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REVIEW ARTICLE

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Current applications of 3D printing in dental implantology: A scoping review mapping the evidence

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Abstract

Objectives: This scoping review aimed to identify the available evidence in the use of 3D printing technology in dental implantology. Due to the broad scope of the subject and its application in implantology, three main areas of focus were identified: (1) *customized dental implants*, (2) *manufacturing workflow for surgical implant guides*, and (3) *related implant-supported prostheses factors*, which include the metallic primary frameworks, secondary ceramic or polymer superstructures, and 3D implant analog models.

Materials and Methods: Online databases (Medline, Cochrane, Embase, and CINAHL) were used to identify the studies published up to February 2023 in English. Two experienced reviewers performed independently the screening and selection among the 1737 studies identified. The articles evaluated the additive manufacturing (AM) technology, materials, printing, and post-processing parameters regarding dental implantology.

Results: The 132 full-text studies that met the inclusion criteria were examined. Thirteen studies of customized dental implants, 22 studies about the workflow for surgical implant guides, and 30 studies of related implant-supported prostheses factors were included.

Conclusions: (1) The clinical evidence about AM titanium and zirconia implants is scarce. Early data on survival rates, osseointegration, and mechanical properties are being reported. (2) 3D printing is a proven manufacturing technology to produce surgical implant guides. Adherence to the manufacturer's instructions is crucial and the best accuracy was achieved using MultiJet printer. (3) The quality of 3D printed prosthetic structures and superstructures is improving remarkably, especially on metallic alloys. However, better marginal fit and mechanical properties can be achieved with milling technology for metals and ceramics.

KEYWORDS
3D printing, additive manufacturing, implantology, prosthodontics, scoping review

1 | INTRODUCTION

In recent years, dentistry has undergone a great digital revolution. Two major technologies, subtractive and additive manufacturing (AM) technologies, have been developed to move from the virtual world of Computer-Aided Design (CAD) of our devices to Computer-Aided Manufacturing (CAM). The subtractive or milling technologies normally refer to computer numerically controlled (CNC) milling machines that drill and cut a block of solid material (Revilla-León et al., 2020; Rutkūnas et al., 2022). The AM, also known as three-dimensional (3D) printing or rapid prototyping, is a variety of technologies capable of creating physical objects by sintering powder or polymerizing liquid materials layer by layer in cross-sections from digital designs. 3D printing was first patented in 1986 by Charles Hull (Hull & Gabriel, 1986) and has been used in dentistry since the early 2000s (Elliott et al., 2022). AM has become a fast-growing alternative to subtractive methods in dentistry and presents some advantages as the creation of complex geometries and the reduction of material waste. The American Society for Testing and Materials (ASTM) divides the AM technologies into seven categories: (1) vat-photopolymerization (SLA), (2) material jetting, (3) material extrusion, (4) binder jetting, (5) powder bed fusion (PBF), (6) sheet lamination, and (7) direct energy deposition (ISO/ASTM 52900, 2021; Alexander et al., 2021). The main 3D printing categories applied to implant dentistry are: 3D polymer printing technologies (vat-photopolymerization, material extrusion, and material jetting) and 3D metal printing technologies (PBF) (Table 1 and Figures 1–4). Currently the main application of 3D printing in implant dentistry is the fabrication of surgical guides with light-curing polymers for guided implant surgery (Revilla-León et al., 2020). There are potential applications such as the manufacture of dental implants fully customized to the patient's anatomical situation (Oliveira & Reis, 2019; Revilla-León et al.,2017). However, the advantages and disadvantages of the devices are not yet defined and are currently in an experimental phase. In implant-supported prosthetic rehabilitation 3D printing has been used for some years now. The manufacture of primary metal structures in titanium or cobalt–chromium alloys achieves an accuracy similar to conventional structures, though post-processing with a milling machine is often necessary (Revilla-León et al., 2019). Additively manufactured superstructures have mainly been studied with polymers, however the rapid development of this technology and the materials available is leading to the emergence of new applications such as new ceramics and hybrid materials that will need to be evaluated prior to clinical application (Rutkūnas et al., 2022).

The goals of a scoping review are to identify the types of evidence available and the knowledge gaps in a particular research area and to clarify existing concepts in order to consider how research should be conducted. Given that 3D printing is relatively recent manufacturing technology in implant dentistry, it is necessary to carry out an analysis of the available scientific evidence to map the main applications and concepts in the field of dental implantology. For this reason, a scoping review was conducted to provide an objective interpretation of the literature reviewed and a structure that can be replicated in the future to evaluate the evolution of the technologies assessed (Munn et al., 2018). The following research question was formulated: "What is the main application and impact of three-dimensional printing technology in dental implantology?" The search strategy was based on a PCC (population, concept, and context) framework. The population was "human/all ages," the concept was "three-dimensional printing," and the context was "dental implants." Once the available scientific evidence had been analyzed, it was decided to group the studies by fields of knowledge and application of the different technologies for a better analysis of their

TABLE 1 Definition of the main 3D printing technologies applied to dental implantology.

AM technology category (ASTM)	3D printer technology	Operational definition
Vat-polymerization	Stereolithography (SLA)	An ultraviolet laser photopolymerized liquid polymers layer by layer (Figure 1a)
	Digital light processing (DLP)	The liquid resin is cured by a projector that flash a single image of each layer in the entire platform (Figure 1a)
	Continuous liquid interface (CLIP)	A window at the bottom of the vat is opened to let the ultraviolet light beam enter through an oxygen permeable membrane and polymerize a precise layer in a dead zone while the object rises slowly (Figure 1c)
Material extrusion	Fused deposition modeling (FDM)	A thermoplastic material is extruded in layers through a nozzle onto the platform (Figure 2)
Material jetting	MultiJet printers (MJP)	Multiple print nozzles dispense selectively droplets of photopolymers, with different colors and materials, onto a build platform where each layer is cured with a ultraviolet light (Figure 3)
Powder bed fusion (PBF)	Selective laser sintering (SLS)	High-powered Nd:YAG laser beam is applied onto a bed of powdered metal, which fuses in thin solid layers at a temperature below the melting point of the metal (Figure 4a)
	Selective laser melting (SLM)	Powerful fibers laser beams are applied onto a metal powder bed to complete melting the layers obtained from the bed of powdered metal (Figure 4a)
	Electron beam melting (EBM)	An electron beam with magnetic coils melt layers of powder of 100 μm in an inert environment such as purified argon (Figure 4b)

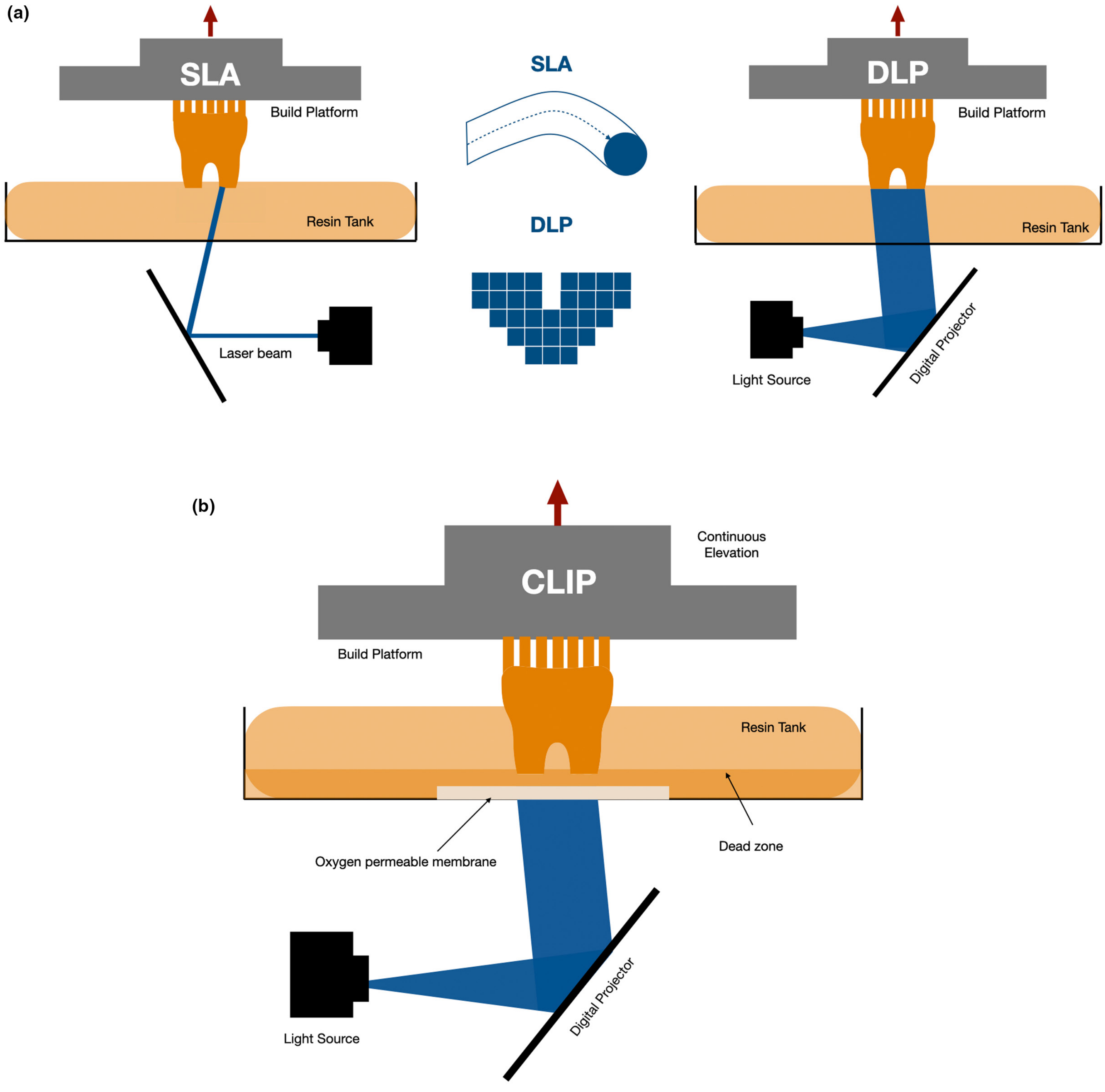

FIGURE 1 Main vat-polymerization printers used in implant dentistry. (a) Stereolithography (SLA) and digital light processing (DLP) printer with a scheme of the polymerization by a laser beam spot in the SLA and by the pixels of the projector in the DLP. (b) Continuous liquid interface production (CLIP) printer scheme.

impact. Three areas were defined according to the different stages of oral rehabilitation with dental implants. The first group "3D printed customized dental implants" referred to the surgery phase and the selection of the type of dental implant and the evaluation of their characteristics according to the manufacturing method. The second group "3D printing manufacturing workflow for surgical implant guides" also referred to the surgery phase and the evaluation of the manufacturing process and post-processing parameters of devices for guided surgery. The third group "3D printing related implant-supported prostheses factors" referred to the restorative phase and the application of different manufacturing technologies in the fabrication of implant-supported devices such as the metallic primary frameworks, secondary ceramic or polymer superstructures, and 3D implant analog models.

