germany)	Esterification products of 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide. Total content of inorganic fillers (particle size 0.7 µm) is 30–50% by mass (*)	Manufacturer information	Author
APPLICATION NOT SPECIFIED			
TNG-GPM101, GC	Hybrid resin composite	(114)	(114)

(*) Percentage values for the components of the 3D-printed resin were not disclosed by the reviewed study or the manufacturer.

materials, as it reflects their resistance to the propagation of internal flaws or cracks under applied stress[58]. In dental applications, load to failure is a key indicator of a material's structural integrity and its ability to endure occlusal forces in clinical use. Ten studies in this review assessed the LF of 3D-printed resins[45,58,67,73,84,86,88,93,95,98]. The reported values showed a mean load to failure of 1397.47 N, with a SD of 1051.25 N, ranging from 321.13 N to 3991.88 N, and a median value of 1214.93 N *(Figure 3* – Appendix). One study evaluated compressive strength using cylindrical specimens measuring 3 mm diameter and 5 mm in heigh. The reported compressive strength was 297.7 MPa when the force was applied perpendicular to the printing layers, and 257.7 MPa when applied parallel to the layers[32].

Flexural Modulus (FM)

Flexural modulus, or bending modulus, is a measure of a material's stiffness, indicating its resistance to deformation under bending forces[31]. In this review, 16 studies tested and reported the FM of various 3D-printed resin materials[16,19,31,37,39,44,49,54,56,60,74,79,82,87,103,109]. From these studies, a total of 57 results were collected, reporting a mean FM of 2818.47 MPa (SD=1443.60 MPa), with a range from 300 MPa to 7660 MPa, and a median value of 2700 MPa *(Figure 4* – Appendix).

Vickers Microhardness (VHN)

Microhardness can be used as an indicator of material density, and it can be hypothesized that a denser material would be more resistant to wear and surface deterioration[96]. This type of test evaluates a material's resistance to plastic deformation under a standardized indenter. Fifteen studies assessed the VHN of different 3D-printed resins[16,19,41,43,54,57,60,74,77,82,87,91,96,102,109], with a total of 35 results gathered. The mean value was 20.94 kgf/ mm^2 (SD=7.51 kgf/ mm^2), with a maximum value of 40.30 kgf/ mm^2, a minimum value of 9.70 kgf/ mm^2, and a median value of 20.00 kgf/ mm^2 *(Figure 5* – Appendix).

CHEMICAL PROPERTIES

Degree of Conversion (DC)

Degree of conversion (DC) is commonly measured to estimate the extent of polymerization and indirectly assess the residual monomer content in resin-based materials. It reflects the percentage of monomeric double bonds converted into polymeric structures during curing. DC is influenced by several factors, including monomer size, the number of reactive functional groups, temperature, and the initiator system used[115]. Seven studies, presenting a total of twenty results, were included[16-18,53,74,90,115]. DC values varied significantly across studies, ranging from 27% to 95.2%, with a median value of 53.40%.

SURFACE CHARACTERISTICS

Wear Loss (WL)

Wear loss assesses the material's surface durability resulting from mechanical interactions, such as sliding contact under loading[76]. WL can be measured in two primary ways: as vertical weal loss (in µm) – reflecting height reduction – typically using surface profilometry or microscopy; or as volumetric wear loss (in mm^3), which accounts for the total volume of material lost and allows better comparison between materials with different densities. In this review, eight studies analyzed the WL of 3D-printed resins, yielding 18 distinct outcomes. From these, a total of 21 results were collected, yielding a vertical loss ranging from 62 µm to 257 µm[38,76,86] and volumetric wear loss ranging from 0.08 mm^3 to 20 mm^3 [22,42,66,69,106]. The protocols varied from study to study, including differences in abrasive tool, number of cycles per specimen, and method and scale of measurements *(Table 4)*.

Surface Roughness (SR)

SR quantifies the texture of a material's surface by measuring fine irregularities that deviate from an ideally smooth plane[110]. These irregularities can significantly impact the material's esthetic and functional performance. In this review, twenty-six studies reported SR outcomes, contributing a total of 90 results. Most of the studies reported their findings using Ra (arithmetical mean roughness)[22,35,41-43,48,53,54,57,60,68,69,76,77,80,86,87,90,92,100,104,107,110] *(Figure 6* – Appendix), four studies showed their findings in Sa (area surface roughness)[15,52,54,103] *(Figure 7* – Appendix). For Ra measurements, the average value was 2.16 µm (SD=5.383 µm), with a maximum 39.00 µm, a minimum value of 0.06 µm, and a median value of 0.63 µm. For Sa measurements, the average value was 0.72 µm (SD= 1.038 µm), with a maximum value of 3.80 µm, a minimum value of 0.01 µm, and a median value of 0.27 µm.

DIMENSIONAL ACCURACY

Internal Fit (IF) or Internal Gap (IG)

The internal fit refers to the discrepancy between the inner surface of a dental crown and the surface of the prepared tooth structure[47]. A total of 24 studies included in this review assessed the internal fit of dental crowns fabricated from various resins, contributing a total of 116 results[2,9,13,14,24,27,29,30,40,47,59,61,63,65,81,83,97,98,101,105,111,114]. The results were reported in micrometers (µm), either as direct internal gap measurements or using the root mean square (RMS) method to assess the deviation across the intaglio surface between the printed specimen and a reference replica. Internal gap measurements were categorized by location, including overall, axial, and occlusal spaces. RMS values provided a global assessment of internal adaptation. Table 5 provides a descriptive analysis of these findings.

Table 4. Wear loss by resin, type of abrader, force applied and number of cycles.

Study	Resin	Vertical Loss (µm)	SD (µm)	Type of abrader	Force	No. of cycles
(38)	3D Delta temp	62	4	Metal wheel with third-body medium of ground millet seeds	15N	200,000
(38)	Nextdent C&B MFH	255	13	Metal wheel with third-body medium of ground millet seeds	15N	200,000
(38)	Freeprint Temp	257	24	Metal wheel with third-body medium of ground millet seeds	15N	200,000
(86)	P Pro Crown&Bridge	163.8	21.4	Steatite balls	50N	120,000
(86)	Provisional Crown&Bridge	114.5	25.8	Steatite balls	50N	120,000
(86)	Varseo Smile Crown temp	132.4	56.2	Steatite balls	50N	120,000
(86)	CB Resin	120	27.5	Steatite balls	50N	120,000
(86)	VarseoSmile Crown Plus	126.6	28.4	Steatite balls	50N	120,000
(76)	Varseo Smile Crown	212.9	32.49	Stainless-steel ball	49N	250,000
(76)	NextDent C&B MHF	75,43	13.65	Stainless-steel ball	49N	250,000
(76)	Saremco Crowntec	143.94	16.05	Stainless-steel ball	49N	250,000
Study	**Resin**	**Volume loss (mm^3)**	**SD (mm^3)**	**Type of abrader**	**Force**	**No. of cycles**
(22)	Dima Print	20	-	Molar deciduous tooth	30N	20,000
(22)	ZMD-1000B Temporary	6	-	Molar deciduous tooth	30N	20,000
(22)	Freeprint Temp	5	-	Molar deciduous tooth	30N	20,000
(22)	DT-1 Temporary Teeth	14	-	Molar deciduous tooth	30N	20,000
(66)	Nextdent C&B MFH	1.11	-	Milled Zirconia abrader	49N	30,000
(66)	Nextdent C&B MFH	1.22	-	CoCr alloy abrader	49N	30,000
(42)	Freeprint Temp	10.81	2	Composite Filtek Z350 XT	50N	20,000
(69)	Nextdent C&B MFH	0.08	0.09	CoCr alloy	49N	30,000
(69)	Nextdent C&B MFH	0.1	0.01	CoCr alloy	49N	60,000
(106)	Permanent Crown Formlabs	0.68	0.14	-	49N	400,000

Table 5. Descriptive analysis of IF.

