

## Review

# Three-Dimensional Printing in Dentistry: A Scoping Review of Clinical Applications, Advantages, and Current Limitations

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**Abstract:** Three-dimensional (3D) printing is transforming dentistry by enabling precise and personalized treatments in prosthodontics, orthodontics, and endodontics. However, challenges such as high costs, material limitations, and post-processing requirements hinder its broader adoption. This scoping review aims to explore and map the breadth of evidence regarding the clinical applications, benefits, and limitations of 3D printing in these disciplines, while identifying research gaps and future opportunities. A scoping review was conducted following the PRISMA for scoping reviews framework. Research from PubMed, Google Scholar, and Scopus was systematically searched, covering studies from January 2006 to November 2024. Key topics included applications, material properties, and technological challenges in prosthodontics, orthodontics, and endodontics. Results: In prosthodontics, 3D printing facilitates the fabrication of crowns, bridges, and dentures with high accuracy, though material strength and stability remain challenges. Orthodontics benefits from 3D-printed aligners and diagnostic models, improving patient comfort and treatment precision, but issues with material durability persist. In endodontics, 3D-printed surgical guides and training models enhance procedural accuracy and educational outcomes. Across disciplines, 3D printing reduces production time and enhances customization but incurs high costs and requires significant post-processing. This scoping review highlights the transformative potential of 3D printing in dentistry, providing an overview of current and future advancements and limitations. While 3D printing has improved precision, efficiency, and patient satisfaction, material and cost-related barriers remain. Future research should address these challenges to expand its clinical applicability and enhance personalized dental care.

**Keywords:** three-dimensional printing; 3D printing; dental prosthodontics; 3D-printed aligners; 3D-printed guide; 3D-printed dental implants



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## 1. Introduction

Recent advancements in 3D printing technology within the dentistry field have catalyzed transformative innovations across a wide range of treatment methodologies [1]. In particular, the integration of 3D printing in prosthodontics, orthodontics, and endodontics has significantly enhanced the precision and efficiency of treatments [2–4]. Three-dimensional printing offers numerous advantages clinically, including increased patient

satisfaction and reduced production time [5]. Consequently, there is an increasing necessity for more comprehensive analysis in research on the clinical applications of 3D printing technology. The rapid adoption of 3D printing technology in the dental and medical fields has led to growing interest in both user experience and sustainability. A recent survey-based study indicated that accuracy, affordability, and professional recommendations are primary criteria influencing the adoption of 3D printing among dentists, dental technicians, and CAD/CAM experts [6]. These findings underscore the importance of developing reliable and cost-effective 3D printing solutions tailored to clinical needs.

Three-dimensional printing technology is emerging as an innovative approach that provides customized solutions in the field of dentistry [7]. Traditional dental treatments have limitations in offering patient-specific, optimized care due to various constraints [8]. However, the advancement of digital technology alongside 3D printing opens up possibilities to overcome these limitations.

Traditional methods often involve extended production times for prosthetics or orthodontic appliances, which may result in prolonged discomfort for patients [1]. Patients may need multiple visits to complete the desired treatment, further compounding their discomfort. Additionally, prosthetics produced manually by technicians tend to increase overall treatment costs due to labor and production expenses, potentially limiting accessibility for some patients [2]. Enhancing patient satisfaction and achieving rapid prosthetic rehabilitation at a reduced cost require careful consideration of various factors during the preoperative planning phase. Thorough treatment planning significantly contributes to the success and survival rates of prosthetic rehabilitation following dental implant treatment [9,10]. Notably, the use of digital planning prior to immediate implant placement after surgical extraction facilitates the precise fabrication of surgical guides through 3D printing techniques [11]. This approach not only shortens the surgical duration but also minimizes patient discomfort and enhances aesthetic outcomes, thereby promoting overall procedural efficiency and clinical success. Three-dimensional printing technology enables personalized treatment by generating precisely designed prosthetics or orthodontic devices tailored to the patient's tooth and periodontal tissue [7]. This contributes to maximizing treatment outcomes. Through 3D printing, digital scan-based modeling and manufacturing are achieved, minimizing human error and significantly reducing production time [5]. Such precision can directly enhance patient safety and treatment effectiveness.

Various 3D-printable materials play a crucial role in enhancing the durability and biocompatibility of dental appliances [12–14]. For instance, prosthetics made with recent innovations in biocompatible metals or high-performance polymers have been effectively developed, contributing to improved treatment outcomes by minimizing contaminants.

Three-dimensional printing has the potential to simplify and automate production processes, reducing labor and material costs, which can greatly enhance the efficiency of dental practice operations [15]. Cost reduction in treatments directly affecting patients is a crucial factor in improving dental treatment accessibility.

Despite these advantages, 3D printing technology faces several challenges, such as the cost of technical equipment, maintenance expenses, and surface finishing techniques [16]. Firstly, the initial purchase cost of 3D printers is considerably high [17,18]. Moreover, maintenance and material costs add to the expense. This makes it challenging for privately owned dental practices to adopt this technology. Secondly, the quality of printed products varies significantly depending on the materials used and the printing technology [12,19]. Although it allows for design, incorrect settings or substandard materials may lead to unsatisfactory results. Furthermore, additional surface finishing steps are often required to improve the quality of the final product [20]. Printed products frequently require post-processing, including surface finishing, minor adjustments, and sterilization, which add

time and effort to the process. Nevertheless, continuous research and technological development should aim to overcome the limitations of 3D printing and enhance personalized treatments. Such research benefits both dentists and patients. This research related to these challenges is essential for the advancement and dissemination of 3D printing technology, providing an important foundation for its broader application in clinical settings.

Three-dimensional printing has rapidly transformed dental practice by offering precise and personalized solutions in prosthodontics, orthodontics, and endodontics. However, existing research often focuses on isolated applications or narrow subfields, leaving a fragmented understanding of the broader landscape. Traditional systematic reviews, while valuable, typically address specific research questions or outcomes and may overlook emerging trends, diverse applications, or interdisciplinary challenges. In contrast, a scoping review provides a flexible and broad approach, making it possible to gather and organize information from various areas of research. This method helps to map out what is currently known, identify gaps where more research is needed, and point to key areas for future studies. By offering a clear and comprehensive picture, this scoping review aims to support both clinical applications and future investigations, giving a better understanding of how 3D printing is being used and evolving in modern dentistry.

The objective of this scoping review is to explore and map the breadth of evidence regarding the clinical applications, advantages, and challenges of 3D printing in dentistry. By synthesizing findings across prosthodontics, orthodontics, and endodontics, this review aims to provide an overview of current advancements, identify gaps in existing knowledge, and highlight opportunities for future research.

## 2. Materials and Methods

### 2.1. Protocol and Search Strategy

This scoping review was conducted following the PRISMA for scoping review guidelines to ensure methodological rigor and transparency. A review protocol was developed prior to the initiation of the study but was not formally registered in an external database. Should the journal or reviewers require access to the protocol, it can be provided upon request. This narrative review examines how 3D printing technology is utilized across the fields of dental prosthodontics, orthodontics, and endodontics. By analyzing recent literature, this study aims to evaluate clinical applications, advantages, material properties, and technical challenges. The study methodology includes identifying relevant research, defining inclusion and exclusion criteria, selecting studies, extracting relevant data, and summarizing the results. The literature search was conducted using major databases such as PubMed, Google Scholar, and Scopus, employing relevant MeSH terms and keywords. The search period covered publications from January 2006 to November 2024. The final search was conducted on 15 November 2024. Common search keywords included “3D printing” or “three-dimensional printing” and “dentistry” or “dental” and “prosthodontics” or “orthodontics” or “endodontics”.