2 | MATERIALS AND METHODS

2.1 | Research questions

Following the protocol drafted by the research team using the PRISMA extension for scoping reviews (PRISMA-ScR), a primary research question (RQ) was formulated: "What is the main application and impact of three-dimensional printing technology in dental implantology?" (Tricco et al., 2018). The research protocol can be obtained on request from the authors. Due to the large amount of scientific evidence available, it was decided to divide the analysis of articles into three areas based on the different stages of implant rehabilitation. This allowed a detailed assessment of the current status and clinical applications of 3D printing in implant dentistry. The secondary research questions were: (1) In 3D printing, what is the current status in the technology used and materials available for printing customized dental implants? (2) Regarding static guided surgery in dental implant, what is the impact of the different 3D printing technologies, materials available, and post-processing on the result of the surgical implant guide? (3) In 3D printing, what is the current status in the technology used, the materials available, and related factors for making implant supported prosthesis?

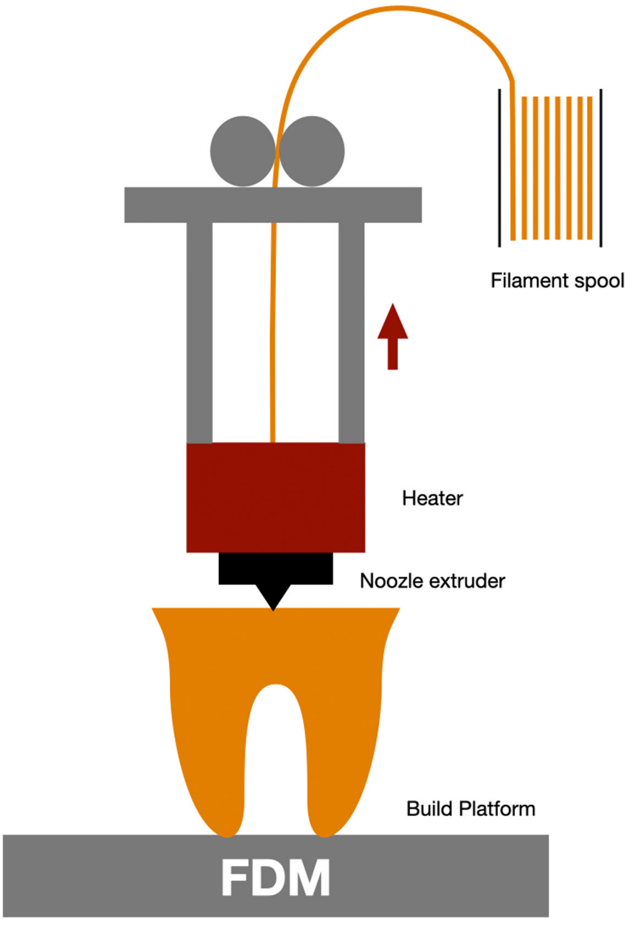

FIGURE 2 Fused deposition modeling (FDM) printer scheme.

2.2 | Electronic search strategy

Four electronic databases were used as sources in the search to identify potentially relevant studies: (1) Medline – PubMed, (2) Cochrane, (3) CINAHL, and (4) Embase. These databases were searched for studies published up to February 2023 and reported in English. Information on the databases search strategies is available in Appendix S1.

2.3 | Screening methods and identification of relevant evidence

Two experienced reviewers performed independently the screening of titles and abstracts (S.B. and B.MC.) using Ryyan web application (https://www.rayyan.ai). Three main fields were identified to select and classify full manuscript studies according to the research questions: "3D printed customized dental

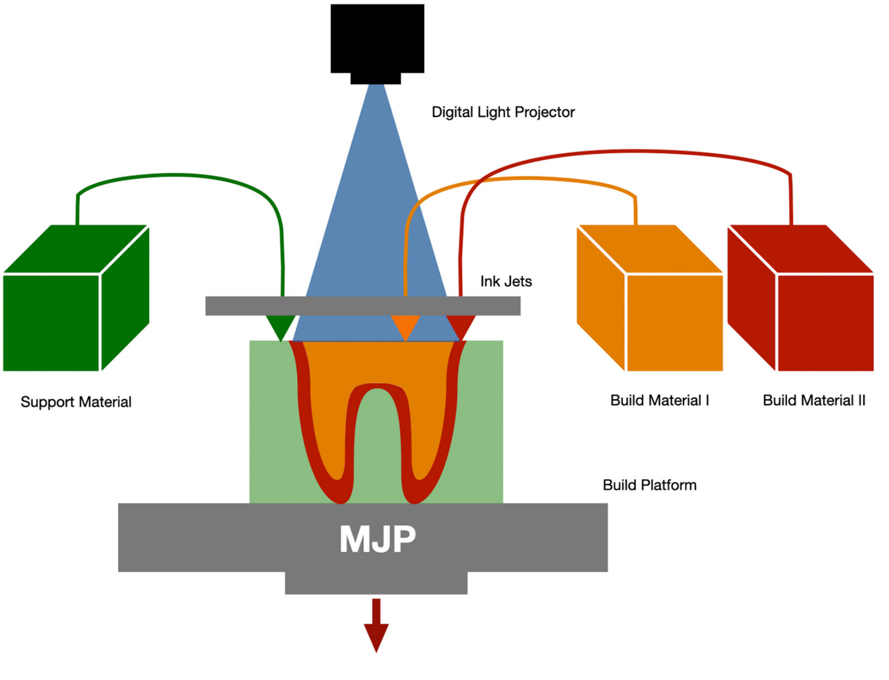

FIGURE 3 MultiJet printer (MJP) printer scheme.

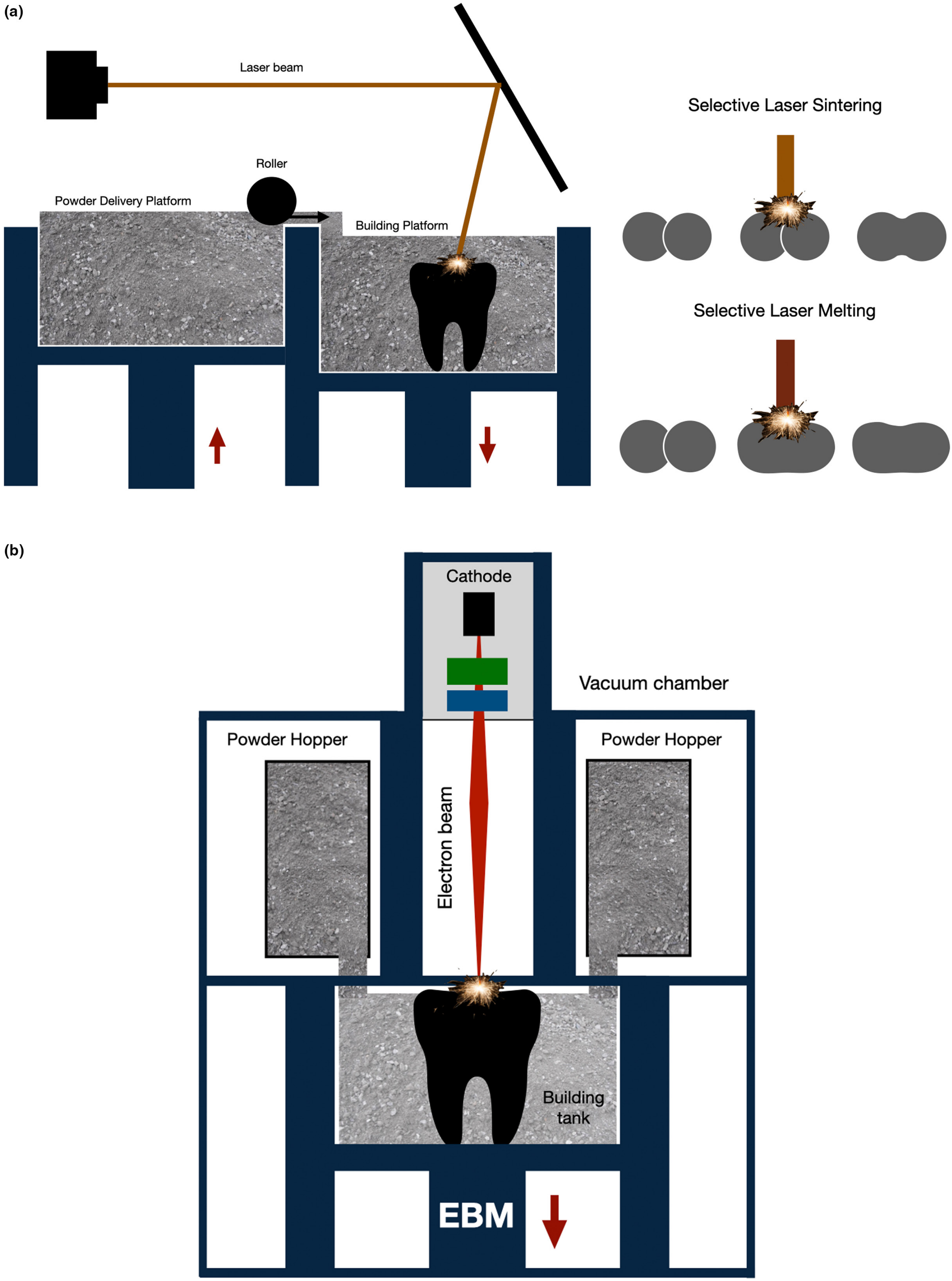

FIGURE 4 Main powder bed fusion (PBF) printers used in dentistry. (a) Selective laser sintering (SLS) and selective laser melting (SLM) printer and powder fusion scheme. (b) electron beam melting (EBM) printer scheme.

implants," "3D printing manufacturing workflow for surgical implant guides," and "3D printed related implant-supported prostheses factors." The same reviewers selected full-text studies or those with insufficient data in the title or abstract to make a clear inclusion decision. Articles met the inclusion criteria when their main outcomes evaluated the AM technology, materials, printing parameters, or post-processing protocols regarding dental implantology. Studies were excluded if they reported data on maxillofacial surgery, orthodontics, removable or tooth-supported prostheses, endodontics, implant position in guided surgery, or if the main outcome was not related to 3D printing manufacturing parameters. The clinical cases and dental techniques articles commonly used in the field of prosthodontics were also excluded. Any disagreement was discussed with a third reviewer (G.P.) and a final decision was made (Figure 5). The inter-reviewer reliability (kappa correlation coefficient) of the full-text analysis was calculated.