	Mean (µm)	SD (µm)	Maximum (µm)	Minimum (µm)	Median (µm)
Overall (gap distance) (n=17)	137.36	81.11	269.01	0.00	129.80
Occlusal gap (n=19)	170.28	70.59	317.00	75.05	154.00
Axial gap (n=17)	88.24	45.57	170.00	23.00	69.00
RMS (n=63)	40.415	21.07	116.00	13.00	35.00

***Note: Root mean square (RMS) refers to a 3D digital analysis method in which the intaglio surface of the restoration is evaluated by superimposing it onto a reference model using a specialized inspection software.**

Marginal Fit (MF) or Marginal Gap (MG)

The marginal gap refers to the vertical distance between the edge of the dental crown and the finish line of the tooth preparation, usually reported in micrometers (µm)[47]. A total of 19 studies[14,25,26,30,40,42,47,50,59,61,63,65,81,83,89,97,98,112,114] reported a total of 43 results concerning the MF for 3D-printed crowns. The mean marginal gap value was 86.49 µm (SD=54.72 µm), with the maximum value recorded at 233.00 µm, the minimum value at 6.00 µm, and a median of 71.00 µm.

ADHESION

Bond Strength (BS) - Tensile and Shear

Bond strength refers to the force required to separate two bonded surfaces and is a critical factor assessing the durability of adhesive interfaces. Shear bond strength characterizes the resistance to forces that induce sliding between surfaces, while tensile bond strength characterizes the resistance to forces that pull the bonded surfaces apart perpendicularly. In this review, eight studies examined the bond strength (tensile and shear) between 3D-printed resin specimens and different cements or repair materials, using different adhesion strategies and surface pre-treatment protocols[15,43,51,68,78,85,92,108]. Among these studies, two[78,92] provided 16 results related to tensile bond strength, with values averaging 24.75 MPa (SD=3.53 MPa), and ranging from 19.50 MPa to 31.00 MPa, with a median of 25.55 MPa (*Figure 8* - Appendix). One study[108] tested different pre-treatment methods on the same resin, using Variolink Esthetic DC as the cement, reporting bond strengths ranging from 1051.9 N to 1430 N. Shear bond strength was evaluated in the remaining five studies, collectively reporting 27 results. The average shear bond strength value was 16.97 MPa (SD=14.20 MPa), ranging between 1.45 MPa and 43.30 MPa, and a median of 16.00 MPa (*Figure 9* - Appendix). Additionally, one study[75] reported the use of a chevron-notch test to measure interfacial bond strength in terms of energy per unit area, with results spanning from 0.22 to 1.50 J/m^2.

BIOLOGICAL ASSESSMENT

3D-printed resins used for dental crowns must exhibit specific biological properties to ensure their safety and biocompatibility with human tissues. The gathered data on the biological assessment of these resins was primarily derived from *in vitro* assays utilizing cell cultures, with a primary focus on evaluating cell viability and cytotoxicity. In addition, several studies have extended this evaluation to investigate the biological response of these resins to bacterial interactions, providing a more comprehensive understanding of their behavior in the oral environment.

Studies assessing cell viability reported good biocompatibility for 3D-printed specimens[16,17,46,55,56,74,77,116]. Results from these studies were often expressed as percentages relative to control groups – usually cells grown on standard tissue culture plates. Cell viability values ranged from 48.6% to 100%, indicating a generally favorable response to the materials tested[16,17,55,74,77,116]. Three of these studies further assessed the relationship between post-curing time, washing time, and cytotoxicity levels[16,17,56]. Depending on the type of resin and post-curing procedures employed, cytotoxicity levels were comprehended between 2% and 16%, illustrating the influence of post-processing on material biocompatibility. Another study[46] compared four different provisional restoration materials, irrespective of post-curing and washing times, and found cytotoxicity levels ranging between 1.2% and 13.7%.

Four studies accessed bacterial biofilm formation comparing different 3D-printed resins, further investigating the effects of various post-production processes, including glazing and polishing, on bacterial adhesion[52,80,87,100]. Glazing was suggested as being important since it reduces surface roughness and, consequently, the formation of biofilm[52]. In one study, no significant differences were found for *S. mutans* adhesion across various materials, except for Saremco Crowntec, which exhibited higher adhesion compared with VarseoSmile Crown Plus, Permanent Crown Formlabs and other CAD/CAM materials[100]. The study also noted that *S. sanguinis* displayed lower adhesion levels compared to *S. mutans*, likely due to differing adhesion characteristics between species[100]. One study found favorable results for two types of 3D-printed resins while comparing acrylic resin and bis-acryl resin[87]. Additionally low fungal adhesion was verified in certain resins, further indicating that material composition plays a role in modulating fungal colonization[80].

DISCUSSION

The present scoping review aimed to collect and summarize the key findings from primary studies published between January 2013 and 18th August 2024 regarding 3D-printed resins used for dental crowns. The review focused on identifying the available products, their composition, mechanical, accuracy and surface characteristics, and biological functionality.

COMPOSITION, MECHANICAL AND TRIBOLOGICAL PROPERTIES

3D-printed resins are typically composed of photopolymerizable monomers and oligomers in a polymer matrix. These components are designed to undergo a curing process initiated by UV light, resulting in solid, high-resolution structures. A critical factor in 3D-printed resins' composition is the filler content. Fillers enhance mechanical properties but also increase viscosity, which can adversely affect print resolution due to gravity and surface tension effects[117]. Highly viscous resins are more likely to produce rough surfaces and encountering processing defects such as incomplete curing, voids, and low accuracy[44]. Therefore, achieving an optimal balance between filler content, optimal mechanical properties, and fluidity is challenging[88,117]. Most manufacturers do not report filler content for provisional resins, whereas permanent resins typically contain 30-50% fillers (*Table 3*). In contrast, composite CAD/CAM blocks generally have a higher filler content, typically ranging from 70-80%[118]. Common fillers include silica, barium glass, aluminum, and zirconium silicate[119]. The incorporation of filler nanoparticles (NPs) can further optimize the mechanical characteristics of these resins. Ceramic NPs, in particular, have been shown to increase the flexural strength of 3D-printed resins[37,53,103]. This improvement is primarily due to the nanoparticles' ability to reinforce the polymer matrix, thereby increasing the material's resistance to deformation under stress[120,121]. The shape and size of these nanoparticles further play a crucial role in their effectiveness; they influence void distribution between the printed layers, which directly impacts the mechanical behavior of the final product[72]. Smaller, well-dispersed nanoparticles can fill these voids more effectively, leading to a denser, more uniform structure that exhibits superior mechanical properties. Additionally, the unique properties of ceramic NPs, such as their high hardness and thermal stability, contribute to enhancing the overall performance of the resin[2,38].