For the field of dental prosthodontics, search keywords were defined as follows: “Prosthodontics”, “3d-printed fixed prosthesis”, “Prosthesis”, “Denture”, “Removable Dental Prostheses”, “Removable Denture”, “3d-printed dentures”, “Complete Denture”, “Dental implants”, and “Crowns and bridges”.

For orthodontics, the keywords included “Orthodontics”, “Dental aligners”, “braces”, “Clear aligners”, “3d-printed dental aligner”, “3d-printed clear aligner”, “mouthguard”, “3d-printed indirect bonding tray”, “3d-printed orthodontic model”, “3d-printed surgical splint”, “Digital orthodontics”, and “Orthodontic treatment”.

For the field of endodontics, search keywords included “Endodontics”, “clinical endodontic applications”, “3d-printed guide”, “endodontic surgical guide”, “guided

endodontic surgery", "3d-guided endodontic surgery", "guided endodontic access", and "guided endodontic autotransplantation". "3d-printed root canal model", "3d-printed model".

## 2.2. Literature Selection and Eligibility Criteria

The literature selection process involved reviewing titles and abstracts to identify studies evaluating the use of 3D printing in dental clinical procedures, encompassing fields such as prosthodontics, orthodontics, and endodontics. For articles meeting the inclusion criteria, a thorough full-text review was conducted. Data extraction was performed independently by two reviewers (MK, JW). In cases of disagreement, the reviewers engaged in discussion to reach a consensus. When necessary, a corresponding reviewer [21] was consulted to make the final decision. The quality of the chosen articles was assessed based on qualitative evaluation criteria, and comparisons were made regarding each study's design, applied technology, and validity of results.

### 2.2.1. Inclusion Criteria

This narrative review included original research studies, systematic reviews, and meta-analyses published in peer-reviewed journals between 2006 and 2024. Only studies focusing on the technique, applications, materials (e.g., polymers, ceramics, biocompatible metals), or limitations of 3D printing in dentistry were considered.

### 2.2.2. Exclusion Criteria

Articles not primarily centered on 3D printing or lacking sufficient methodological detail were excluded. Studies were excluded if they were narrative reviews, not peer-reviewed, lacked sufficient methodological detail, were not published in English, or focused on non-dental applications of 3D printing. Additionally, studies published before 2006 or containing duplicate data were excluded to ensure relevance and quality.

## 2.3. Data Analysis

The data analysis for this narrative review was conducted through a comprehensive examination of the selected literature. The process involved the following steps:

1. **Categorization:** The selected studies were categorized into three main dental specialties: prosthodontics, orthodontics, and endodontics. This classification allowed for a structured analysis of 3D printing applications in each field.
2. **Thematic analysis:** Within each specialty, key themes were identified, including clinical applications of 3D printing, advantages and limitations of 3D printing techniques, comparison with traditional methods, material properties and their impact on outcomes.
3. **Comparative assessment:** Where available, comparative data between 3D printing and other manufacturing methods (e.g., milling, traditional casting) were analyzed. This included accuracy and precision of fabricated products, mechanical properties of materials used, time efficiency in production, and cost-effectiveness.
4. **Technological evaluation:** the analysis included an assessment of different 3D printing technologies used in dentistry, such as stereolithography (SLA) and digital light processing (DLP), focusing on their specific advantages and limitations in dental applications.
5. **Clinical relevance:** the clinical significance of findings from various studies was evaluated, particularly in terms of the applicability and effectiveness of 3D-printed dental products in real-world clinical settings.

6. Quality assessment: the quality of evidence presented in each study was assessed, considering factors such as study design, sample size, and methodological rigor.
7. Synthesis of findings: the analyzed data were synthesized to form comprehensive conclusions about the current state and future potential of 3D printing in dentistry, highlighting both its promising aspects and areas needing further research and development.

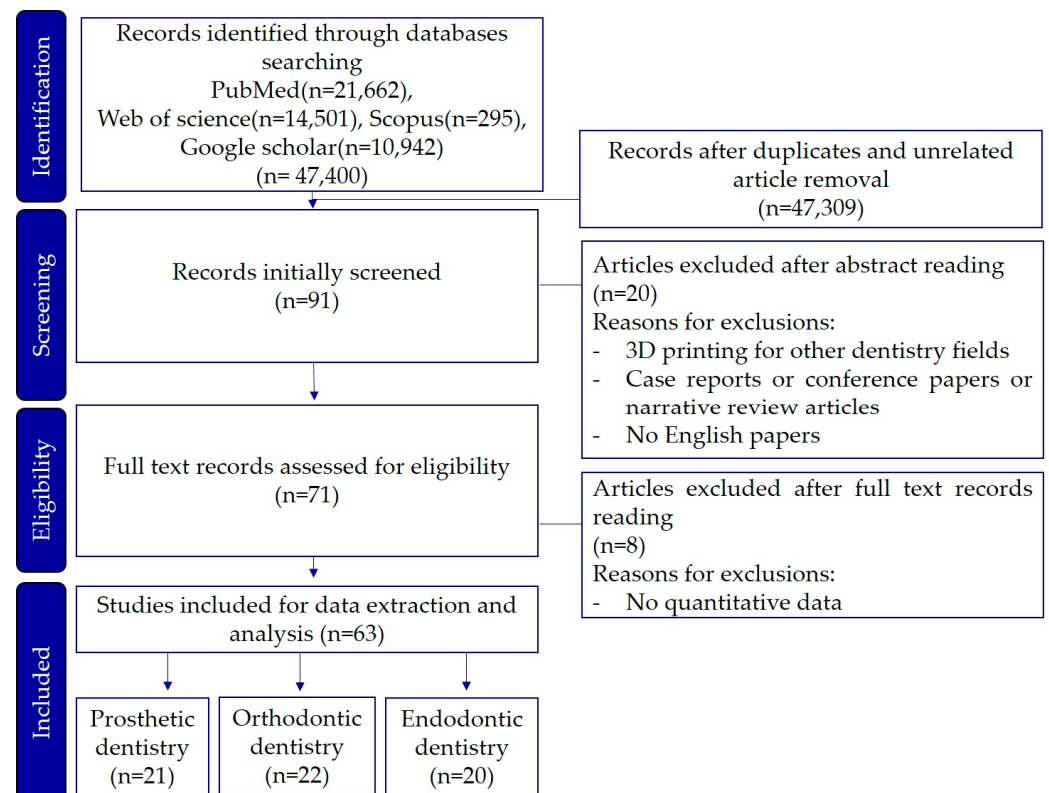
This multi-faceted analysis approach enabled a thorough examination of the current landscape of 3D printing in dentistry, providing insights into its clinical applications, technological advancements, and future prospects across different dental specialties