Zotero bibliographic reference manager (version 6) was used for data management when assessing the eligibility of full-text articles. An Excel spreadsheet (Excel 16.64 for Mac; Microsoft) per research question was sketched with the full-text selected articles to identify and classify the most representative evidence, and a descriptive analysis was performed.

3 | RESULTS

Figure 5 shows the flow chart summarizing the result of the selection process. The search of Medline, Cochrane, CINAHL, and Embase yielded 1937 articles, of which 1737 remained after removing duplicates. The full text of 132 articles after title and abstract were analyzed in detail. After this analysis, only 65 studies were included for data extraction in this scoping review. According to the research questions: 13 studies were included for the RQ1 about "3D printed customized dental implants," 22 studies for the RQ2 about "3D printing manufacturing workflow for surgical implant guides," and 30 studies for the RQ3 about "3D printing related implant-supported prostheses factors." The main information retrieved from the included studies is given in Table 2 for RQ1, Table 3 for RQ2, and Tables 4–6 for RQ3. The kappa correlation coefficient for the full-text analysis was 0.71.

3.1 | RQ1: "In 3D printing, what is the current status in the technology used and materials available for printing customized dental implants?"

The RQ1 included 13 studies published between 2016 and 2022 (Table 2) (Anssari Moin et al., 2017; Chang Tu et al., 2020; Han et al., 2022; Lee et al., 2022; Liu et al., 2022; Oliveira & Reis, 2019; Osman et al., 2017; Ren et al., 2021; Sonaye et al., 2022; Tedesco et al., 2017; Tunchel et al., 2016; Zhang et al., 2022). The studies investigate the feasibility of successfully fabricating printed implants, as well as their long-term clinical success. In addition, four of the studies focus on investigating the surface of the implant, since this factor has an important influence on osseointegration (Anssari Moin et al., 2017; Chang Tu et al., 2020; Ren et al., 2021; Tedesco et al., 2017). Of these studies, four were in vitro (Anssari Moin et al., 2017; Han et al., 2022; Osman et al., 2017; Sonaye et al., 2022), seven in vivo (Chang Tu et al., 2020; Lee et al., 2022; Liu et al., 2022; Ren et al., 2021; Tedesco et al., 2017; Tunchel et al., 2016; Zhang et al., 2022), and one was a systematic review of the literature (Oliveira & Reis, 2019). Studies were classified according to the material and technology they use: six studies use as material titanium alloys that are processed EBM or SLM (Chang Tu et al., 2020; Lee et al., 2022; Liu et al., 2022; Ren et al., 2021; Tedesco et al., 2017; Tunchel et al., 2016), two used PEEK processed with the FFF (Han et al., 2022; Sonaye et al., 2022), and the last three studies used zirconia as a material for the manufacture of implants through the use of DLP technology (Anssari Moin et al., 2017; Osman et al., 2017; Zhang et al., 2022).

3.2 | RQ2: "Regarding static guided surgery in dental implant, what is the impact of the different 3D printing technologies, materials available, and post-processing on the result of the surgical implants guides?"

The RQ2 included 18 in vitro studies and 4 narrative reviews published between 2013 and 2022 (Table 3 and Figure 6; Abduo & Lau, 2020; Ammoun et al., 2021; Chen et al., 2019; Dalal et al., 2020; Dandekeri et al., 2013; Dawood et al., 2015; De Moraes et al., 2022; Elliott et al., 2022; Kim et al., 2020; Marei et al., 2019; Matta et al., 2017; Mukai et al., 2021; Oh et al., 2019; Revilla-León et al., 2020; Reyes et al., 2015; Rouzé l'Alzit et al., 2022; Sharma et al., 2020; Sommacal et al., 2018; Tahir & Abduo, 2022; Török et al., 2020; Unkovskiy et al., 2018; Wegmüller et al., 2021). Articles evaluating the accuracy of the printed guided surgery splints were included, not those that evaluated the final position of the implants after surgery. Nine in vitro studies studied the 3D printer technology (Abduo & Lau, 2020; Kim et al., 2020; Matta et al., 2017; Mukai et al., 2021; Oh et al., 2019; Reyes et al., 2015; Rouzé l'Alzit et al., 2022; Sommacal et al., 2018; Wegmüller et al., 2021), three studies evaluated the resin and printing parameters (Dalal et al., 2020; Tahir & Abduo, 2022; Unkovskiy et al., 2018), and six in vitro studies analyzed the post-processing and sterilization methods (Ammoun et al., 2021; Chen et al., 2019; De Moraes et al., 2022; Marei et al., 2019; Sharma et al., 2020; Török et al., 2020). The surgical implant guide was printed in resin with MJP technology in nine studies (Chen et al., 2019; Kim et al., 2020; Oh et al., 2019; Reyes et al., 2015; Rouzé l'Alzit et al., 2022; Sharma et al., 2020; Tahir & Abduo, 2022; Török et al., 2020; Wegmüller et al., 2021), SLA printers in eleven studies (Ammoun et al., 2021; Chen et al., 2019; Dalal et al., 2020; Kim et al., 2020; Marei et al., 2019; Oh et al., 2019; Reyes et al., 2015; Rouzé l'Alzit et al., 2022; Sharma et al., 2020; Unkovskiy

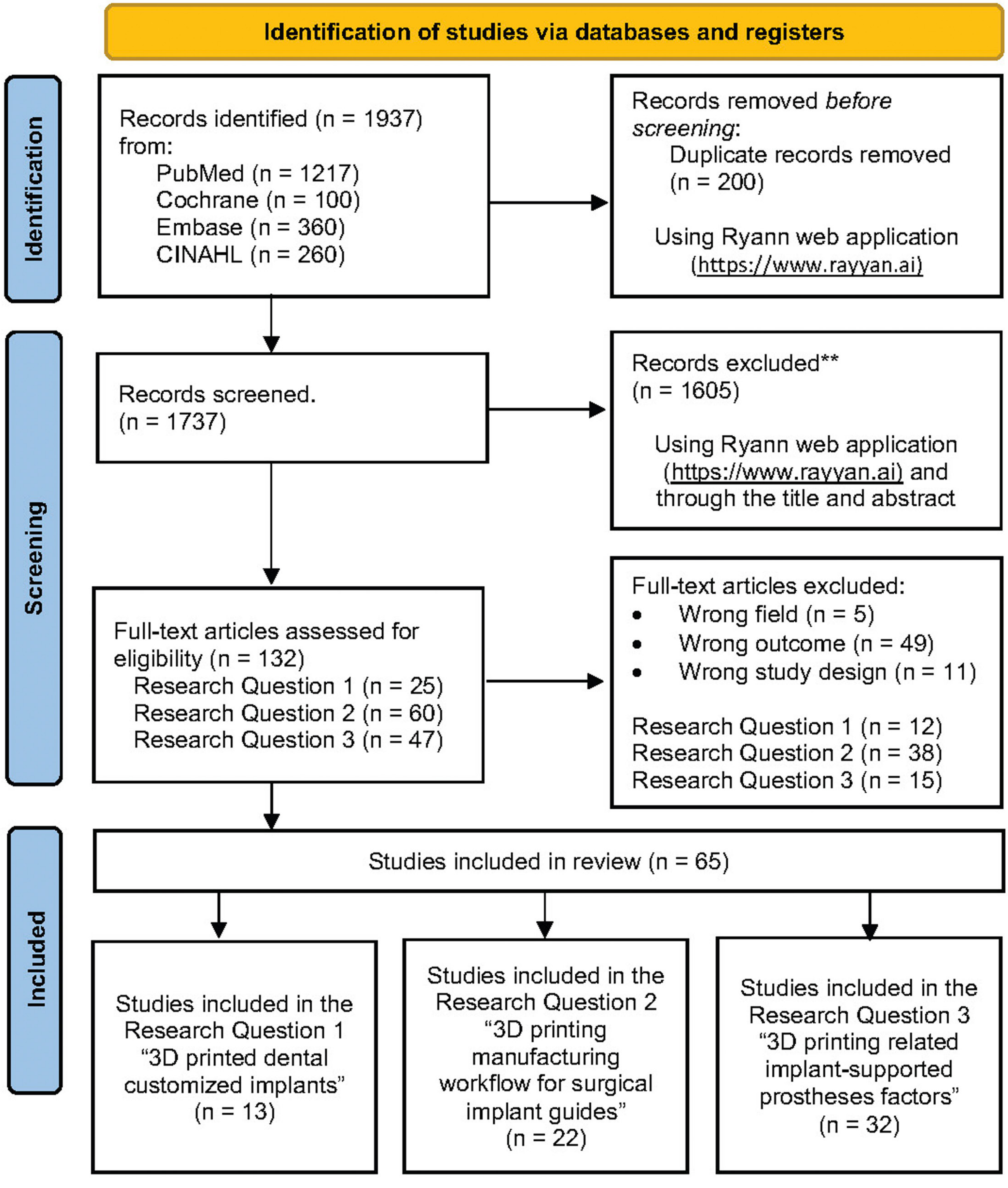

FIGURE 5 PRISMA 2020 flow diagram: selection of studies evaluating 3D printing in implantology. From: Page et al. (2021). For more information, visit: http://www.prisma-statement.org/.

et al., 2018; Wegmüller et al., 2021), DLP printers in seven studies (De Moraes et al., 2022; Mukai et al., 2021; Oh et al., 2019; Rouzé l'Alzit et al., 2022; Sommacal et al., 2018; Tahir & Abduo, 2022; Wegmüller et al., 2021), and FDM or FFF printers in four studies (Abduo & Lau, 2020; Rouzé l'Alzit et al., 2022; Sommacal et al., 2018; Wegmüller et al., 2021). The surgical implant guides were manufactured in metal with SLS printers in three studies (Chen et al., 2019; Matta et al., 2017; Rouzé l'Alzit et al., 2022). The printing parameters

TABLE 2 Characteristics of the included studies about the Research Question 1: "Customized dental implants."