Masticatory forces applied to a dental restoration normally involve a complex combination of tensile, compressive, and shear forces[122]. The ISO 4049:2019 standard specifies that the minimum requirement for the flexural strength of polymer-based restorative materials is 80 MPa. The results from our review, encompassing 101 results revealed that the mean flexural strength of 3D-printed resins was 124.01 MPa, with a median value of 113.60 MPa. These results emerged from three-point bending flexural tests. This type of test measures the material's resistance to bending forces by applying load at the midpoint of a beam supported at both ends. Notably, permanent resins exhibited a mean flexural strength approximately 21 MPa higher than provisional resins. These values are comparable to the flexural strength of leucite-reinforced pressable all-ceramics, which ranges from 92 to 122 MPa, but are lower than those of lithium disilicate, which typically exhibits a value of around 350 MPa[123]. CAD/CAM crowns fabricated from composite resin blocks reported flexural strengths ranging from 120 MPa to 247 MPa, underscoring the enhanced mechanical properties achieved through these materials[119,124]. Industrial polymerization, conducted under high temperatures (180°C) and pressure (250 MPa for 60 min), contributes significantly to enhance the overall mechanical properties of these materials, including their flexural strength, hardness and density[125]. However, the long-term behavior of 3D-printed resins' flexural strength remains uncertain, with some studies reporting a decrease with aging[48,60,103], while others report an increase following artificial aging protocols[79,80].

Another critical aspect of polymeric materials is fracture resistance, which depends on the material used, as well as the complex created between the crown, abutment, and cement. None of the studies included in this review used human or bovine ex vivo teeth for load to failure tests; instead studies used SLA fabricated dies, epoxy resin dies, resin bases and/or metal abutments during tests[58,67,84,86,88,95]. The mean and median fracture resistance strength values for 3D-printed crowns were 1397.47 N and 1214.93 N respectively, which are higher than normal masticatory forces. Studies assessing human bite force suggested values ranging from 262.8 N to 999.3 N[127,128], indicating that 3D-printed crowns can withstand typical masticatory forces. A thickness of at least 1.5 mm of material seems advisable to ensure sufficient strength[73,86,93]. Additionally, the type of tooth may also influence the crown's fracture resistance[58,67,70,84,86,95]. Nevertheless, CAD/CAM milled restorations, irrespective of crown thickness, generally showed increased fracture resistance compared to their 3D-printed counterparts, with values ranging from 1580.4 N to 2988 N[73,84,86,93]. Of additional relevance, favorable results for 3D-printed specimens compared to TelioCAD PMMA have been reported[67].

For the flexural modulus of 3D-printed resins, the mean and median values were approximately 2.8 GPa and 2.7 GPa, respectively. These results are significantly lower than those of CAD/CAM composite blocks, which range from 8.26 to 16.95 GPa[119]. While more flexible materials can absorb energy and resist brittle failure, they may not withstand higher forces before deforming excessively or failing. In contrast, enamel and dentin have much higher flexural moduli, ranging from 74 up to 130 GPa and 17.7 to 28.8 GPa, respectively[128-130]. A dental restorative material with a lower flexural modulus results in greater transmission of masticatory loads to the underlying tooth structures compared to stiffer materials, as ceramics[132]. Reducing the flexural modulus imparts a more elastic behavior to the material, allowing it to absorb and distribute forces more effectively, reducing the likelihood of fracturing and results in less brittle behavior[131]. Therefore, increasing the filler content in 3D-printed resins could enhance the flexural modulus, contributing to a stiffer and more brittle material[109].

One clinical trial included in this review showed comparable clinical performance between 3D-printed and conventional PMMA provisionals for single implants, although a significant difference in the fracture rates was observed, with 3D-printed provisionals being more prone to fractures[132]. In another randomized controlled trial (RCT), the clinical outcomes of 3D-printed dental crowns were compared to stainless-steel crowns as restorative treatment for primary molars. After a 12-months follow-up, it was reported that while the 3D-printed group was aesthetically superior, their survival rate was significantly lower compared to the stainless-steel group, 82.1% and 100% respectively[113]. These findings highlight the need for further refinement in the durability of 3D-printed materials, particularly in high-stress environments such as pediatric dentistry.

SURFACE PROPERTIES

Surface roughness plays a critical role in both the longevity and performance of dental restorations, directly impacting the material's susceptibility to microbial adhesion and overall wear. Previous studies have determined the Ra values for various dental tissues and restorative materials, providing benchmarks for comparison: enamel (0.012 µm), zirconium dioxide ceramics (inCoris TZI: 0.026 µm), hybrid ceramics (VITA Enamic: 0.027 µm), nanocomposite CAD/CAM blocks (Lava Ultimate: 0.025 µm), and direct light-cure nanocomposites (Filtek XTE: 0.020 µm)[134]. Ra, the arithmetical mean roughness, measures the average deviation of surface heights along a line, while Sa reflects the average roughness across a surface area. Our review found a mean and median Sa values of 2.16 and 0.71 µm, respectively. Given the variability in methodologies and the higher values reported in some studies, the median value is likely a more representative indicator of the typical surface roughness. However, even the median Sa value of 0.71 µm exceeds the commonly cited threshold of 0.20 µm recommended for minimizing microbial adhesion and biofilm formation[134]. Furthermore, material aging may further affect roughness values over time, due to the hydrolytic degradation of the resins in aqueous environments[135]. The degree of conversion and the presence of residual surface monomers may compromise material's structural integrity, leading to increased surface roughness[107]. Notably, increasing post-curing time may not significantly influence Ra, suggesting that other factors, such as material composition and printing protocols, play a more critical role in determining surface smoothness[45,107].

Regarding durability, zirconia generally has a harder and more durable surface than lithium disilicate ceramic[136]. Ceramics exhibit lower wear than resin composites under clinical conditions. Our review found a vertical wear loss of 62 to 256 µm[38,76,86] comparable to some hybrid ceramics (Vita Enamic - 153.40 µm)[137]. Research comparing the wear characteristics of different restorative CAD/CAM materials with human enamel has found that zirconium dioxide ceramics show low wear against enamel antagonists[138]. CAD/CAM silicate and lithium disilicate ceramics, hybrid ceramics, and nanocomposite, both CAD/CAM and direct, exhibit wear characteristics that do not significantly differ from human enamel. In contrast, polymers have higher material wear than other permanent materials[139-141]. Materials with high VHV, which are harder and stiffer, exhibit strong wear resistance. In addition, glazing acrylic-based resins can enhance their microhardness, improving abrasion resistance and lifespan[77]. Extended post-curing is crucial to increase the hardness of 3D-printed resins[19,125]. However, it has been further suggested that high VHV can be achieved if a strong light intensity is used, even with a short post-polymerization time[74]. Our review found that 3D-printed restorations have an average VHV of approximately 21 kgf/mm^2, with permanent 3D resins showing higher VHV values than provisional resins, though still lower than 35 VHV. This is approximately three times lower than the hardness value of composite CAD/CAM blocks used for permanent restoration[142]. Other factors that are material-dependent will also influence the final hardness, as photoinitiators, the size, refraction index, and load of the fillers, as well as the characteristics of the curing machine – including area of emission and wavelength of the curing light[19]. Limited polymerization at the center of the specimen compared to the outer layers has been observed, suggesting that the thickness of the restoration affects overall VHV due to the degree of conversion[54]. Special attention should be given after occlusal adjustments, as the hardest superficial layer may expose a softer layer with lower mechanical resistance, making it more prone to wear against occlusal loads[19]. A possible solution to this problem may be the application of a final glaze and post-curing for 5 min, after occlusal adjustments.

LEVEL OF ACCURACY

The internal fit and marginal fit of 3D-printed crowns are critical factors that determine the success and longevity of dental restorations. Promising results were gathered from the results of primary research, indicating that 3D-printed crowns can achieve internal and marginal discrepancies that are equal or even lower than those of milled restorations[30,50,54,89,97,114]. The abutment preparation for milled restorations requires smooth edges and usually a chamfer margin design because sharp preparations are challenging to recreate with milling machines, while 3D-printed crowns are less constrained by such limitations. Higher discrepancy values observed in milled specimens have been attributed to the tolerance errors of milling burs. On the other hand, the accuracy of 3D-printed specimens is affected by multiple factors including the speed and intensity of light exposure, the type of resin used, print orientation, the number of layers, the use of supports, and the post-curing process[13,15,29,50,63,82].