### 3. Results and Discussion

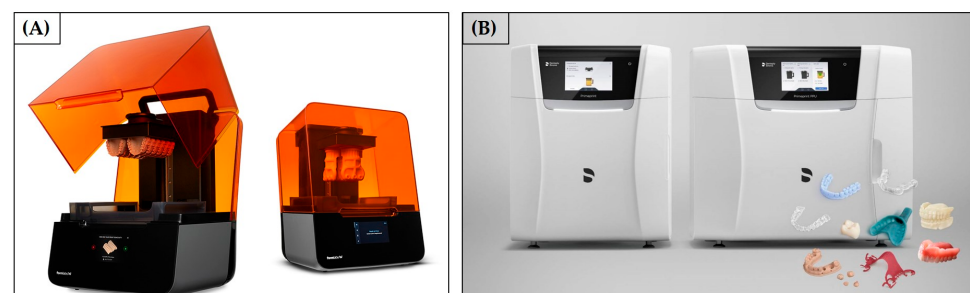
#### 3.1. Study Selection

The review process diagram is shown in Figure 1. Three-dimensional printing technology is utilized across various specialties in the dental field, with dental milling technology also playing a prominent role alongside 3D printing [22]. The dental milling technique, a popular technique, employs computer-aided design/computer-aided manufacturing (CAD/CAM) systems and is widely adopted in clinical dental practices. Numerous previous studies have compared the accuracy and strength of 3D printing and milling technologies [23–25]. The foundational principle of 3D printing involves additive manufacturing, where materials are layered sequentially to form the desired shape, allowing the use of diverse materials such as plastics, metals, and ceramics [26]. In contrast, milling operates on a subtractive manufacturing basis, in which solid blocks of material are carved into the desired shape using cutting tools, typically utilizing harder materials like metals and ceramics [27]. The advantages of 3D printing include the ability to easily produce complex structures and reduce material waste by manufacturing only the necessary portions [28]. However, limitations include longer production times compared to milling for large-scale manufacturing and potentially lower strength [29]. Milling technology, on the other hand, offers high precision and superior strength, making it highly durable. Its disadvantages include material waste from the subtractive process and challenges in creating intricate internal structures [30]. In dental applications, 3D printing and milling technologies play complementary roles, and selecting the appropriate technology based on the treatment objective is essential.

Notable 3D printing techniques in dentistry include stereolithography (SLA) and digital light processing (DLP) (Figure 2) [31]. The SLA technique operates by using a laser to selectively cure liquid polymer resin, building the model layer by layer. Following printing, a post-curing process using UV light is required [12]. While SLA offers the advantage of high resolution, it also has the drawback of requiring additional post-processing, which can extend production time. In contrast, DLP cures each layer simultaneously with projected light, enabling the entire layer to be cured at once [32]. While DLP has a limited build volume, posing challenges for larger parts, it offers faster print times than SLA, making it suitable for mass production. In the dental field, SLA is preferred for tasks that require detailed, high-resolution work.



**Figure 1.** Flow diagram of data filtration process.



**Figure 2.** Representative 3D printing systems utilizing different techniques for dental applications. (A) Form 3+ printer (Formlabs, Boston, MA, USA), manufactured by Formlabs, exemplifies stereolithography (SLA) 3D printing technique and (B) Primeprint system (Sirona Dental Systems GmbH, Bensheim, Germany), developed by Dentsply Sirona, represents digital light processing (DLP) 3D printing technique.

### 3.2. Three-Dimensional Printing Techniques in Prosthetic Dentistry

The methods of using 3D printers in each dentistry field are presented in Table 1. Table 1 provides a comparative overview of different 3D printing technologies used in prosthodontics, highlighting their respective advantages and limitations. In prosthetic dentistry, 3D printing technology is currently employed for a range of applications, including the fabrication of prostheses (e.g., zirconia crowns, Co-Cr copings, and bridge crowns), surgical guides for dental implants, and complete and partial dentures [2,33,34].

The application of 3D printing technology in the fabrication of prostheses has significantly enhanced the precision and efficiency of prosthetic rehabilitation. Various printing techniques, including selective laser melting (SLM), SLA, PolyJet, and DLP, have been employed to produce high-quality metal copings, crowns, and frameworks. Studies conducted by Huang et al. (2015), Chang et al. (2019), Khaledi et al. (2020), Addugala et al. (2022), Ali Majeed et al. (2023), Kim et al. (2018), Qian et al. (2015), and Goguta et al.

(2021) demonstrated that 3D-printed prosthetic components exhibit superior dimensional accuracy and clinical viability compared to those created using conventional methods. However, optimizing material properties and ensuring long-term durability remain challenges [33,35–41].

**Table 1.** Comparison of 3D printing technologies in prosthodontics: applications, evaluation criteria, advantages, and limitations.

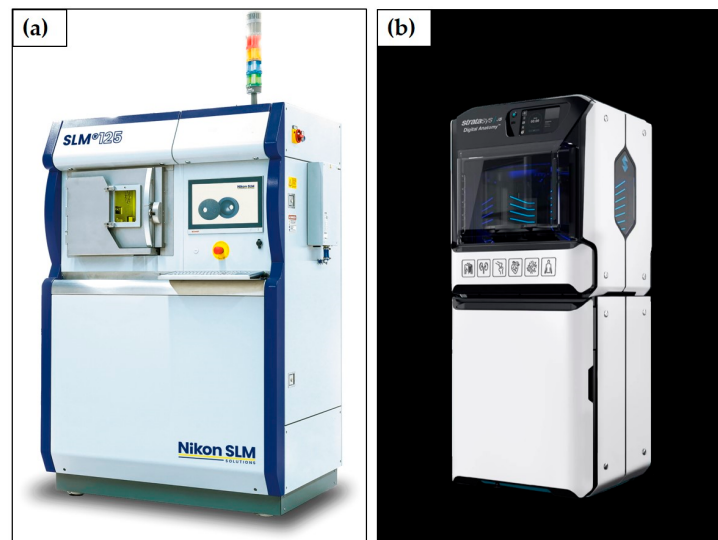
| Dentistry Field | 3D Printer Type | Objective                      | Evaluation Criteria                         | Advantages                                                    | Disadvantages                                                        |
|-----------------|-----------------|--------------------------------|---------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------------|
| Prosthodontics  | SLA             | Fabrication of prosthetics     | Accuracy, resolution, post-processing needs | High resolution, suitable for detailed work                   | Requires post-curing, longer production time                         |
|                 | DLP             | Mass production of prosthetics | Production speed, build volume              | Faster print times, cost-effective for large-scale production | Limited build volume                                                 |
|                 | Milling         | Final crown fabrication        | Accuracy, durability                        | Superior strength and durability, high precision              | Material waste, difficulty in creating intricate internal structures |
|                 | PolyJet         | Fabrication of metal coping    | Accuracy, resolution, safety                | Multi-material printing, high precision for coping            | Higher material costs, low durability, post-processing required      |

SLA = stereolithography, DLP = digital light processing.

Studies comparing traditional casting methods with 3D printing techniques (with no information about the type of 3D printing) for prosthesis fabrication indicate that, for maxillary molar crowns, crowns produced via casting achieved the smallest marginal gaps [33]. However, several studies report no significant differences between 3D printing (SLA- and DLP-type) and milling in terms of accuracy, with both methods providing clinically acceptable results [34,35,42–45]. When fabricating fixed prostheses, metal copings produced via 3D printing (DLP-type, SLM-type, PolyJet-type) exhibited better marginal fit than those produced by milling (Figure 3) [36–38].

While there is limited clinical research evaluating the effectiveness of 3D-printed metal/ceramic crowns (SLM-type), one study reported that the crown retention force was not yet satisfactory for clinical application [41]. Nonetheless, with further technological advancements, clinical use of 3D-printed metal/ceramic crowns may become feasible because of better internal and marginal fit.