Authors (year)	Study design	Sample size	Printer technology	Material	Layer thickness	Angulation to platform	Study outcomes measured
Anssari et al. (2017)	In vitro	1	DLP: ADMATEC Europe BV, Moergestel, The Netherlands	ZrO_2	25 µm	0°	Feasibility of fabrication 3D printed zirconia implant by DLP technology
Chang Tu et al. (2020)	In vivo	20	SLM: EOSINT M 280 system (EOS GmbH, Munich, Germany)	Ti6Al4V	X	X	Bone regeneration and osseointegration by histomorphometric and micro-CT analysis
Han et al. (2022)	In vitro	288	FFF: Apium P220, Apium Additive Technologies GmbH, Karlsruhe, Germany	PEEK	X	X	After plasma surface treatment, the study evaluates: • Microstructure and roughness by scanning electron microscopy (SEM) and a profilometer • The wettability using a drop shape analyzer (DSA) • Cell adhesion, metabolic activity
Lee et al. (2022)	In vivo	8	SLM: X	Ti6Al4V	X	X	• Peri-implant bone volume/tissue volume (BV/TV) and bone mineral density (BMD) by micro-computed tomography • Bone-to-implant contact (BIC) and bone area fraction occupancy (BAFO) were measured in histomorphometric analyses
Liu et al. (2022)	In vivo	8	SLM: SLM 280 HL machine from SLM Solutions AG, Germany	Ti6Al4V	30 µm	X	Geometric accuracy of the 3D printed dental implant using a monkey maxilla incisor model
Osman et al. (2017)	In vitro	45	DLP: ADMAFLEX 2.0; ADMATEC Europe BV, The Netherlands	ZrO2	30 µm	0° 45° 90°	Dimensional accuracy, surface topography of a custom designed, 3D printed zirconia dental implant, and the mechanical properties
Ren et al. (2021)	In vivo	X	EBM: Arcam machine (Q10 plus, Arcam, Sweden)	Ti6Al4V	50 µm	X	Bioactivity and osteogenesis of 3D implants by constructing a hierarchical micro/nano-topography on the surface
Sonaye et al. (2022)	In vivo	X	FFF: FUNMAT HT Enhanced (Intamsys, China)	PEEK	10–30 µm	X	Analyze the impacts of various critical 3D printing parameters: • Layer height • Print speed • Thermal conditions And analyze the mechanical properties: • Compressive strength • Fatigue properties
Tunchel et al. (2016)	In vivo	82	SLA: EosyntM270, EOS GmbH, Munich, Germany	Ti6Al4V	10 µm	X	3 years of follow-up was to evaluate the survival and success rates of single SLA titanium dental implants
Tedesco et al. (2017)	In vivo	12	SLM: EOSINT M 280 (EOS GmbH, Krailling, Germany)	Ti6Al4V	X	X	Bone regeneration and osseointegration
Zhang et al. (2022)	In vitro	X	Material jetting: XJET Carmen 1400, Rehoyot Israel	ZrO_2	10.5 µm	X	Microstructural and mechanical characterization

Abbreviations: DLP, digital light processing printer; EBM, electron beam melting; FFF, fused filament fabrication; PEEK, polyetheretherketone; SLA, stereolithography printer; SLM, selective laser melting; Ti6Al4V, titanium alloy; ZrO_2, zircona.

TABLE 3 Characteristics of the included studies about the Research Question 2: "Manufacturing workflow for surgical implant guides."

Authors (year)	Study design	Group of analysis	Sample size	Printer technology	Material	Layer thickness	Angulation to platform	Study outcomes measured
Abduo et al. (2020)	In vitro	3D printing technologies	30	MJP: Projet 3510, 3DSystem	X	32 µm	0°	Trueness (RMS) Precision (SD)
				FFF: Zortrax M20, Zortrax	X	50 µm	0°	
Kim et al. (2020)	In vitro	3D printing technologies	12	SLA: Form2, Formlabs	Clear resin, Formlabs	25 µm	X	Trueness (MAD and MRD)
				MJP: Polyjet Objet 500 Connex3, Stratasys	Vero Magnet, Stratasys	32 µm	X	
				MJP: Projet 3510 SD, 3D Systems	VisiJet Crystal, 3D Systems	30 µm	X	
Matta et al. (2017)	In vitro	3D printing technologies	26	SLS: Phidias Technologies, France	Metal	X	X	Sleeve deviation (xyz axes and dxyz)
Mukai et al. (2021)	In vitro	3D printing technologies	20	DLP: Perfactory P4K Life Series, Envision-TEC	EnvisionTEC's E-Guide Tint	X	45°	Trueness: MAD
Oh et al. (2019)	In vitro	3D printing technologies	60	MJP: Objet Eden260VS, Stratasys	MED610, Stratasys	100 µm	X	Seating accuracy Sleeve linear deviation
				DLP: D1, Veltz	NextDent SG, Nextdent	100 µm	X	
				SLA: Form 2, Formlabs	Dental SG, Formlabs	100 µm	X	
				DLP: OneJetm Osstem	Dentrial S 2, DIC	100 µm	X	
				DLP: Perfactory Micro Advantage, EnvisionTEC	Dentrial S 2, DIC	100 µm	X	
				SLA: Zenith U, Dentis	ZMD-100 B Clear SG, Dentis	100 µm	X	
Reyes et al. (2015)	In vitro	3D printing technologies	80	SLA: VipeN12, 3D Systems	Somos Watershed XC11122, Somos Manufacturer	X	X	Seating accuracy
				MJP: Objet Eden 260 V, Stratasys	MED610, Stratasys	X	X	
Rouzé l'Alzit et al. (2022)	In vitro	3D printing technologies	72	SLA: Form2, Formlabs	Dental SG, Formlabs	X	15°	Trueness (RMS) Precision (SD)
				DLP: Rapidshape D40, Rapidshape	Sheraprint SG 100, SHERA	X	0°	
				DLP: Caraprint 4.0	Dima Print Guide, Kulzer	X	0°	
				SLS: Prodways P1000, Prodways	Polyamide powder PA12-L 1600	X	0°	
				MJP: Stratasys J750, Stratays	Vero WhitePlus, Stratasys	X	X	
				FDM: Raise 3D Pro2	Premium PLA filament, Raise 3D technologies	X	60°	

(Continues)

TABLE 3 (Continued)

Authors (year)	Study design	Group of analysis	Sample size	Printer technology	Material	Layer thickness	Angulation to platform	Study outcomes measured
Sommacal et al. (2018)	In vitro	3D printing technologies	16	FFF: Replicator 5th Generation 3D printer, MakerBot	MakerBot True white PLA filament, MakerBot	100 µm	X	Trueness (MAD and MRD)
				DLP: Perfactory 4 DLP DDP4 M, EnvisionTEC	Perfactory EnvisionTEC Clear Guide, EnvisionTEC	100 µm	X	
Wegmüller et al. (2021)	In vitro	Evaluation of 3D printing technologies	40	MJP: Objet 30 Prime, Stratasys	MED610 & SUP760, Stratasys	28 µm	X	Trueness (RMS) Precision (SD)
				SLA: Formlabs 3, Formlabs	Dental SG, Formlabs	50 µm	30–45°	
				FFF: Ultimaker 3 Extended, Ultimaker	Nylon 680 ProFill PVA	100 µm	X	
				DLP: Wanhao Duplicator 7 Plus, Wanhao	Freeprint Ortho 405, Detax	50 µm	30–45°	
Dalal et al. (2020)	In vitro	Evaluation of different printing parameters	60	SLA: Form 2, Formlabs	Dental SG, Formlabs	50 vs. 100 µm	0° 45° 90°	Linear discrepancies of the intaglio Sleeve angular discrepancies
Tahir et al. (2022)	In vitro	Evaluation of different printing parameters	30	DLP: MoonRay S, SprintRay	SP-RG1001, SprintRay	20 µm	0° 45° 90°	Trueness (RMS) Seating accuracy
Unkovskiy et al. (2018)	In vitro	Evaluation of different printing parameters	30	SLA: Form 2, Formlabs	Dental SG, Formlabs	50 µm	0° 45° 90°	Accuracy (linear mean difference) Flexural strength Flexural modulus
Ammoun et al. (2021)	In vitro	Evaluation of the post-processing and sterilization methods	20	SLA: Form 2, Formlabs	Dental SG, Formlabs	X	45°	Trueness (average+ and average −)
Chen et al. (2019)	In vitro	Evaluation of the post-processing and sterilization methods	30	SLA: Form 2, Formlabs	Dental SG, Formlabs	X	X	Trueness (RMS) Precision (SD)
				MJP: Objet Eden, Stratasys 260VS	MED 610, Stratasys	X	X	
				DMP: ProX DMP 200, 3D Systems	Laser Form Cr-Co., 3D Systems	X	X	
Marei et al. (2019)	In vitro	Evaluation of the post-processing and sterilization methods	27	SLA: Form 2, Formlabs	Dental SG, Formlabs	X	X	Sleeve deviation (xyz axes and dxyz)
De Moraes et al. (2022)	In vitro	Evaluation of the post-processing and sterilization methods	20	SLH-C 9100, RenShape	X	X	X	Accuracy (linear measurements)

TABLE 3 (Continued)

Authors (year)	Study design	Group of analysis	Sample size	Printer technology	Material	Layer thickness	Angulation to platform	Study outcomes measured
Sharma et al. (2020)	In vitro	Evaluation of the post-processing and sterilization methods	X	MJP: Objet 30 Prime, Stratasys	MED610, Stratasys (Polyjet) and SUP705, Stratasys (Polyjet)	X	X	Trueness (RMS) Precision (SD)
				SLA: Form2, Formlabs	Dental LT Clear, Formlabs LuxaPrint Ortho Plus, DMG Ortho Clear, Nextdent	X	45°	
Török et al. (2020)	In vitro	Evaluation of the post-processing and sterilization methods	15	MJP: Objet Eden 350 V, Stratasys	Objet MED 610, Stratasys	X	X	Sleeve deviation (linear measurements) Hardness measurement Flexural strength Compressive strength

Abbreviations: DLP, digital light processing printer; DMP, direct metal printing; FFF, fused filament fabrication; MAD, mean absolute difference; MJP, MultiJet printer; MRD, mean relative difference; RMS, Root mean squared 3D comparison; SD, standard deviation; SLA, stereolithography printer; SLS, selective laser sintering; μm, Microns.

reported were the material, the layer thickness, and angulation to the printing platform.