ADHESION

Adhesion is a critical factor ensuring the long-term success of a restoration, particularly in permanent applications. Effective bonding is a result of micromechanical retention of the adhesive agent with both the abutment and the restorative material. Various pre-treatment methods were described for enhancing adhesion in 3D-printed specimens[15,51,68,78,85,92]. Due to the inherent differences in material manufacturing processes, specific surface treatment procedures are required for both 3D-printed and milled resins[78]. Studies have shown that higher bond strengths were typically found with the use of resin cement compared to resin-modified glass ionomer cement.The mean and median values for tensile bond strength in 3D-printed crowns were 24.75 MPa and 25.55 MPa, respectively, while shear bond strength values averaged 16.97 MPa, with a median of 16.00 MPa. Bond strength of composite to etched tooth structure (enamel) typically ranges between 20 and 30 MPa[143]. These bond strength values are at the lower end of the expected range for indirect resin composites (25.5-32.7 MPa), but are inferior to those of lithium disilicate (23.9-35.3 MPa)[144].

PRINTING AND POST-PRINTING

Regarding printing parameters, selecting the optimal build direction is critical not only for improving accuracy but also for decreasing production time, minimizing cost, and decreasing the number of supports required[9]. While it remains unclear to what extent printing direction influences flexural strength and elastic modulus[32,37,39,44,45,82], the choice of material seams to exert a high influence[44,82]. Although varying the layer thickness was found to have little to no impact on flexural strength[54,64], most studies used a 50 µm layer thickness as standard printing parameter.

Multiple studies recommend aligning the layers perpendicular to the direction of the load[14,44,45,59,72,73,82]. For instance, when printing a molar dental crown, the layers should ideally start at the occlusal surface or cusps and progress towards the apical end of the crown to reduce shear stress. However, while this approach can help in managing mechanical forces, it may also compromise the precision of the occlusal anatomy, potentially affecting the functional and aesthetic outcomes of the restoration[125]. Also, build direction may impact other critical factors such as surface roughness, internal fit, and marginal fit, which are essential for the long-term success of the restoration[15,24,45,59,64].

Post-printing processes, particularly washing and curing, also play a crucial role in determining the final quality of 3D-printed restorations. The choice of washing solvent can impact surface quality, mechanical properties and bonding behavior[70,75,90]. Different compositions of 3D-printed resins may require different solvents for optimal results. Most studies have reported using solvent isopropyl alcohol at 91% or 99% for post-washing. However, other solvents such as ethanol 96%, bio-ethyl alcohol 100%, and tripropylene glycol monomethyl ether have also been recommended depending on the specific resin used[53,70,75].

BIOLOGICAL PROPERTIES

The biocompatibility of 3D-printed resins is a critical consideration in their application for dental restorations, particularly in relation to cytotoxicity and bacterial adhesion. According to the standard ISO 10993-5, which sets the requirements for *in vitro* cytotoxicity testing for medical devices, specimens with a cell viability lower than 70% relative to the control are considered to have cytotoxic potential. Ensuring proper post-polymerization is crucial to mitigate the cytotoxic effects of 3D-printed resins when interacting with human cells[74]. The degree of polymerization directly affects cell viability; specimens in their “green state”, immediately after printing, exhibit a low degree of polymerization, which is associated with increased monomer release and higher cytotoxicity. Without adequate post-polymerization and effective washing, higher levels of cell death are likely to occur[16-18,55,56]. Studies investigating different resins and 3D printers evaluated the impact of the post-curing and washing procedures on the degree of conversion. From the results of the review, a degree of conversion in the green state ranged between 15 to 27%, increasing to between 40 to 95% after final post-treatment as washing and curing[16-18,53,90,115]. However, some authors did not find a direct correlation between monomer release and the DC[17,115,145]. Broadly, monomer release and DC are dependent on the manufacturing method, with network density and structure influencing monomer elution[115]. Additionally, it has been suggested that the application of a glazing solution may be beneficial, potentially binding to residual monomers on the resin surface and further reducing cytotoxicity[77]. Resins with higher filler content generally exhibit higher DC and lower monomer release compared to unfilled resins, which may also contribute to improved biocompatibility[115].

Cell adhesion studies revealed a trend toward increased cell attachment with well-extended filopodia in the presence of 3D-printed specimens or their extracts[16], indicating superior biocompatibility of 3D-printed specimens compared to their self-curing counterparts (provisional materials)[23]. However, a minority of studies reported more favorable cytotoxicity outcomes for specimens milled from resin blocks rather than for 3D-printed specimens, attributing these differences to the industrial polymerization methods used in milling, which typically omit photoiniatiators and result in a more stable polymer network[34]. Based on the findings from this review, several key practices have been identified to enhance the biological response elicited by 3D-printed materials. In addition to a thorough polishing, implementing a glazing protocol can significantly reduce surface roughness, bacterial adhesion, and monomer leaching[77,100,137]. Furthermore, extending the post-washing time (from 6 to 30 min) and increased the post-curing time (from 15 to 60 min) at higher curing temperatures (around 60°C) can effectively reduce the amount of residual monomers. A plausible justification for the benefits elapsing form the increased post-curing temperature is the more efficient polymerization of the resin, which enhances the molecular mobility of free radicals and other reactive specimens, leading to improved biocompatibility[16]. However, the clinician should be aware that by benefiting biologically from the increased post-curing and washing periods it can negatively affect other clinical parameters, such as, flexural strength and adhesion[17,56,75].

Bacterial adhesion on dental materials is a critical determinant influencing the long-term success and durability of dental restorations. High levels of bacterial adhesion can lead to the formation of biofilms, which are associated with local tissue inflammation, infections, and ultimately, the failure of the restorations. The development of materials with low bacterial adhesion is crucial for maintaining oral health and extending the longevity of dental treatments. The studies included in this review provided insights into the dynamics of bacterial adhesion. Evidence from these studies indicates that bacterial adhesion occurs rapidly and robustly across different species, affecting both raw and polished printed samples[52,80,100]. The findings suggest that the type of resin and post-production treatments, such as glazing and polishing, play a significant role in surface roughness. This aspect influences bacterial adhesion and subsequent biofilm formation. Surface treatments appear to be particularly effective in reducing microbial adhesion, potentially decreasing the risk of biofilm-related complications in dental restorations. Furthermore, the observed variations in microbial adhesion among different microorganisms on the same material underscore the complexity of biofilm formation, and the need for further research to fully understand these dynamics. Despite these insights, there remains no clear consensus on the relationship between bacterial adhesion and the structural content of 3D-printed materials.

Notwithstanding the comprehensive scope of this review, several limitations must be acknowledged. A primary challenge was the heterogeneity in study designs, materials, and testing protocols, which limited the ability to make direct comparisons across studies and precluded quantitative synthesis through meta-analysis. Inconsistencies were particularly noted in specimen preparation, post-processing procedures, and measurement methods, introducing potential variability in reported outcomes. Secondly, the overwhelming majority of studies were *in vitro*, with very few clinical trials available, thereby restricting the generalizability of findings to clinical practice. Another limitation stems from the incomplete or inconsistent reporting of material compositions by manufacturers, which hindered attempts to conduct subgroup analyses based on resin type or classification.