Selective laser melting (SLM) and stereolithography (SLA) are two distinct 3D printing technologies with significant differences in their mechanisms, materials, and applications. SLM, primarily used for metal fabrication, employs a high-power laser to selectively melt and fuse metal powder particles, building the object layer by layer (Figure 3) [39,40]. This technique is particularly suitable for creating complex metal structures in dentistry, such as metal copings and metal frameworks.



**Figure 3.** Representative 3D printing systems utilizing different techniques for dental applications. (a) SLM®125 (Nikon SLM Solutions AG, Lübeck, Germany), manufactured by Nikon SLM Solutions, exemplifies selective laser melting (SLM) 3D printing technique and (b) J5 Digital Anatomy™ system (Stratasys Ltd., Eden Prairie, MN, USA), developed by Stratasys, represents PolyJet 3D printing technology.

In contrast, SLA utilizes a laser to cure and solidify liquid photopolymer resin, producing highly detailed plastic parts [46]. SLA is widely used in dentistry for creating diagnostic models, surgical guides, and some temporary prosthetics due to its high resolution and smooth surface finish. While SLM offers the advantage of producing functional metal parts with high strength, it typically requires post-processing and can be more time-consuming [39]. SLA, on the other hand, provides faster printing speeds for smaller objects and requires post-curing but is limited to photopolymer materials. The choice between these technologies in dental applications depends on the specific requirements of the final product, such as material properties, precision, and intended use.

Three-dimensional printing technology has also been widely applied in the fabrication of complete dentures, primarily using the SLA and DLP techniques. Studies conducted by Herpel et al. (2021), Kalberer et al. (2019), Gad et al. (2024), Helal et al. (2023), Prpić et al. (2020), Freitas et al. (2023), and Zeidan et al. (2023) have reported favorable outcomes regarding fit, mechanical strength, and aesthetic quality. Despite these advantages, issues related to color stability and mechanical wear persist, necessitating further improvements in material formulation [23,47–52].

In denture and denture base production, achieving precise fit between the denture base and underlying mucosal tissue is crucial for successful retention. Comparative studies on the surface adaptation of dentures fabricated via 3D printing (SLA- and DLP-type) versus traditional manual methods reported no significant difference [23,52]. However, 3D-printed dentures (SLA-type) showed a decrease in dimensional stability over time and in color stability, with milling yielding superior results in this regard [47,48]. Although deformation of 3D-printed dentures over time has been observed, the clinical significance of these changes has yet to be evaluated. In terms of mechanical properties, the strength of 3D-printed denture materials (DLP type) remains lower than that of materials fabricated through milling or traditional methods, primarily due to weaker interlayer bonding and strength variation based on build orientation [49–51].

Recent studies have reported on the use of 3D printing techniques for bone graft substitutes, particularly in cases of periodontal bone defects. These 3D-printed bone scaffolds, incorporating vascularized structures, have demonstrated potential in animal models [53].

This innovation is expected to contribute significantly to reducing bone resorption and maintaining aesthetic outcomes after immediate anterior tooth extraction [54]. Despite the growing adoption of 3D printing in prosthodontics, significant advancements are required in four key areas before it can fully replace milling machines: material properties, surface quality, speed and cost efficiency, and workflow standardization.

Firstly, 3D printing materials currently lag behind milling materials in the strength, durability, and biocompatibility required for dental applications. Further research is needed to develop new high-performance photocurable resins and composite materials that can match or exceed the properties of milled prosthetics.

Secondly, 3D printing must achieve precision and a smooth surface finish comparable to milling. The technology needs to provide clinically acceptable surface quality without requiring additional polishing or coating processes, thereby reducing post-processing steps.

Thirdly, reproducibility is crucial. There is a need to develop processes that ensure consistent results under identical conditions. This includes seamless integration between CAD software and 3D printing technology through standardization.

Addressing these challenges will be essential for 3D printing to become a viable alternative to milling in prosthodontics. Future research should focus on enhancing material properties, improving surface quality, increasing speed and cost-effectiveness, and standardizing workflows to fully realize the potential of 3D printing in dental applications.

In conclusion, while 3D printing technology achieves clinically acceptable levels of accuracy, it currently exhibits lower mechanical strength and stability compared to milling and traditional methods, highlighting areas for future improvement.

3.3. Three-Dimensional Printing in Orthodontic Dentistry

Three-dimensional printing technology has ushered in significant innovations within orthodontic dentistry, playing a crucial role in generating precise digital dental models and enabling the development of custom orthodontic appliances and treatment plans. Applications of 3D printing in orthodontics include 3D-printed orthodontic cast models, 3D-printed indirect bonding trays, customized clear aligners, dental aligner molds, and mouth guards [55–57]. Table 2 outlines various 3D printing applications in orthodontics, detailing the printing techniques, objectives, evaluation metrics, and key features of each approach.

**Table 2.** Summary of 3D printing applications in orthodontics: printing techniques, objectives, evaluation metrics, and key features.

| Dentistry Field | 3D Printer Type | Objective                        | Evaluation Criteria         | Advantages                                                 | Disadvantages                      |
|-----------------|-----------------|----------------------------------|-----------------------------|------------------------------------------------------------|------------------------------------|
| Orthodontics    | SLA             | Fabrication of clear aligners    | Aesthetics, patient comfort | High precision for clear aligners, biocompatible materials | Post-processing required           |
|                 | DLP             | Fabrication of diagnostic models | Reproducibility, accuracy   | Faster production of aligners, minimal deformation         | Limited size for larger appliances |

SLA = stereolithography, DLP = digital light processing.

Three-dimensionally printed orthodontic appliances are being utilized to treat temporomandibular disorders (TMD), offering a non-invasive therapeutic approach to musculoskeletal conditions affecting the temporomandibular joint and masticatory muscles [58]. Notably, digital fabrication techniques, such as those using 3D-printed occlusal splints, have demonstrated significant advantages over conventional methods by markedly reduc-

ing production time while improving the precision of mandibular motion analysis through digital facebows and virtual articulators.

Three-dimensional printing has significantly impacted orthodontic dentistry, particularly in the fabrication of clear aligners, diagnostic models, and bonding trays. SLA and DLP remain the primary technologies employed due to their precision and ability to produce high-quality surface finishes. Recent studies conducted by Venezia et al. (2022) and Willi et al. (2023) have demonstrated that SLA-printed aligners maintain better trueness and lower geometric distortion compared to those produced by other techniques. However, concerns regarding durability and prolonged use persist [59,60].

The popularity of 3D-printed aligners among both clinicians and patients is primarily due to their aesthetic aspect and functionality [61]. When fabricated with transparent resins, they demonstrate high biocompatibility, minimal deformation, and long-term stability. Traditional metal brackets tend to irritate the oral mucosa, often causing abrasions; in contrast, 3D-printed aligners provide a smoother experience, significantly reducing discomfort for patients [62]. This meticulous production approach has been favorably assessed for its enhanced adaptability and wearability [62]. Generally, the process involves scanning the patient's teeth, designing the aligner using CAD software, and fabricating it via high-resolution 3D printing techniques such as SLA and DLP. Two studies have noted that certain materials may develop minor fractures or undergo physical property changes during use [63,64]. A study comparing the accuracy of clear aligners produced using different 3D printing technologies found that models fabricated using SLA printing exhibited significantly lower trueness errors than those created with DLP printers [59]. Another study also indicates that SLA technology yields more precise clear aligners compared to DLP and LCD technologies, with the color-coded map showing that trueness errors primarily affect the occlusal and proximal surfaces of teeth [65]. Recent studies also explore advanced polymer and composite materials for these devices, aiming to refine the elastic properties of aligners in response to tooth movement [60]. Resin-based 3D-printed aligners, when appropriately cured, have been reported to achieve high accuracy, potentially offering greater mechanical strength and elasticity than traditional thermoplastic-based thermoformed clear aligners while also reducing production time [61]. Compared to traditional aligner fabrication, 3D printing streamlines the entire design, production, and inspection workflow through digitalization, significantly reducing overall production time. Some studies have reported that 3D-printed aligners improve productivity by 40–60% over traditional manufacturing methods [62]. It is anticipated that further advancements in material science and printing technologies will be essential to resolve these issues. Furthermore, comprehensive long-term clinical studies involving larger patient populations are necessary to substantiate the efficacy and clinical viability of 3D-printed orthodontic devices.