3.3 | RQ3: "In 3D printing, what is the current status in the technology used, the materials available, and related factors for making implant-supported prosthesis?"

The RQ3 included 32 studies published between 2016 and 2022 and focused either in additive manufactured metallic primary frameworks (*n* = 9), 3D printed implant-supported secondary superstructures (*n* = 9), or 3D printed implant analog models (*n* = 12). No randomized control trials (RCTs) were identified to explore the RQ3.

Regarding the additive manufactured metallic primary frameworks, five in vitro studies (Alenezi et al., 2022; AlRasheed & AlWazzan, 2022; Barbin et al., 2020; Presotto et al., 2019; Velôso et al., 2022), two narrative reviews (Revilla-León et al., 2019, 2020), and one systematic review were analyzed (Papadiochou & Pissiotis, 2018; Table 4 and Figure 7). The AM technologies applied were selective laser melting (SLM) in five in vitro studies (Alenezi et al., 2022; AlRasheed & AlWazzan, 2022; Barbin et al., 2020; Presotto et al., 2019; Velôso et al., 2022) and electron beam melting (EBM) in two in vitro studies (Barbin et al., 2020; Velôso et al., 2022). The Ti-6-Al-4-V alloy powder were used in two studies (Alenezi et al., 2022; AlRasheed & AlWazzan, 2022; Presotto et al., 2019) and the Co-Cr alloy in three studies (Barbin et al., 2020; Velôso et al., 2022). All the in vitro studies manufactured full-arch frameworks with one exception (Presotto et al., 2019).

The reviewed evidence for 3D printed secondary superstructures was analyzed with seven in vitro studies (Donmez & Okutan, 2022; Mohajeri et al., 2021; Papaspyridakos et al., 2023; Park et al., 2016, 2019; Zandinejad et al., 2019, 2021), one narrative review (Revilla-León et al., 2020), and one systematic review (Rutkūnas et al., 2022; Table 5 and Figure 8). The marginal adaptation and fracture resistance compared to milled or layered control groups were studied, not the final shape of the printed object comparing different printing parameters. Three studies manufactured the prostheses with SLA printers (Papaspyridakos et al., 2023; Zandinejad et al., 2019, 2021), five studies with DLP printers (Donmez & Okutan, 2022; Mohajeri et al., 2021; Papaspyridakos et al., 2023; Park et al., 2016, 2019), and one study with CLIP printer (Papaspyridakos et al., 2023). Five studies evaluated 3D printed temporary or definitive resins (Donmez & Okutan, 2022; Mohajeri et al., 2021; Papaspyridakos et al., 2023; Park et al., 2016, 2019). Two studies evaluated printed zirconia ceramics (Zandinejad et al., 2019, 2021).

The 3D printed implant analog models' evidence was analyzed with 11 in vitro studies (Abdeen et al., 2022; Alshawaf et al., 2018; Banjar et al., 2021; Buda et al., 2018; Jin et al., 2022; Mathey et al., 2021; Morón-Conejo et al., 2022; Olea-Vielba et al., 2020; Papaspyridakos et al., 2020; Revilla-León et al., 2018; Tas et al., 2022; Table 6). There was one narrative review about the topic (Revilla-León et al., 2020). The 3D printing technologies applied to

TABLE 4 Characteristics of the included studies about the implant-supported primary frameworks in the Research Question 3: "Related implant-supported prostheses factors."

Authors (year)	Study design	Sample size	Printer technology	Material	Layer thickness	Study outcomes measure
Alenezi et al. (2022)	In vitro	30	SLM	Co-Cr alloy powder	X	Marginal fit (µm) Passivity and internal gap (µm)
AlRasheed et al. (2022)	In vitro	30	SLM: CONCEPTLASER, Germany	Co-Cr alloy powder: Starbond Easy Powder 30, Scheftner	X	Marginal of fit (µm) in xyz axes
Barbin et al. (2020)	In vitro	15	SLM: MLab Cusing 200R, Concept Laser	Ti-6Al-4V powder: CL 41TI ELI, Concept Laser	25 µm	Marginal fit (µm)
			EBM: Arcam Q10plus, Arcam EBM, Ge Additive Company	Ti-6Al-4V powder: Arcam Titanium Ti6Al4V, Arcam	50 µm	
Presotto et al. (2019)	In vitro	30	SLM: Mlab Cusing 200R; Concept Laser	Powdered Co-Cr alloy: Remanium Star CL.	25 µm	Marginal fit (µm)
Velôso et al. (2022)	In vitro	15	SLM: 3D printing; MLab Cusing 200R, GE Additive	Powder Ti6Al4V	25 µm	Marginal fit (µm) Screw-loosening torque (Ncm) Strain (µstrain)
			EBM: Arcam Q10plus, GE Additive	Powder Ti6Al4V	50 µm	

Abbreviations: Co-Cr, cobalt chromium alloy; EBM, electron beam melting; FDP, fixed dental prosthesis; SLM, Selective laser melting; Ti-6Al-4 V, titanium valladium alloy; µm, microns.

manufacture implant analog models were MultiJet, SLA, DLP, and CLIP. The 3D printing parameters reported in the studies were the layer thickness, the angulation to the printing platform, and the characteristics of the printing cast base.

4 | DISCUSSION

This scoping review identified studies that investigated the main application and impact of 3D printing technology in dental implantology. In order to make our review more feasible, studies analyzing different parameters and applications of 3D printing were divided into three knowledge areas: (1) "customized dental implants," (2) "manufacturing workflow for surgical implant guides," and (3) "related implant-supported prostheses factors."

4.1 | RQ1: 3D Printing technologies, materials, and characteristics of the 3D printed customized dental implants

The manufacture of customized dental implants with special geometric characteristics is an indication for the use of AM technology, saving time, costs, and material (Oliveira & Reis, 2019).

The metallic implants obtained from AM are porous structures and have excellent mechanical properties, including high fracture resistance. This porosity positively influences the transmission of forces in the bone, due to its lower rigidity, as well as at the level of osseointegration (Chang Tu et al., 2020; Ren et al., 2021; Tunchel et al., 2016). Metallic implants are manufactured using SLA or EBM technology and no significant differences have been reported in the literature between these two techniques, at the level of the generated surface and the peri-implant bone growth capacity (Oliveira & Reis, 2019). Tedesco et al. (2017) demonstrated that implants made with 3D printing integrated better and faster than conventional implants in the first 12 weeks. Traditional implants had better mechanical integration, but 3D printed ones favored the growth of trabeculated bone around them (Tedesco et al., 2017). The same results were obtained by Chang Tu et al. (2020) studying a new implant design (Bio-ActiveTRI dental implant). There are few in vivo studies on humans that study the survival of this type of implant. Tunchel et al. (2016) followed up 3 years of 110 implants in 82 patients. Survival was 94.5% at 3 years. Considering these results, they concluded that the AM implants were a successful option for the rehabilitation of single implants. Therefore, more studies are needed to evaluate this option, especially in the longer term (Tunchel et al., 2016).

One of the best applications of this technology is the creation of customized dental implants for each patient based on a 3D radiological study. Starting from a tomographic study, implants can be generated with the same anatomy as the roots that are going to be extracted in patients, implanting the titanium replica of the tooth in the same surgical act. The accuracy of this process was studied

TABLE 5 Characteristics of the included studies about the implant-supported secondary superstructures in the Research Question 3: "Related implant-supported prostheses factors."

Authors (year)	Study design	Sample size	Type of superstructure	Printer and technology	Resin	Layer thickness	Angulation to platform	Study outcomes measured
Donmez et al. (2022)	In vitro	40	Definitive resin single crowns.	DLP: Max UV, ASIGA	Saremco Print Crowntec (SP)	50 µm	X	Marginal fit (µm) Fracture resistance (N)
Park et al. (2019)	In vitro	100	Definitive resin three-unit resin dental prosthesis with two implants.	DLP: D2-120, Hephzibah	NextDent C&B, Nextdent	50 vs. 100 µm	0° (supports perpendicular to the occlusal surface) 30° 45° 60° 90° (supports perpendicular to the lingual surface)	Marginal and internal fit (µm)
Mohajeri et al. (2021)	In vitro	32	Temporary resin single crowns	DLP: Prodent Labx, Tabriz	Freeprint Temp UV, Detax	X	X	Marginal fit (µm)
Papaspyridakos et al. (2023)	In vitro	90	Temporary resin full-arch prosthesis with four implants	DLP: Sprintray Pro 95, Sprintray SLA: Form 3b+, Formlabs CLIP: M2 Carbon 3D, Carbon	X X X	50 µm 50 µm 50 µm	X X X	Passivity (screw-resistance test)
Park et al. (2016)	In vitro	120	Temporary resin single crowns and two-unit prosthesis.	DLP: Perfactory PixCera, Envisiontec	E-Dent, Envision TEC	50 µm	X	Marginal and internal fit (µm)
Zandinejad et al. (2019)	In vitro	30	Definitive ceramic crown.	SLA: CeraMaker 900, 3D Ceram Co.	Ceramic powder: 3D Mix ZrO2 paste, 3D Ceram Co.	X	X	Fracture resistance (N)
Zandinejad et al. (2021)	In vitro	20	Definitive ceramic crown	SLA: CeraMaker 900, 3D Ceram Co.	3D Mix ZrO2 paste, 3D Ceram Co. (Zr with yttria) 3D Mix ATZ paste, 3D Ceram Co. (Alumina 20%, Zirconia 80%)	X	X	Fracture resistance (N)

Abbreviations: CLIP, continuous liquid interface printer; DLP, digital light processing printer; MJP, MultiJet printer; SLA, stereolithography printer; µm, Microns.