Nevertheless, the findings of this scoping review are consistent with recent reviews that have focused on the mechanical behavior of 3D-printed dental materials. A systematic review and meta-analysis by Valenti *et al.*[146] reported that polymer-based materials produced through additive manufacturing demonstrate significantly lower flexural strength, hardness and fracture load, but comparable marginal fit, when compared to milled or conventionally fabricated alternatives. Similarly, Pot *et al.*[147] found that properties such as flexural strength and hardness varied considerably across 3D-printed composites, largely due to differences in composition, printing orientation, and post-processing protocols. Their findings further emphasized that these materials generally perform below ceramics and conventionally processed composites. These findings closely align with the present review, which also highlights the considerable variability and performance limitations among currently available 3D-printed resins. Collectively, these reviews emphasize the need to standardize testing protocols and pursue clinical validation to ensure the reliable and effective application of 3D printing in restorative dentistry.

CONCLUSION

This scoping review provides a broad synthesis of current in-laboratory evidence on the performance of 3D-printed resins used for provisional and final single-tooth dental crowns. The literature reveals a wide variety of available provisional resins, with a more limited selection of materials for long-term applications. In general, 3D-printed resins generally exhibit lower flexural strength, elasticity modulus, and hardness, compared to resins utilized under milling applications. However, reported fracture resistance values fall within the range of typical masticatory forces. Studies also indicate that 3D-printed crowns may achieve favorable internal and marginal fit, as well as bond strength, though these outcomes vary depending on material type and pre-treatment protocols. Importantly, surface roughness and biocompatibility are strongly influenced by post-processing procedures. Polishing and glazing appear to be essential steps in optimizing surface quality and enhancing the overall performance of 3D-printed restorations. While the available *in vitro* data are promising, further clinical studies are required to validate these findings and assess the long-term suitability of 3D-printed resin materials for crown fabrication.

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CONFLICTS OF INTEREST

There is no conflicts of interest by the authors of this research.

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APPENDIX

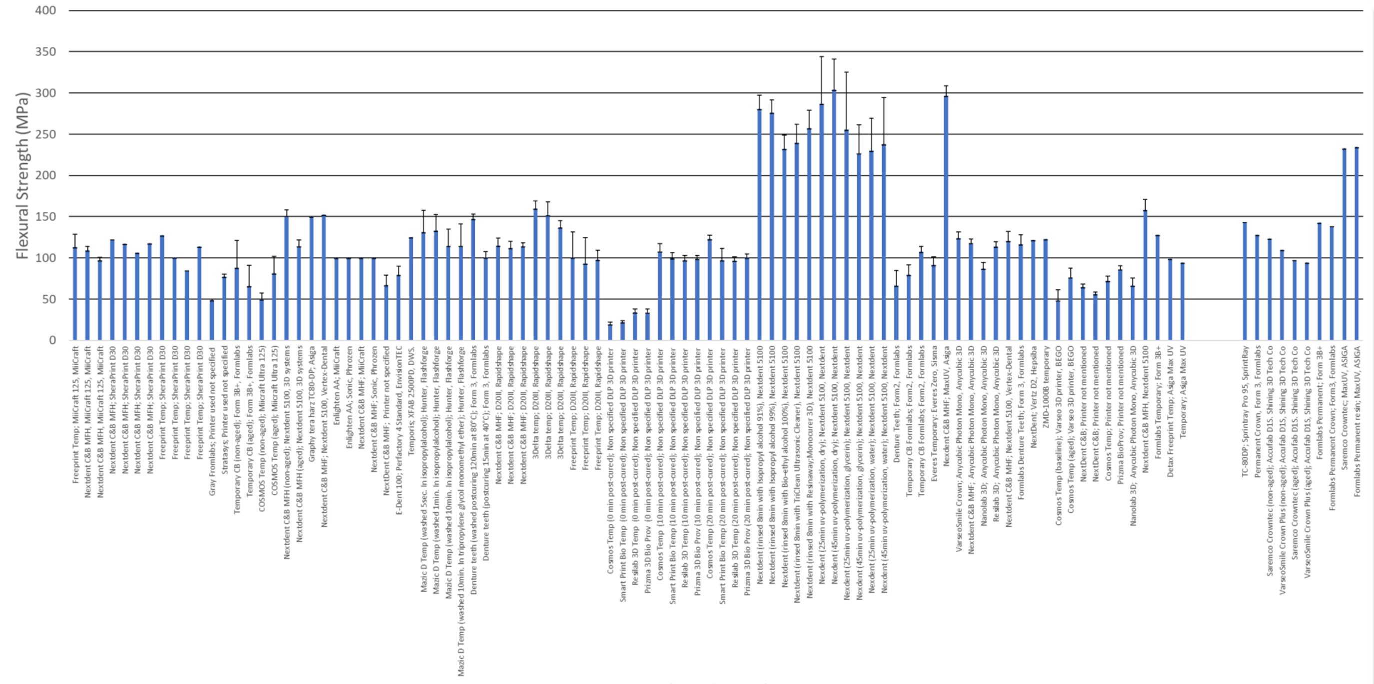

Figure 2: Appendix - Bar graph with the flexural strength values reported by primary studies.