The utilization of 3D printing in orthodontics has enabled the production of highly precise and customized aligners. The use of 3D printing extends beyond the production of orthodontic aligners; it is also employed in the fabrication of molds suitable for aligner manufacturing. Several prominent companies dominate this field by integrating advanced 3D printing technologies into their manufacturing processes. First, Align Technology (San Jose, CA, USA), the creator of Invisalign, is a global leader in the orthodontic aligner market [66]. The company employs SLA and DLP technologies to produce molds for aligners [62,67]. These molds are subsequently used to thermoform aligners made from thermoplastic polyurethane (TPU) [67]. Second, ClearCorrect (Basel, Switzerland), owned by Straumann Group, employs SLA-based 3D printers for creating detailed and precise aligner molds [68,69]. Their aligners are designed to compete with Invisalign, offering a similar level of customization and quality. ClearCorrect emphasizes affordability and flexibility for both patients and providers.

The application of 3D printing technology in orthodontic dentistry has shown significant potential, particularly in the fabrication of dental cast models. Various printing techniques, including SLA, DLP, PolyJet, and CLIP, have been utilized to produce accurate and detailed models that support precise diagnosis and treatment planning. Several studies, including those conducted by Jeong et al. (2018), Park et al. (2018), Grassia et al. (2023), Ellakany et al. (2022), Rungrojwittayakul et al. (2020), and Brown et al. (2018), have demonstrated the clinical feasibility of using 3D-printed dental cast models as reliable alternatives to conventional plaster models [22,55,65,70–72]. These models not only offer superior dimensional accuracy but also enhance workflow efficiency through digital reproducibility. Diagnostic models for initiating orthodontic treatments and retention devices post-treatment are also fabricated using 3D printing [7]. While traditional models tend to be bulky, difficult to store, and challenging to replicate, 3D-printed cast models allow the creation of optimal tooth movement using software simulations [70]. Studies comparing traditional cast stone models with 3D-printed cast models have demonstrated that, regardless of whether the printed model is solid or hollow, the precision of the 3D-printed models is inherently influenced by the printing technology employed [71]. Specifically, CLIP (Continuous Liquid Interface Production) printers showed notably lower deviations from traditional cast models than DLP printers. The CLIP and DLP technologies are both photopolymerization-based 3D printing methods, yet they exhibit significant differences in their operational principles and outcomes [29,71]. CLIP technology employs a continuous printing process, utilizing an oxygen-permeable window to create a “dead zone” between the light source and the resin. This allows for uninterrupted part growth without discrete layering [29]. In contrast, DLP operates on a layer-by-layer basis, necessitating a peel step between each layer, which can significantly impact printing speed. While CLIP technology offers significant advantages over DLP in terms of printing speed and surface quality, it currently faces limitations in build volume and remains dependent on underlying DLP principles. This dichotomy presents both opportunities and challenges for the advancement of additive manufacturing technologies. Another study demonstrated that DLP printing achieved clinically acceptable accuracy in measuring tooth dimensions such as mesiodistal crown width and crown height, potentially making 3D-printed models a viable alternative to traditional models [72]. However, comparisons between conventional casts and models fabricated using PolyJet and DLP printing indicated that traditional casts exhibited lower dimensional changes over time, suggesting that while 3D-printed models showed the smallest initial change, they had slightly lower accuracy and reproducibility [55].

For producing indirect bonding trays and orthodontic splints, PolyJet technology has proven effective. Bachour et al. (2022) demonstrated that PolyJet-printed trays facilitate accurate bracket positioning, reducing chair time and improving patient comfort [56]. Similarly, CLIP technology has been explored for fabricating orthodontic models, providing faster production with consistent accuracy. Orthodontic brackets and indirect bonding trays are also being produced using 3D printing, although studies on bracket applications in patient use are limited [56]. The production of indirect bonding trays through 3D printing offers increased precision by creating trays that conform closely to the tooth structures, allowing for more accurate bracket placement, improving patient comfort, and reducing procedure time for clinicians. Another study reported on the reproducibility of digital indirect bonding using 3D models and 3D-printed transfer trays [73]. The results showed no statistically significant differences in bracket positions, except for minor mesial–distal discrepancies. This study concluded that the digital indirect bonding technique using 3D-printed transfer trays demonstrates high reproducibility in bracket positioning, regardless of the orthodontist’s experience level.

In orthodontics, the durability and biomechanical properties of 3D-printed aligners remain underexplored, particularly in long-term clinical scenarios. While 3D printing offers precise and customizable solutions, research on material degradation and its impact on treatment outcomes is limited. Additionally, the workflow for digital orthodontic applications lacks standardization, with few studies comparing the accuracy and efficiency of SLA and DLP technologies. Furthermore, existing research is predominantly laboratory-based, necessitating large-scale clinical trials to validate the effectiveness of 3D-printed aligners across diverse patient populations.

The introduction of 3D printing into orthodontics has facilitated customized design, cost savings, and productivity improvements, resulting in high satisfaction among both patients and clinicians. Nevertheless, further studies are needed to evaluate the durability and long-term efficacy of 3D-printed materials to strengthen clear aligners as a sturdy and effective orthodontic solution.

3.4. Endodontic Application of 3D Printing in Dentistry

The integration of 3D printing technology into endodontics has significantly advanced diagnostic accuracy, treatment planning, education, and research. Table 3 summarizes the role of 3D printing in endodontics, including the technologies utilized, clinical applications, evaluation parameters, and performance characteristics.

**Table 3.** Overview of 3D printing in endodontics: technology, clinical applications, evaluation parameters, and performance characteristics.

| Dentistry Field | 3D Printer Type | Objective                                                 | Evaluation Criteria                                           | Advantages                                                                       | Disadvantages                                   |
|-----------------|-----------------|-----------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------------------------|-------------------------------------------------|
| Endodontics     | SLA             | Fabrication of surgical guides and anatomical models      | Accuracy of surgical planning support, training effectiveness | High accuracy for surgical guides                                                | Longer production time                          |
|                 | DLP             | Fabrication of endodontic training for root canals models | Similarity to actual clinical environment                     | Faster production of root canal models                                           | Limited build volume for larger models          |
|                 | PolyJet         | Fabrication of complex surgical guides                    | Accuracy, safety                                              | Multi-material printing capability, high precision for complex anatomical models | Higher material costs, post-processing required |

SLA = stereolithography, DLP = digital light processing.

In endodontics, 3D printing is predominantly utilized for surgical guide fabrication and training models. SLA and PolyJet technologies are favored due to their ability to create highly accurate and detailed guides. Connert et al. (2018) and Lara-Mendes et al. (2018) reported that 3D-printed guides enhance precision during apicoectomy and root canal procedures, minimizing tissue damage and reducing operative time [74,75].