TABLE 6 Characteristics of the included studies about the 3D printed implant analog models in the Research Question 3: "Related implant-supported prostheses factors."

Authors (year)	Study design	Sample size	Printer technology and layer thickness	Material	Layer thickness (μm)	Angulation to platform	Study outcomes measured
Abdeen et al. (2022)	In vitro	50	DLP: Straumann P30+ printer, Straumann AG	P-Pro Master Model, Straumann	50	X	Trueness (RMS) Precision (SD)
			DLP: Varseo S printer, BEGO	Varseo Wax Model, BEGO	100	X	
			SLA: Form 3b, Formlabs	Dental Model V2, Formlabs	100	X	
			CLIP: M2 Carbon 3D printer (Carbon, USA)	DPR10, Carbon	100	X	
Alshawaf et al. (2018)	In vitro	30	SLA: Varseo 3D printing system, BEGO	X	25	X	Trueness (RMS) Precision (SD)
Banjar et al. (2021)	In vitro	30	DLP: Varseo S, Varseo 3D, BEGO	X	100	45°	Trueness (RMS) Precision (SD)
			SLA: Form 2, Formlabs	X	100	45°	
Buda et al. (2018)	In vitro	20	MJP: Objet500, Stratasys	X	16	X	Trueness and precision (linear measurements)
			SLA: Form 2, Formlabs	X	50	X	
Jin et al. (2022)	In vitro	96	DLP/LCD: Phrozen Shuffle, Phrozen Printing cast base: hollow or solid	NextDent model, Nextdent	50 vs. 100	X	Trueness (RMS) Precision (SD) Implant angular distortion (°) Implant depth distortion (μm)
Mathey et al. (2021)	In vitro	20	DLP: CARES P-Series P30	SHERA model plus UV grey, SHERAprint	X	X	Trueness Precision 3D Vector analysis (xyz axes)
Morón-Conejo et al. (2022)	In vitro	225	MJP: Project MJP 2500, 3D system Printing cast base: hollow	Visijet	32	0°	Trueness (RMS) Precision (SD) 3D Vector analysis (xyz axes)
			MJP: Objet 30 Orthodesk, Object Printing cast base: hollow	Support SUP750	30	0°	
			DLP: NextDent 5100, NextDent Printing cast base: hollow	Model 2.0 Peach	50	0°	
			DLP: Rapidshape D30, Rapidshape Printing cast base: hollow	Model 2.0 Peach	50	0°	
			SLA: Form2, Formlabs Printing cast base: hollow	Dental Model Peach	25	0°	

TABLE 6 (Continued)

Authors (year)	Study design	Sample size	Printer technology and layer thickness	Material	Layer thickness (μm)	Angulation to platform	Study outcomes measured
Olea-Vielba et al. (2020)	In vitro	20	MJP: Project MJP 2500 Plus, 3Dsystem	Visijet M2R-TN; 3D systems	32	0°	Angular distortion (xzy axes) Trueness (MAD) Precision (IQR)
Papaspyridakos et al. (2020)	In vitro	25	SLA: Form 2, Formlabs	Dental Model Resins, Formlabs	25	X	Trueness (RMS) Precision (SD)
Revilla-León et al. (2018)	In vitro	20	MJP: Projet 3510 MP, 3D system.	X	35	X	Mean distortion of the position of the implant analogs (μm)
			MJP: Stratasys, Eden.	X	35	X	
			DLP: Prodways ProMaker D35, Dreve	X	50	X	
			SLA: Infinident, Sirona	X	50–100	X	
Tas et al. (2022)	In vitro	60	DLP/LCD: Accuretta Freeshape 120, Accuretta	MACK 4D Model Resin	70	X	Mean distortion of the position of the implants (μm)

Abbreviations: CLIP, continuous liquid interface printer; DLP, digital light processing printer; IQR, inter quartile range; LCD, liquid crystal display; MAD, mean absolute deviation; Microns (μm); MultiJet printer (MJP); RMS, Root mean square; SD, standard deviation; SLA, stereolithography printer.

by Liu et al. (2021), replicating the shape of a monkey maxillary incisor in a titanium alloy through SLA technology and showed a relatively high level of accuracy of 90.59 ± 4.75 μm (Liu et al., 2022). The high manufacturing dimensional accuracy compared to the control is referenced in several studies, without finding significant differences between different 3D printing technologies like SLM or EBM technologies (Oliveira & Reis, 2019). In addition to anterior implants, new designs for the replacement of posterior teeth have also been studied. Lee et al. (2022) proposed the use of multi-root implants generated from 3D printing with two designs: solid implants and trabeculated implants. They concluded that using multi-root implants better primary stability was obtained, as well as better results with trabeculated implants, since they favored bone growth (Lee et al., 2022).

The porous surface is clearly an important factor for osseointegration. Even though with AM technologies it is achieved naturally, some studies have tried to improve this surface. Ren et al. (2021) tried to improve the surface of 3D printed titanium implants using EBM technology by acid etching and anodizing. The hierarchical micro- or nanostructure obtained improved the hydrophilicity and biological activity of the material. In vitro cell culture experiments and in vivo experiments showed that cell activity and bone formation around modified implants was statistically significantly higher when compared to the same untreated implants (Ren et al., 2021).

In addition to titanium alloys, other materials are being used for the AM of implants. Zirconia printed using DLP technology is a material that is becoming very important in current restorative dentistry. In implantology, many efforts have been made to introduce ceramic implants into daily practice, but they are not as widespread as titanium ones. Osman et al. (2017) carried out a study of implants printed in zirconia, studying the dimensional accuracy, the topography of the surface, as well as its mechanical properties according to the manufacturing angle. Regarding the manufacturing accuracy with respect to the design, it was found that average deviation was 0.089 ± 0.068 μm, homogenously distributed along the length of the printed implant (Osman et al., 2017). These variations in size are considered acceptable and have been reported in other studies such as the one by Anssari Moin et al. (2017). The surface of the zirconia implants was also studied using a scanning electron microscope (SEM). SEM analysis revealed cracks, micro-porosities and interconnected pores ranging in size from 196 nm to 3.3 μm (Osman et al., 2017). This porous surface has also been reported by other studies, indicating its biological importance (Anssari Moin et al., 2017; Zhang et al., 2022). Zhang et al. (2022) concluded that the porosity of zirconia implants facilitated osteoblast morphogenesis, favoring metabolic activity and cell proliferation around 3D printed zirconia implants. In addition to the biological properties, this study concluded that the porous surface increases the fracture resistance of printed implants, when compared to conventional ceramic implants (Zhang et al., 2022). Similar data were reported by Osman et al. (2017), who found a flexural strength similar to that of ceramic implants produced with conventional methods. However, this study did find variations in resistance, depending on the way

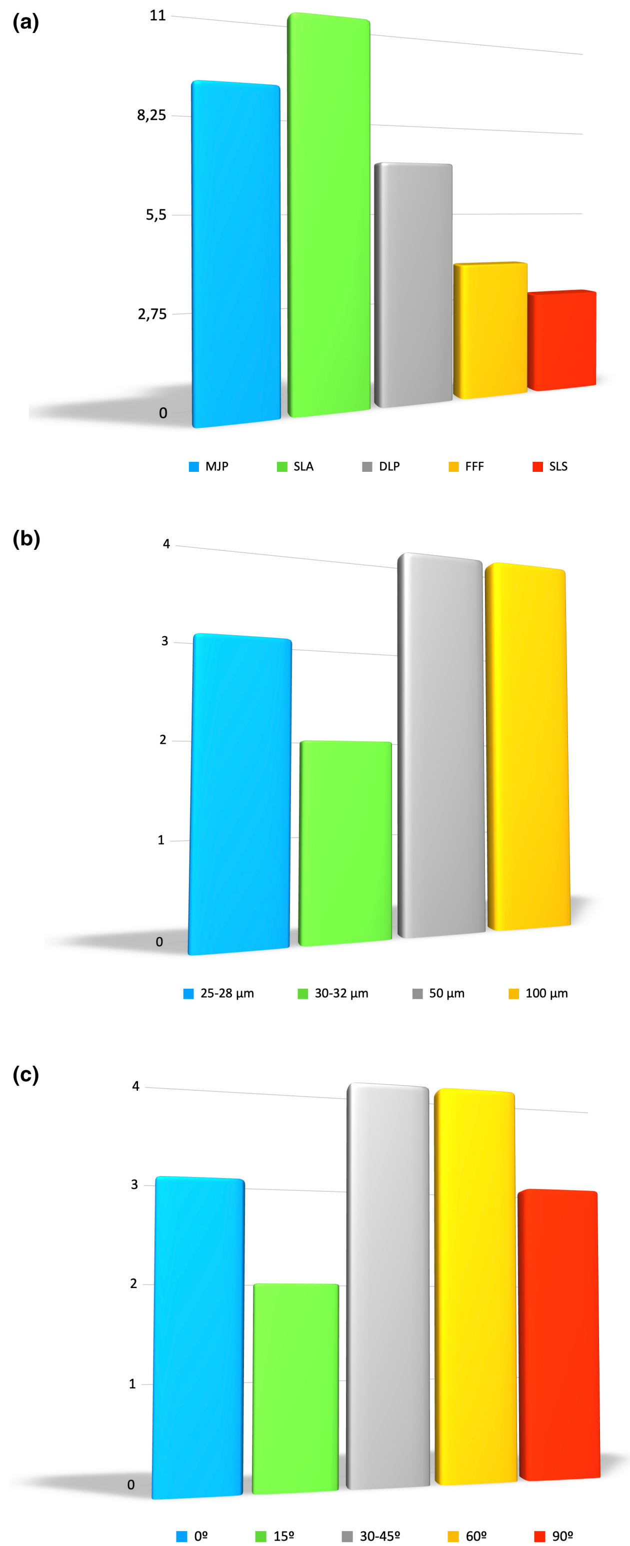

FIGURE 6 Diagram representation of the percentage of the studies regarding the 3D printing manufacturing parameters of surgical implants guides (RQ2): (a) 3D printer technology. (b) Layer thickness. (c) Angulation to building platform.

it was manufactured. The influence of the manufacturing angle to the build platform was investigated. The Weibull analysis revealed a statistically significant higher characteristic strength (1006.6 mPa) of 0° printed specimens compared to the 45° (892.2 mPa) and 90° (866.7 mPa) groups. Further studies are needed to standardize the printing process to achieve the best results in the microstructure of printed objects. This is important because the accumulation of errors during the 3D printing process lead to the collapse of the structure (Oliveira & Reis, 2019).