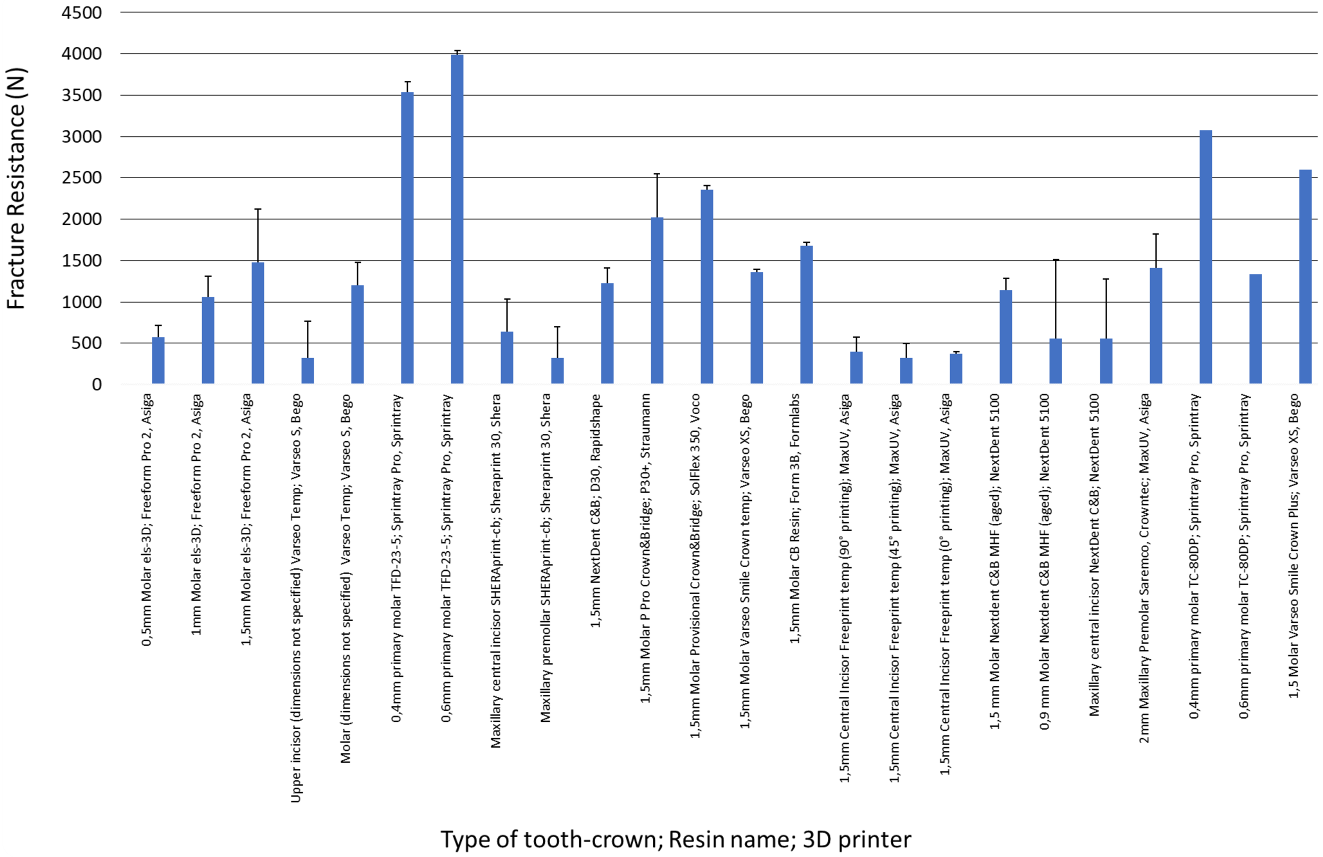

Figure 3: Appendix - Bar graph with the fracture resistance values reported by primary studies.

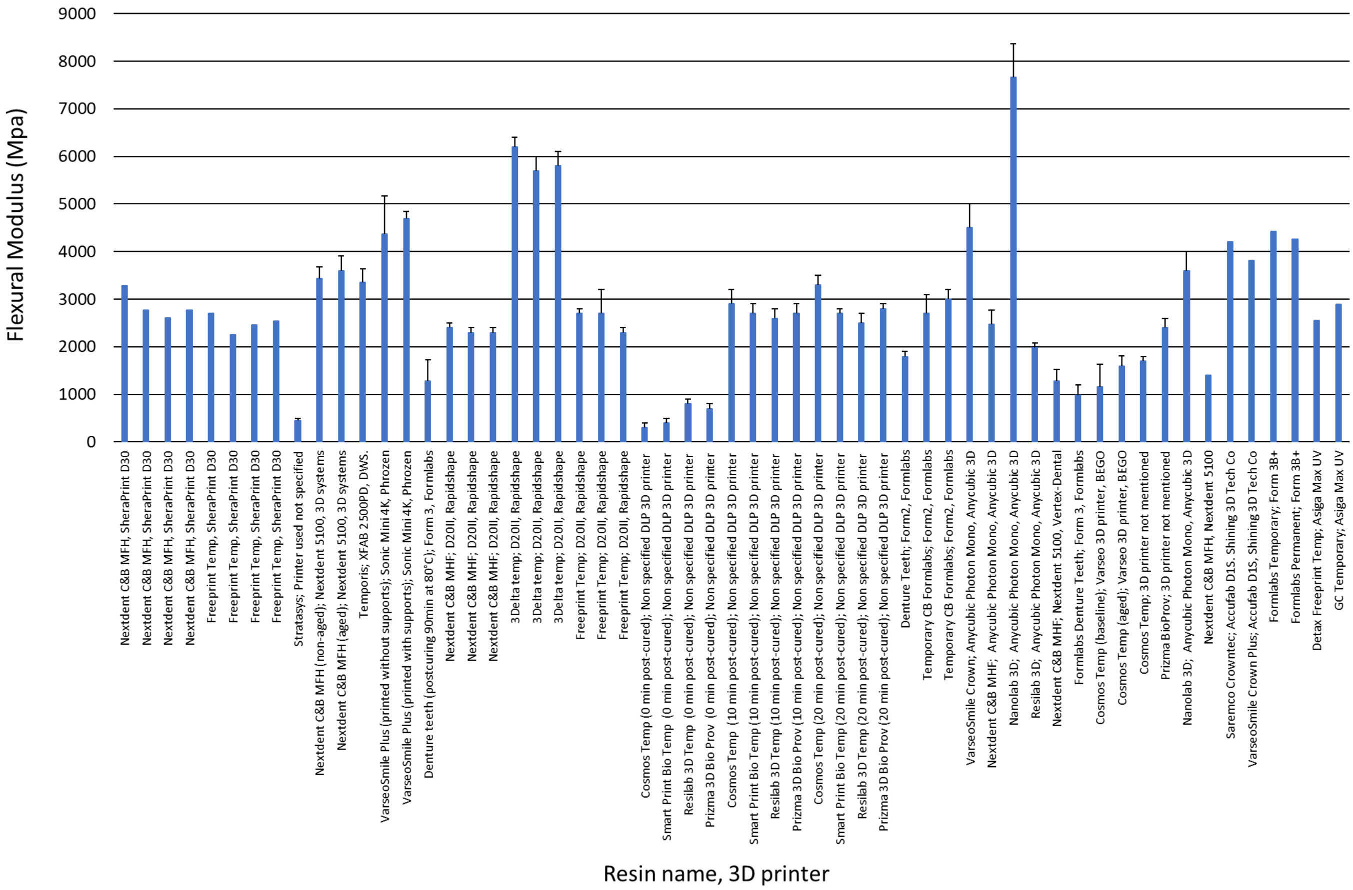

Figure 4: Appendix - Bar graph with the elasticity module values reported by primary studies.

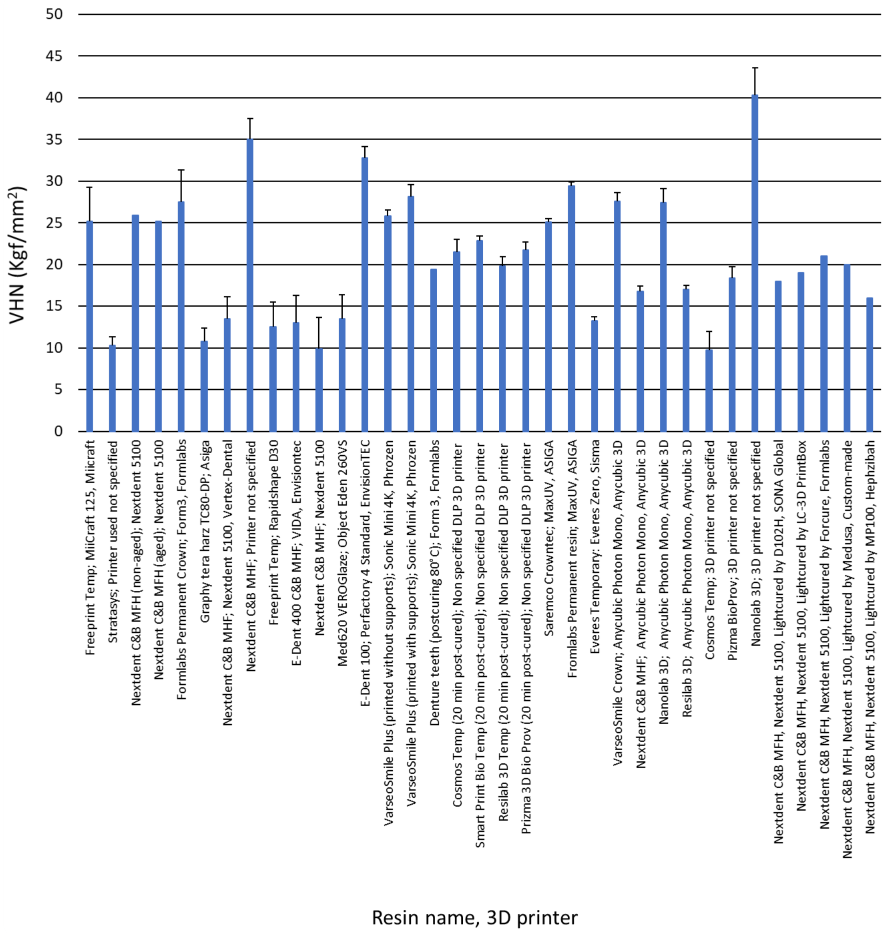

Figure 5: Appendix - Bar graph with the vickers microhardness values reported by primary studies.