Currently, most studies utilizing endodontic surgical guides are limited to case reports. A prominent application is in the fabrication of endodontic surgical guide for procedures such as apicoectomy, where 3D-printed guides assist in precisely positioning surgical instruments, enabling the clinician to accurately access and remove periapical lesions [5]. Studies have shown that utilizing these guides increases precision in locating

canal entrances and establishing access pathways, significantly reducing procedural errors compared to non-guided surgeries, regardless of the clinician's experience level [76,77]. For challenging cases, such as calcified or complex curved canals, 3D-printed guides have demonstrated improved accessibility and higher success rates compared to conventional hand instrumentation [74,75]. The use of these guides allows for safer procedures by minimizing unnecessary removal of tooth structures while searching for canal entrances, thus preserving tooth integrity [74,78,79]. Guided surgical endodontics employs 3D-printed surgical guides designed using integrated CBCT and optical scan data to enhance precision in complex cases [80,81]. The technique utilizes guide sleeves to accurately identify osteotomy sites and control the depth and angle of access, with depth-calibrated instruments maintaining parallelism to limit osteotomy size [21]. This approach not only improves accuracy in determining osteotomy sites and root resection levels but also serves as a valuable tool for skill development in educational settings, representing a significant advancement in surgical endodontic procedures. Multiple studies indicate that 3D-guided endodontic surgery improves lesion removal accuracy and ensures a reliable canal seal, thereby reducing recurrence rates and enhancing long-term treatment outcomes [78,82–84]. Furthermore, patient satisfaction has been reported to increase with the use of surgical guides due to shorter procedure times and reduced discomfort [5].

While surgical guides are commonly used, non-surgical guides are also being utilized in 3D printing and can be applied for guided endodontic access, particularly in cases involving calcified canals. These guides allow clinicians to follow pre-planned drilling paths, reducing errors, preserving tooth structure, and improving the efficiency and success rates of complex procedures [76]. An *ex vivo* study found that guided endodontic access cavity preparation using 3D-printed templates achieved high accuracy, with mean deviations below 0.7 mm [85]. A study on non-surgical guided endodontics in mandibular anterior teeth demonstrated high accuracy, with a mean deviation of 0.2 mm at the bur tip and an angular deviation less than 2° [82]. The technique proved to be efficient and operator-independent, with an average treatment time of 10 min per tooth, suggesting its effectiveness for preparing access cavities in teeth with narrow roots.

In addition to surgical applications, endodontic clinical training models fabricated using SLA and PolyJet technologies offer realistic simulations for pre-clinical education. Several studies have demonstrated their effectiveness at enhancing students' skills and understanding of complex canal anatomies. Notably, studies conducted by Marending et al. (2016), Tonini et al. (2021), Kamburoğlu et al. (2023), Llaquet Pujol et al. (2021), Kröger et al. (2017), and Pouhaër et al. (2022) reported that 3D-printed training models created using these technologies enable precise replication of endodontic structures, providing invaluable hands-on practice in educational settings [86–91]. Nonetheless, challenges remain in replicating the tactile feedback of real tissues, emphasizing the need for further advancements in material properties and haptic simulation. The utilization of 3D printing to create endodontic models has proven to be a valuable tool for training and research in endodontic treatment. These models replicate complex root canal anatomies, allowing for hands-on practice in a controlled and safe environment [92]. This application enhances procedural skills and promotes a deeper understanding of endodontic techniques [93]. A study utilizing commercially available 3D-printed mandibular molar replicas compared the performance of two contemporary rotary instrumentation systems in a pre-clinical student course setting [86]. Numerous studies have highlighted the utility of 3D-printed root canal models as effective platforms for simulating and practicing procedures prior to performing actual root canal treatments in clinical settings [87,88,94]. By practicing with the model, practitioners can familiarize themselves with the specific shape and location of the root canal, allowing them to refine their choice of instruments and approach. This preparatory

step has been shown to reduce the likelihood of unforeseen complications arising during the actual procedure [89]. One study found that clinicians who practiced with these models achieved higher success rates and shorter procedure times in real cases [78,95]. Another study reported that 3D-printed root canal models serve as an essential educational tool for students and novice dental practitioners [90]. Practicing with 3D-printed models of diverse root canal anatomies enables students to deepen their understanding of complex canal structures and enhances their confidence in performing clinical procedures [91]. A study utilizing 3D-printed models of a lower first molar demonstrated high effectiveness for endodontic training, with 85% of students considering the models effective tools, offering them significant improvements in confidence (75% after vs. 38% before), an enhanced understanding of access cavity shape (70%), and better root canal anatomy visualization (83%) [91]. Furthermore, 3D-printed root canal models serve as valuable research tools for evaluating and testing the efficacy of novel instruments and materials used in endodontic treatment. These models can also be employed as visual aids during patient consultations, providing a tangible representation of the endodontic procedure and the necessity of each step. This approach enhances patient understanding and fosters greater trust and confidence in their treatment.

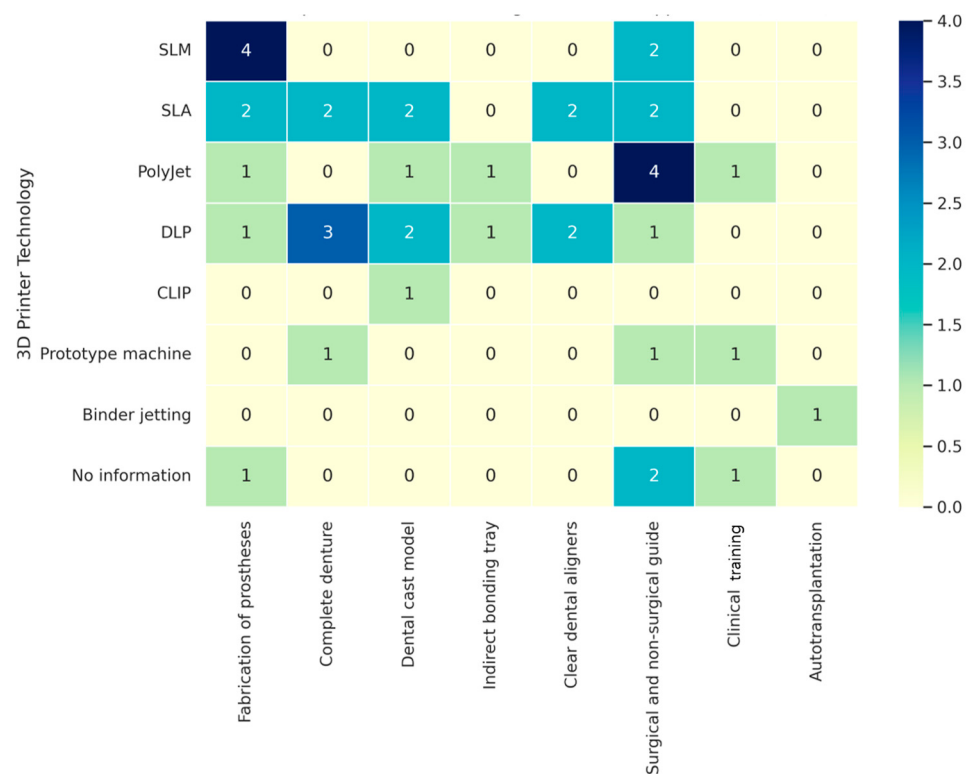
Autotransplantation of teeth has increasingly benefited from the application of 3D printing technology, particularly in enhancing precision and reducing surgical time. Studies utilizing SLA and PolyJet technologies have demonstrated the feasibility of fabricating surgical guides and donor tooth replicas, which significantly improve the accuracy of donor site preparation and recipient socket adaptation. Notably, research conducted by Kamio et al. (2019), Lee et al. (2001), Lee et al. (2012), Honda et al., Keightley et al. (2010), Park et al. (2012), and Strbac et al. (2016) has provided compelling evidence supporting the clinical viability and success of 3D-printed guides in autotransplantation procedures [96–102]. These studies collectively emphasize that accurate replication of donor tooth morphology and optimal positioning significantly contribute to the successful integration and functional outcomes of transplanted teeth. In the field of endodontics in dentistry, efforts are being made to utilize 3D printing technology for autotransplantation to enhance procedural accuracy and clinical outcomes [96–98]. The integration of 3D printing, particularly computer-aided rapid prototyping (CARP), has significantly improved the predictability and outcomes of autotransplantation by addressing challenges such as prolonged extraoral time and periodontal ligament (PDL) damage. By enabling the preoperative preparation of recipient sites with 3D-printed replicas of donor teeth, CARP minimizes trauma and enhances surgical precision. Studies have demonstrated success rates of 80–91%, with extraoral times reduced to under one minute in some cases [99–101,103]. Innovations such as CAD-designed prototypes and 3D-printed surgical guides further optimize procedures by ensuring accurate tooth positioning and preserving critical structures like the apical papilla [102]. These advancements highlight the transformative role of 3D printing in making autotransplantation a reliable and efficient treatment option.