This line of work is important, since it has been shown that there are multiple factors at the time of manufacture that significantly influence ($p < .05$) the fracture resistance of printed implants (Sonaye et al., 2022). Sonaye et al. (2022) studied the influence of impression speed, layer thickness, and impression temperature on the fracture resistance of implants printed in PEEK. The low printing speed, thin layers, and high temperatures give rise to more resistant structures in a statistically significant way. Furthermore, they demonstrated that 3D printed implants exhibit adequate mechanical durability even after simulated (accelerated) aging of 30 years. Polyetheretherketone proves to be another suitable material for implant 3D printing, being a material that promises good results. In 2022, Han et al. performed an in vitro study on the effect of Argon plasma treatment on the surface of these implants. Plasma treatment significantly improved the surfaces hydrophilicity and changed the surfaces morphology and roughness, improving the cellular response around the implant (Han et al., 2022).

The results obtained by the studies that reviewed 3D printing on customized implants tell us about a promising future, where the advantages of AM technologies can be used in the manufacture of implants with similar results to traditional implants. However, more studies are necessary to be able to standardize the processes and obtain the best possible results. The use of these technologies opens the door to more personalized treatments, with freedom in design, to give patients the best results within our reach.

4.2 | RQ2: 3D Printing technologies, materials, and manufacturing workflow for surgical implant guides

The largest number of studies on the application of 3D printing in implant dentistry focused on the production of surgical implant guides for s-CAIS. One of the factors influencing the accuracy of surgical implant guides is the manufacturing technologies. The milling or subtractive technology was found to be more accurate and less vulnerable to seating distortion than printed guides (Presotto et al., 2019). However, recent studies did not observe differences when comparing new industrial 3D printed and milled surgical implant guides for accuracy evaluation (Mukai et al., 2021). The available 3D printers found in the literature can be divided into industrial printers (MJP, SLS, and DMP technologies) and in-office or desktop printers (SLA, DLP, and FFF technologies). The desktop printers, with a smaller size and cost, have increased their presence in dental clinics and laboratories. There is a consensus in the majority of the studies that currently the industrial printers tend to provide superior accuracy printing surgical implant guides (Abduo & Lau, 2020; Chen et al., 2019; Kim et al., 2020; Oh et al., 2019; Reyes et al., 2015;

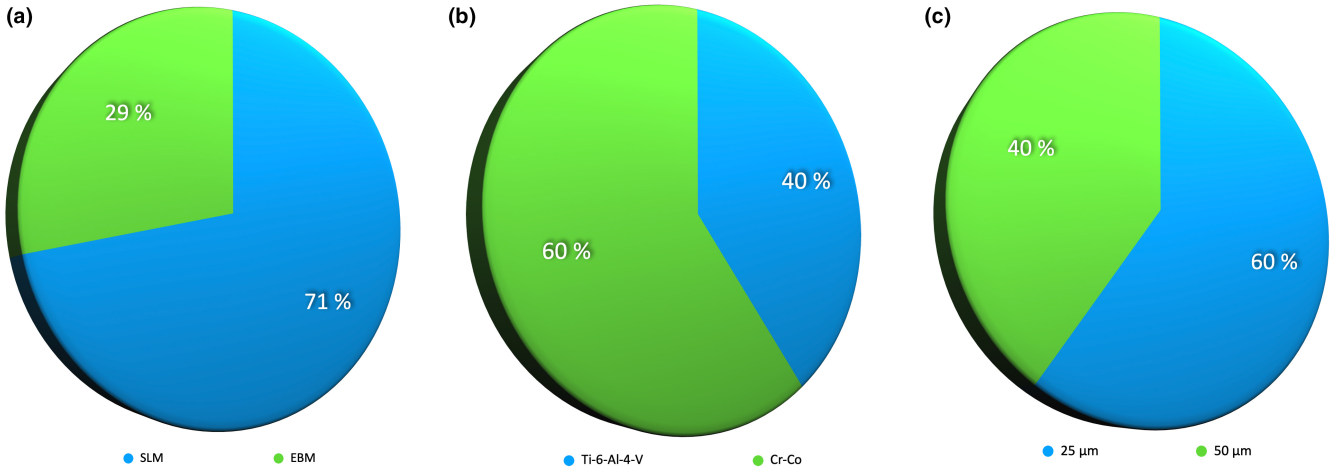

FIGURE 7 Diagram representation of the percentage of the studies regarding the 3D printing manufacturing parameters of the metallic primary structures (RQ3): (a) 3D printer technology. (b) Metallic alloy powder. (c) Layer thickness.

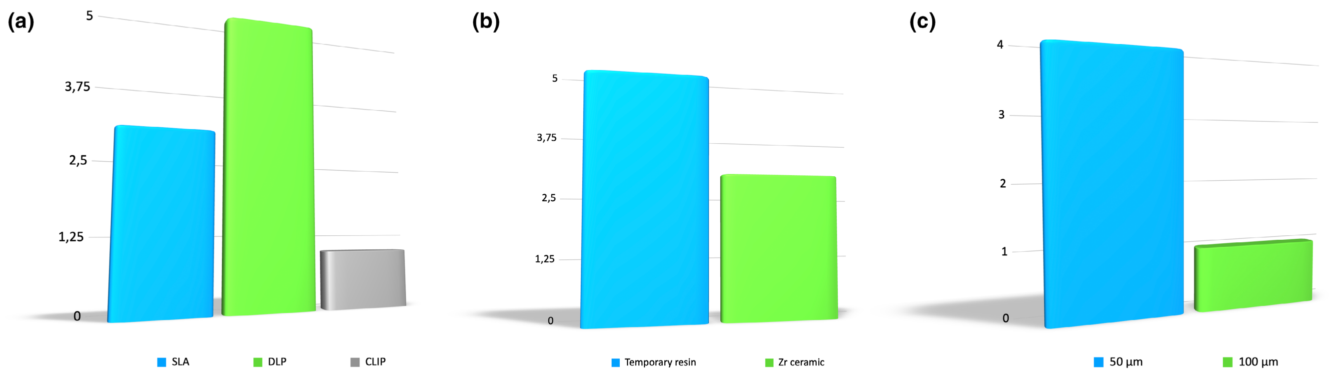

FIGURE 8 Diagram representation of the percentage of the studies regarding the 3D printing manufacturing parameters of the secondary superstructures (RQ3): (a) 3D printer technology. (b) Material. (c) Layer thickness.

Wegmüller et al., 2021). However, some authors concluded that SLA and DLP desktop printers are accurate enough for clinical applications (Kim et al., 2020; Rouzé l'Alzit et al., 2022; Wegmüller et al., 2021). The same does not apply for FFF printers, the least accurate technology (Abduo & Lau, 2020; Rouzé l'Alzit et al., 2022; Sommacal et al., 2018). Sommacal et al. (2018) even concluded that the FFF technology was not suitable for the fabrication of surgical implant guides.

Different printing parameters have also been evaluated regarding the surgical implant guides accuracy. Some authors analyzed the layer thickness (Dalal et al., 2020) and orientation of the guides in the building platform of the printer (Dalal et al., 2020; Tahir & Abduo, 2022; Unkovskiy et al., 2018). Dalal et al. (2020) evaluated an SLA printer and concluded that a 50-µm layer thickness was shown to provide better guide dimension than 100 µm layer thickness for surgical implant guides. The angulation and position to the build platform seem to have an influence on the accuracy of the surgical implant guide. Unkovskiy et al. (2018) assessed the influence of print orientation and positioning of the build platform on the dimensional accuracy of SLA-printed objects. Just as Dalal et al. (2020), they concluded that angulating the object 45° to the build platform may allow more accurate dimension reproduction (Unkovskiy et al., 2018). Tahir and Abduo (2022) also evaluated the effect of different orientations of printing on the accuracy, but with a DLP printer. The surgical implant guides printed horizontally consistently exhibited better internal and seating accuracy, followed by guides printed at a 45° angle and vertically respectively. The recommendation extracted from different authors is to print the guides with the largest dimension to the printing platform where the object showed a superior ability to support the axial load of the printing building process due to the greatest amount of support structures and reduced number of 3D printing increments. The orientation also seemed to influence the mechanical properties, however the surgical implant guide is used a single time so the most important variable is the dimensional accuracy (Tahir & Abduo, 2022; Unkovskiy et al., 2018).

Another step of the manufacturing process is the post-processing procedures involving mechanical structure removal, cleaning, and post-polymerization depending on the technology employed and the manufacturer recommendations. The cleaning procedures with alcohol or chemical ultrasonic baths or agitation procedures removed the unpolymerized resin from the surface of the printed object. This step is followed by a light or/and heat post-polymerization of the material to obtain the optimal mechanical properties. Ammoun et al. (2021) evaluated the effects of two post-processing methods in terms of the overall and intaglio surface dimension of a desktop SLA printer. The automated method recommended by the manufacturer presented more negative discrepancies after 15 min in isopropanol and 30 min at 60°C of photopolymerization compared to an alternative method of ultrasonic bath of 10 min and doubling to 60 min at 60°C the photopolymerization. In any case, both post-processing methods appeared to be clinically acceptable (Ammoun et al., 2021).