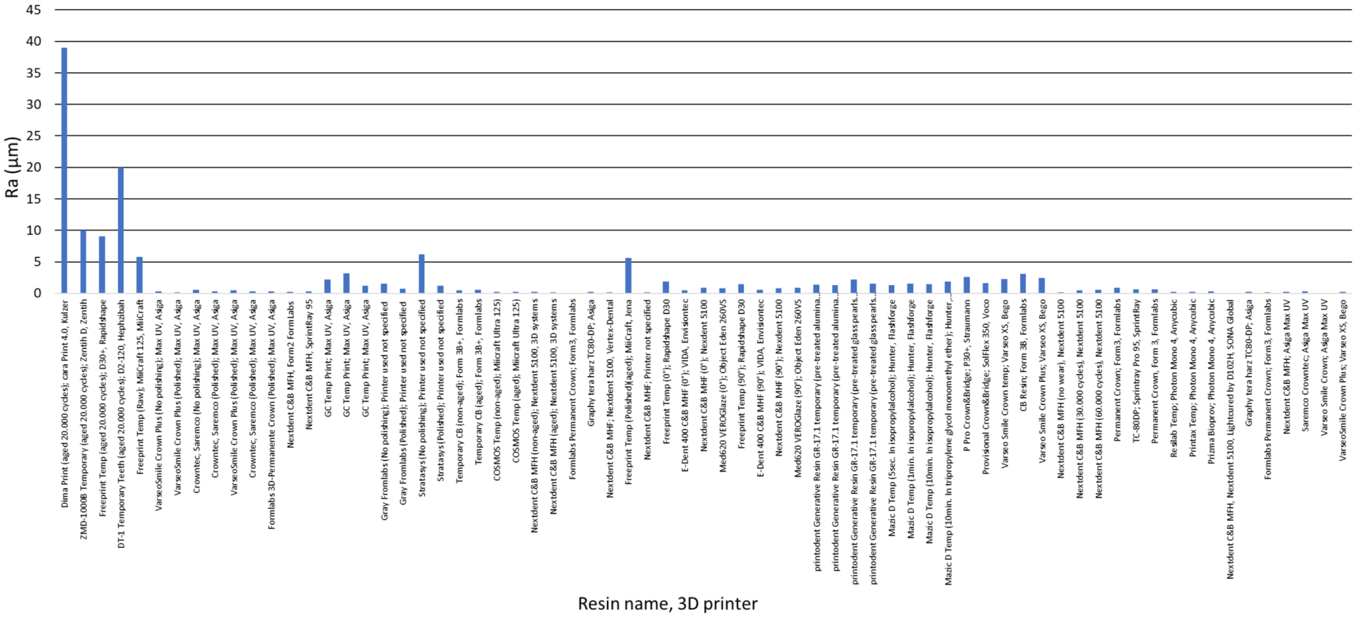

Figure 6: Appendix - Bar graph with the surface roughness in Ra values reported by primary studies.

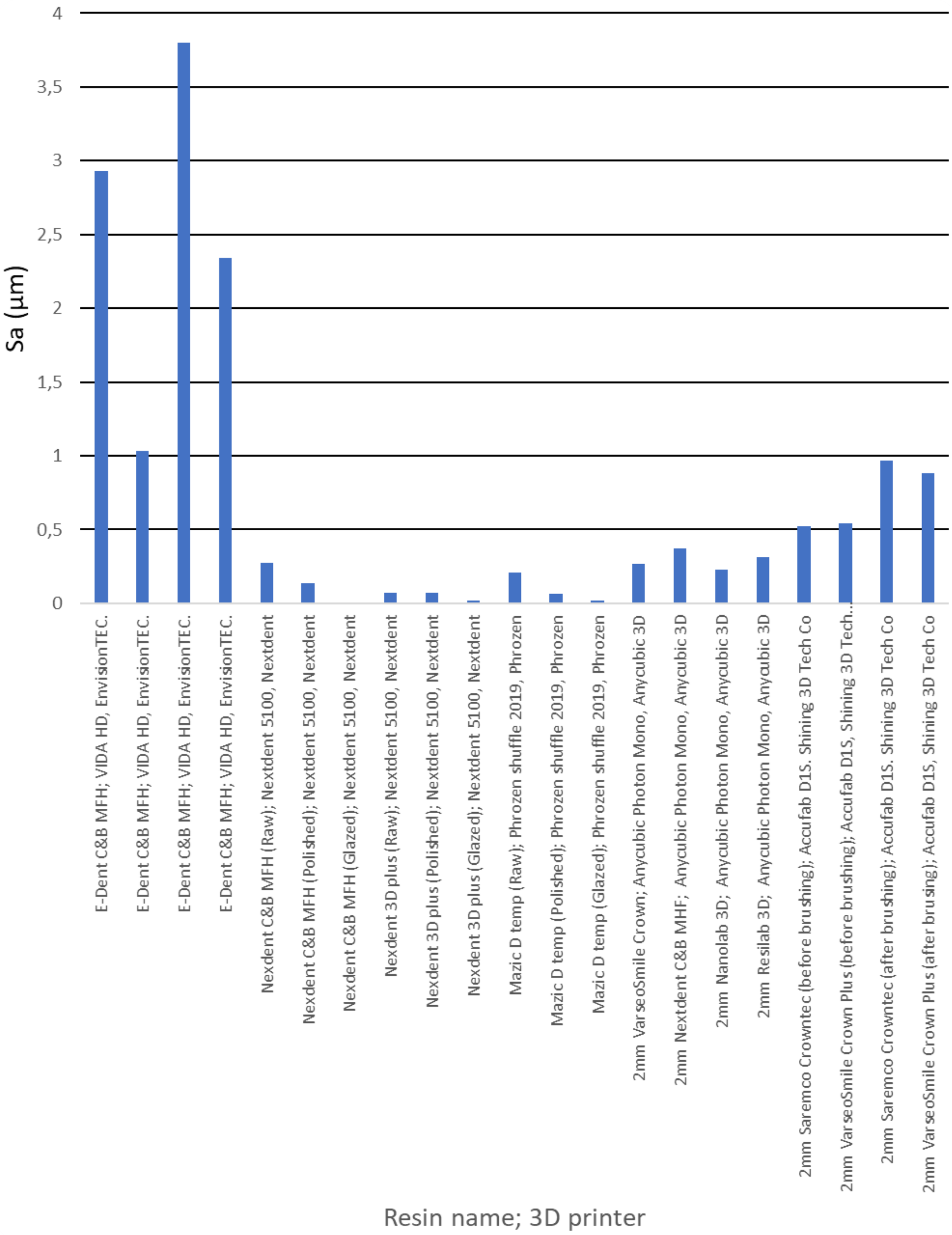

Figure 7: Appendix - Bar graph with the surface roughness in Sa values reported by primary studies.