With the continuous advancement of three-dimensional printing technology, the development and utilization of biocompatible materials have significantly expanded clinical possibilities [104]. These innovative approaches facilitate the fabrication of scaffolds tailored for tissue regeneration, offering unparalleled precision and customization to meet both functional and aesthetic requirements. Furthermore, the integration of digital impression techniques within 3D printing workflows enables highly accurate contour analysis, thereby enhancing the precision of postoperative assessments and contributing to improved clinical outcomes. Despite these promising advancements, challenges remain in maintaining periodontal ligament viability and optimizing the fit between the donor tooth and the

prepared socket. Further research is needed to develop enhanced printing materials and refine digital planning protocols to maximize clinical success and long-term stability.

In endodontics, techniques guided using 3D-printed templates have shown promise, but large-scale studies assessing their safety and efficacy are scarce. Another significant research gap lies in the potential advancements of 3D printing for surgical endodontic treatments, which require further exploration in future studies. First, the development of ultra-miniaturized surgical guides designed specifically to avoid obstructing the surgical field could enhance the precision of procedures while maintaining optimal visibility for clinicians. These guides would be particularly beneficial in complex apicoectomy cases or when access to posterior regions is limited. Second, designing 3D-printed, specialized tools such as spoon-shaped instruments or custom drill tips tailored to the unique anatomy of root apices could facilitate less invasive treatment. These tools would minimize unnecessary removal of surrounding tissues, reducing post-operative complications and improving patient recovery. Lastly, the integration of 3D printing with nanotechnology presents an exciting avenue for innovation. Customizable microstructures could be developed to repair compromised root canal walls or enable drug delivery continuously. Such advancements would not only reinforce structural integrity but also promote long-term healing and prevent reinfection. These areas of research represent promising directions for leveraging 3D printing to achieve more efficient, minimally invasive, and patient-centered endodontic care.

In this result, Figure 4 presents a heatmap illustrating the various 3D printer technologies and their applications, while Table 4 provides a detailed summary of the included 3D printing studies, encompassing authors, study design, printing technologies, and research objectives. Together, these findings offer a comprehensive understanding of the diverse applications of 3D printing across prosthodontics, orthodontics, and endodontics. A critical evaluation of each technology's advantages and limitations informs future research directions and enhances clinical practice.



**Figure 4.** Heatmap of 3D printer technologies and their applications.

**Table 4.** Detailed summary of included 3D printing studies: authors, study designs, printing technologies, and research objectives.

| Application               | Author (Year)                                                | Study Design | Printer Technology | Objective of Study                                                                                                               |
|---------------------------|--------------------------------------------------------------|--------------|--------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Fabrication of prostheses | Huang, Zhuoli et al. (2015) [35]                             | In vitro     | SLM                | To compare the marginal and internal fit of single crown fabrication                                                             |
|                           | Chang, Hao-Sheng et al. (2019) [33]                          | In vitro     | No information     | To evaluate the marginal gaps of dental restorations                                                                             |
|                           | Khaledi, Amir-Alireza et al. (2020) [36]                     | In vitro     | SLA and PolyJet    | To evaluate the marginal fit of metal coping fabrication                                                                         |
|                           | Addugala, Hemavardhini et al. (2022) [37]                    | In vitro     | DLP                | To compare the marginal discrepancy and internal adaptation of coping fabrication                                                |
|                           | Ali Majeed, Zainab et al. (2023) [38]                        | In vitro     | SLM                | To evaluate the trueness and fitness of Co-Cr crown coping fabrication                                                           |
|                           | Kim, Dong-Yeon et al. (2018) [39]                            | In vitro     | SLM                | To evaluate the marginal and internal gaps of Co-Cr alloy coping fabrication                                                     |
|                           | Qian, B. et al. (2015) [40]                                  | In vitro     | SLM                | To investigate the microstructures of SLM specimens and their effect on mechanical properties                                    |
|                           | Goguta, Luciana et al. (2021) [41]                           | In vitro     | SLM                | To ascertain the retention forces for telescopic crowns fabricated with SLM and SLS                                              |
| Complete denture          | Herpel, Christopher et al. (2021) [23]                       | In vitro     | SLA and DLP        | To compare the accuracy of 3D-printed and milled complete dentures                                                               |
|                           | Kalberer, Nicole et al. (2019) [52]                          | In vivo      | Prototype machine  | To compare the differences in trueness of complete dentures                                                                      |
|                           | Gad, Marwa A et al. (2024) [47]                              | In vitro     | SLA                | To assess and contrast the color stability and dimensional accuracy of denture base resins before and after aging                |
|                           | Helal, Mohamed Ahmed et al. (2023) [48]                      | In vitro     | DLP                | To compare the dimensional changes of complete dentures                                                                          |
|                           | Prpić, Vladimir et al. (2020) [49]                           | In vitro     | DLP                | To evaluate the mechanical properties of denture base materials                                                                  |
|                           | Freitas, Rodrigo Falcão Carvalho Porto de et al. (2023) [50] | In vitro     | DLP                | To investigate the surface roughness and contact angle, anti-biofilm formation, and mechanical properties of denture base resins |
|                           | Zeidan, Ahmed Abd El-Latif et al. (2023) [51]                | In vitro     | DLP                | To compare the flexural strength of the denture base resin                                                                       |

Table 4. Cont.