The resins used for surgical implant guides needs to be biocompatible (ISO Standard 10,993 for Biological Evaluation for Medical Devices), suitable for sterilization and translucent to improve the visibility during the procedure (ISO 10993, 2009). A surgical guide that is not appropriately sterilized can lead to infection in the osteotomy site (Elliott et al., 2022). Different studies have evaluated the effect of different procedures as autoclave steam heat, plasma, and chemical sterilization in the dimensional accuracy of the guides. There is no consensus among the authors regarding the dimensional changes of the guides after autoclave steam heat sterilization. De Moraes et al. (2022) and Sharma et al. (2020) found a linear expansion of the surgical guide. In contrast, the groups of Marei et al. (2019) and Török et al. (2020) did not found significant effect on the dimensional accuracy. Török et al. (2020) also evaluated the plasma sterilization with no significant deformation or damage in the guides. De Moraes et al. (2022) found dimensional changes in the physical sterilization by autoclave and proposed the chemical sterilization by glutaraldehyde 2% that did not cause any dimensional alteration.

3D printing is a manufacturing technology that continues to evolve and achieves an accuracy similar to subtractive milling technologies for the fabrication of surgical implant guides. It seems most appropriate to use a thinner layer thickness and to orient the guides with the largest dimension parallel or at 45° to the printing platform to allow the greatest amount of support structures. Until a consensus is reached, the manufacturer's recommendations should be followed, since the combination of type of printer, resin, supporting structures, nesting software, and post-processing process are fundamental to obtain surgical implant guides suitable for use in surgery.

4.3 | RQ3: 3D Printing technologies, materials available, and related factors for implant-supported prostheses

The status of AM technologies and materials available for manufacturing primary metallic frameworks, secondary resin or ceramic superstructures, and 3D printed implant analog models were the focus of the RQ3.

3D printing of metal materials in dentistry is mainly applied to the production of *metallic primary frameworks for implant-supported prosthesis*. The 3D printing technologies for metal printing are inside the power bed fusion (PBF) group: selective laser sintering (SLS), SLM, and EBM (Revilla-León et al., 2019). There is consensus that within CAD/CAM technologies the milled full-arch frameworks showed the most accurate marginal fit and biomechanical behavior (Alenezi et al., 2022; AlRasheed & AlWazzan, 2022; Velôso et al., 2022). However, the metallic full-arch implant-supported prostheses manufactured with 3D printing technologies have an acceptable marginal fit in different studies (AlRasheed & AlWazzan, 2022; Presotto et al., 2019; Rutkūnas et al., 2022; Velôso et al., 2022). Presotto et al. (2019) analyzed printed 3-unit fixed partial dentures (FDPs) on implants with better accuracy than milled or cast ones. The metal materials available for 3D printing are the Cr-Co alloy and the Ti-6Al-4V powder that can be used with SLM and EBM with similar discrepancies (Barbin et al., 2020; Velôso et al., 2022). One of the characteristics of 3D printed metal is the surface roughness texture, therefore milling the implant connection is a common procedure to improve the accuracy of the frameworks (Revilla-León et al., 2019; Rutkūnas et al., 2022; Velôso et al., 2022). The structures also need a subsequent ceramic layering to achieve aesthetic and the anatomy, but the process could induce framework accuracy distortions (Velôso et al., 2022). Nevertheless, Barbin et al. (2020) concluded that ceramic veneers did not reduce the biomechanical aspects. The 3D printing of Cr-Co and Ti-7Al-4V metallic frameworks with SLM and EBM can be considered a promising technology in dental rehabilitation.

According to the *3D printed implant-supported secondary superstructures* cemented to an abutment or primary framework, the materials available are composite or resin and ceramics. There is consensus in the literature that the marginal discrepancies of 3D-printed implant-supported resins restorations are within an acceptable clinical range of marginal fit and the results are comparable to the milled restorations (Donmez & Okutan, 2022; Mohajeri et al., 2021; Park et al., 2016, 2019). Donmez and Okutan (2022) analyzed the marginal adaptation of 3D printed crowns with a definitive resin before (33–57.1 μm) and after the cementation (47.1–69 μm) to the abutment. However, the printing parameters such as the orientation and layer thickness must be properly controlled (Donmez & Okutan, 2022; Mohajeri et al., 2021; Park et al., 2019). Orientation is an important parameter as it determines the position of the printing supports and the shape of the layer that could change and affect the degree of polymerization shrinkage of the resin. Another parameter is layer thickness, a smaller layer thickness means a larger number of layers that could lead to an accumulation of error. The interaction of different build orientation and layer thickness to print three-unit FDPs with definitive resin was analyzed by Park et al. (2019). Considering the marginal fit and the internal gap, build orientation of 45° and 60° was recommended and the marginal fit with a 100 μm was similar to that of 50 μm (Park et al., 2019). All the studies analyzed used DLP printing technology to print single crowns and FDPs. 3D printed immediate loading temporary resin full-arch prosthesis was analyzed for the first time in a recent study of Papaspyridakos et al. (2023) comparing different AM technologies. The 3D printer influenced the accuracy of prosthesis fit, with the DLP printer (Sprintray Pro 95, Sprintray) performing inferiorly to CLIP printer (M2 Carbon, Carbon) and SLA printer (Form 3B+, Formlabs; Papaspyridakos et al., 2023). The other materials of recent appearance that are beginning to be analyzed in implant-supported superstructures are the 3D printed ceramics. Nowadays, milling technology for the fabrication of zirconia or lithium disilicate ceramic restorations is currently the most accepted technology in dentistry. However, it presents some limitations as the use of presintered blocks for milling that could undergo dimensional changes after sintering and the use of abrasion tools could introduce microscopic cracks on the ceramic. The group of Zandinejad has recently performed two in vitro studies to evaluate the fracture resistance of AM ceramic crowns cemented on zirconia abutments (Zandinejad et al., 2019, 2021). The SLA printer CeraMaker 900 (3D Ceram Co., France) was used to print a ceramic powder of ZrO2 (3D Mix ZrO2 paste, 3D Ceram Co.) and bi-layered alumina-toughened zirconia (3D Mix ATZ paste, alumina 20% and zirconia 80%, 3D Ceram Co.). In the in vitro studies, all AM zirconia ceramic crowns had a comparable fracture resistance to milled restorations, but no improvement was found with the bi-layered alumina-toughened zirconia crowns (Zandinejad et al., 2019, 2021). 3D printing of ceramics for different applications has a great potential of improvement, however further research is necessary to validate AM technology for the fabrication of restorations in dentistry.

The *3D printed implant analog models* establish the connection between full digital protocols and protocols that are still at least partially analog or conventional. For this reason, having a very accurate 3D printed model with the scan replica correctly placed in the 3D axis of the space is of outmost importance. The printed models obtained with different technologies were compared with the conventional plaster models with retentive implant analogs placed in the dental implant impression. Implant analogs for 3D printed work models are placed or screwed after the final post-production and polymerization of the model (Anssari Moin et al., 2017). 3D printing technology, printing parameters, material used, post-processing protocol, and time of assessment were studied in different studies. According to different technologies, the industrial MJP printers presented better results than the DLP and SLA desktop printers (Morón-Conejo et al., 2022). When compared to conventional plaster models, both MJP and DLP printing systems showed similar accuracy of implant analog position on completely edentulous casts compared to the conventional stone models (Buda et al., 2018; Olea-Vielba et al., 2020; Revilla-León et al., 2018). SLA technology was also analyzed in different studies. Papaspyridakos et al. obtained a mean deviation of 59 μm in 3D printed models generated from complete-arch digital impressions. The deviations were inside the threshold to obtain clinically accurate fit of definitive prosthesis frameworks (Papaspyridakos et al., 2020). The role played by different printing parameters were analyzed in the study of Jin et al. (2022) with a DLP printer and determined that a hollow inner cast base and a layer thickness of 100 μm maximized the accuracy of the implant analog final position. Abdeen et al. (2022), Mathey et al. (2021), and Tas et al. (2022) reported that the full digital workflow, with digital implant impressions and 3D printed implant analog models, showed statistically significantly lower 3D deviations than plaster models generated from conventional implant impressions. Abdeen et al. (2022) printed solid implant model bases instead of hollow bases, also with 100 μm layer thickness, with a CLIP printer (M2 Carbon), a SLA printer (Form 3b, Formlabs), and a DLP printer (Varseo S, BEGO). Therefore, the digital workflow may achieve favorable results with better cost–benefit ratio and is time efficient, but the evidence comparing the clinical benefits with the conventional non-digitized workflow is limited.

The present scoping review presented some potential limitations and caution is required before interpreting the main findings. Most of the included studies were in vitro, indicating a general lack of high-quality evidence in this field of research. The review has focused on those studies evaluating printing technology and parameters, which may have left out of the analysis information in other studies evaluating other clinical parameters. The analysis was limited to English language journal articles and was not extended to wider literature including reports, dissertations, and theses. Despite a strict methodology, some potentially eligible studies may have been overlooked or not included because of the authors' choice of keywords and terms. Taking all of this into account, almost all of the most important and relevant peer-reviewed studies for our research question have been included in this scoping review.

5 | CONCLUSIONS

This review identifies and maps the scientific evidence on three important aspects of 3D printing technology in implant dentistry:

1. Regarding the manufacturing of individualized titanium and zirconia implants using EBM and stereolithography (SLA) technologies, they show similar behavior in terms of osseointegration, survival rate, and mechanical properties. However, publications in this field are still scarce, and manufacturing protocols are not standardized.
2. It is evident that strict adherence to the instructions provided by each printer and material manufacturer is crucial in the workflow of printing implant surgical guides. The use of industrial MJP printers is recommended over SLA and DLP printers, though the latter are reliable enough, especially when printing at 50 microns and with their major axis parallel to the build platform. Finally, there is no consensus among the different consulted authors regarding the dimensional variation of printed surgical stents when subjected to autoclave sterilization.
3. The quality of 3D printed primary frameworks and secondary superstructures is improving remarkably, especially on metallic alloy manufactured with SLM and EBM techniques. However, CAD/CAM milling technology for both metals and ceramics, such as zirconia, still achieves better results in terms of marginal fit and mechanical properties. The 3D printed implant analog models are equally reliable as the plaster ones.

AUTHOR CONTRIBUTIONS

Guillermo Pradíes and Francisco Martínez-Rus conceived the ideas, Belén Morón-Conejo and María Paz Salido led and checked the bibliographic search, Belén Morón-Conejo and Santiago Berrendero selected the articles and analyzed the data, and Guillermo Pradíes and Belén Morón-Conejo led the writing.

CONFLICT OF INTEREST STATEMENT

This scoping review was self-funded. The authors report no conflicts of interest related to this study.

DATA AVAILABILITY STATEMENT

None.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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