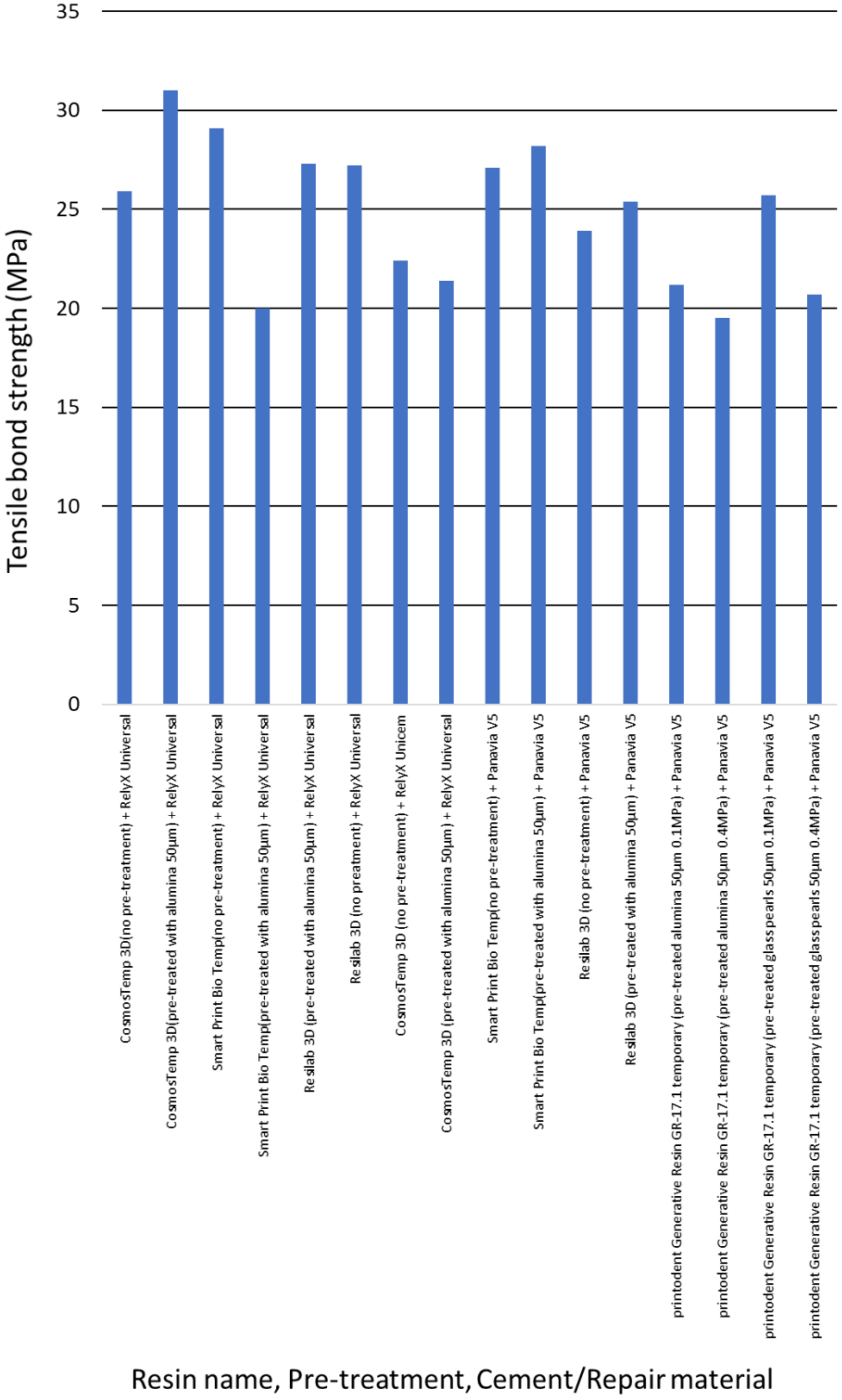

Figure 8: Appendix - Bar graph with the tensile bond strength in MPa reported by primary studies.

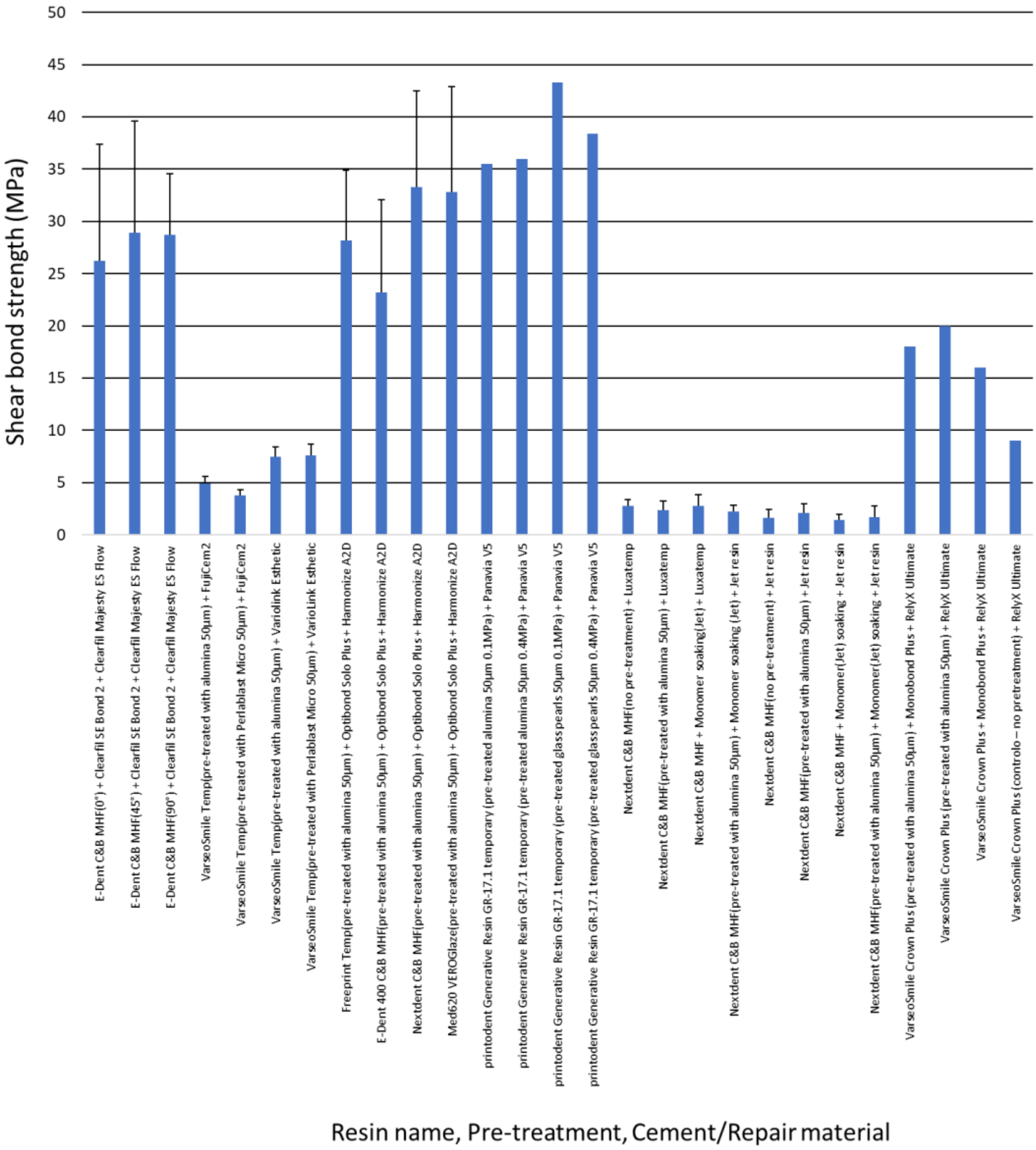

Figure 9: Appendix - Bar graph with the shear bond strength in Mpa reported by primary studies.