| Application                      | Author (Year)                                  | Study Design | Printer Technology | Objective of Study                                                                                       |
|----------------------------------|------------------------------------------------|--------------|--------------------|----------------------------------------------------------------------------------------------------------|
| Dental cast model                | Jeong, Yoo-Geum et al. (2018) [22]             | In vitro     | SLA                | To evaluate the accuracy of models for dental prosthesis production                                      |
|                                  | Park, Mid-Eum et al. (2018) [55]               | In vitro     | PolyJet            | To compare the accuracy and reproducibility of dental cast production                                    |
|                                  | Grassia, Vincenzo et al. (2023) [65]           | In vitro     | SLA and DLP        | To assess the trueness and precision of orthodontic models                                               |
|                                  | Ellakany, Passent et al. (2022) [70]           | In vitro     | SLA                | To compare the accuracy of dental casts                                                                  |
|                                  | Rungrojwittayakul, Oraphan et al. (2020) [71]  | In vitro     | CLIP and DLP       | To evaluate the accuracy of 3D-printed model production                                                  |
|                                  | Brown, Gregory B et al. (2018) [72]            | In vitro     | DLP and PolyJet    | To assess the accuracy of 2 types of 3D printing techniques                                              |
| Indirect bonding tray            | Bachour, Petra C. et al. (2022) [56]           | In vivo      | DLP                | To evaluate the transfer accuracy of indirect bonding trays                                              |
|                                  | Duarte, Maria Eduarda Assad et al. (2020) [73] | In vitro     | PolyJet            | To evaluate the reproducibility of digital tray transfer fit on digital indirect bonding                 |
| Clear dental aligners            | Jindal, Prashant et al. (2019) [61]            | In vitro     | SLA                | To compare compressive mechanical properties and geometric inaccuracies of dental aligners               |
|                                  | Venezia, Pietro et al. (2022) [59]             | In vitro     | SLA and DLP        | To evaluate the accuracy of the production of clear aligners                                             |
|                                  | Willi, Andreas et al. (2023) [60]              | In vitro     | DLP                | To quantitatively assess the degree of conversion and water-leaching compounds                           |
|                                  | Šimunović, Luka et al. (2024) [68]             | In vitro     | SLA                | To evaluate the aligners' response to common staining agents in terms of color and chemical stability    |
|                                  | Pasaoglu Bozkurt, Aylin et al. (2025) [69]     | In vitro     | SLA                | To compare and evaluate time-dependent biofilm formation and microbial adhesion of clear aligners        |
| Surgical and non-surgical guides | Sarkarat, Farzin et al. (2023) [57]            | In vivo      | PolyJet            | To investigate the accuracy of surgical splints for practical use                                        |
|                                  | van der Meer, Wicher J. et al. (2016) [76]     | In vivo      | PolyJet            | To describe the application of 3D digital mapping technology for navigation of obliterated canal systems |
|                                  | Ackerman, Shira et al. (2019) [77]             | In vivo      | SLA                | To evaluate the accuracy of CBCT-designed surgical guides                                                |
|                                  | Connert, T. et al. (2018) [74]                 | In vivo      | PolyJet            | To present a novel treatment for root canal localization                                                 |

Table 4. Cont.

| Application                      | Author (Year)                                | Study Design | Printer Technology | Objective of Study                                                                                                             |
|----------------------------------|----------------------------------------------|--------------|--------------------|--------------------------------------------------------------------------------------------------------------------------------|
| Surgical and non-surgical guides | Lara-Mendes, Sônia T de O et al. (2018) [75] | In vivo      | PolyJet            | To describe a guided technique for accessing root canals                                                                       |
|                                  | Connert, Thomas et al. (2019) [78]           | In vitro     | PolyJet            | To compare endodontic access cavities in teeth with calcified root canals                                                      |
|                                  | Loureiro, Marco Antônio Z et al. (2021) [79] | In vivo      | DLP                | To discuss the impact of new technologies on treating a complex case                                                           |
|                                  | Lee, Seung-Jong et al. (2006) [80]           | In vivo      | Prototype machine  | To demonstrate the anatomy of 3 distal roots of a right mandibular first molar                                                 |
|                                  | Byun, Chanhee et al. (2015) [81]             | In vivo      | PolyJet            | To present a case of successful root canal treatment                                                                           |
|                                  | Connert, Thomas et al. (2017) [82]           | In vitro     | PolyJet            | To assess the accuracy of guided endodontics for mandibular anterior teeth                                                     |
|                                  | Pinsky, Harold M. et al. (2007) [83]         | In vitro     | No information     | To introduce periapical surgical guidance computer-aided manufacturing surgical guides                                         |
|                                  | Buchgreitz, J. et al. (2016) [85]            | Ex vivo      | No information     | To evaluate the accuracy of a preparation for teeth with pulp canal obliteration                                               |
|                                  | Kfir, A. et al. (2013) [92]                  | In vivo      | PolyJet            | To report on the use of a 3D plastic model for the diagnosis and treatment of dens invaginatus                                 |
| Clinical training                | Hawkins, T. K. et al. (2020) [95]            | In vitro     | PolyJet            | To compare surgical time, bevel angle, and site volumetric profiles of osteotomy and resection area of endodontic microsurgery |
|                                  | Marending, M. et al. (2016) [86]             | In vitro     | No information     | To assess contemporary rotary instrumenting systems in a pre-clinical student course setting                                   |
|                                  | Tonini, Riccardo, et al. (2021) [87]         | In vivo      | No information     | To evaluate the applicability of a novel print and try technique in the presence of aberrant endodontic anatomies              |
|                                  | Kamburoğlu, Kivanç, et al. (2023) [88]       | In vitro     | SLA                | To evaluate the accuracy of guides prepared using CBCT images on 3D-printed teeth for root canal treatment                     |

Table 4. Cont.

| Application         | Author (Year)                               | Study Design | Printer Technology                 | Objective of Study                                                                                                                  |
|---------------------|---------------------------------------------|--------------|------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Clinical training   | Llaquet Pujol, Marc et al. (2021) [89]      | In vivo      | SLA                                | To describe the endodontic management of pulp canal obliteration using guided endodontics and a virtually designed 3D guide         |
|                     | Kröger, E et al. (2017) [90]                | In vitro     | PolyJet                            | To introduce workflow to create 3D-printed simulation models based on real patient situations for hands-on practice                 |
|                     | Pouhaër, Matéo et al. (2022) [91]           | In vitro     | SLA                                | To show the design phases of different dental models of a lower first molar, showing root canal anatomy and the ideal access cavity |
| Autotransplantation | Kamio, Takashi et al. (2019) [96]           | In vivo      | Fused filament fabrication         | To describe 3D morphological evaluation, preoperative treatment planning, and surgical simulation                                   |
|                     | Lee, Seung-Jong, et al. (2001) [97]         | In vivo      | Prototype machine                  | To minimize extraoral time and achieve optimal contact in autotransplantation                                                       |
|                     | Lee, Seung-Jong, et al. (2012) [98]         | In vivo      | Prototype machine                  | To reduce extraoral time and secure optimal contact in autogenous tooth transplantation                                             |
|                     | Honda, M. et al. [99]                       | In vivo      | SLA                                | To simplify the surgical technique in autotransplantation                                                                           |
|                     | Keightley, Alexander J. et al. (2010) [100] | In vivo      | Binder jetting (powder-based type) | To develop and apply a surgical template for autotransplantation                                                                    |
|                     | Park, Young-Seok et al. (2012) [101]        | In vivo      | Prototype machine                  | To develop autotransplantation with simultaneous sinus floor elevation and implant installation                                     |
|                     | Strbac, Georg D. et al. (2016) [102]        | In vivo      | PolyJet                            | To introduce a method for autotransplantation of teeth                                                                              |

### 3.5. Discussion of 3D Printing in Dentistry

Despite the growing prominence of 3D printing techniques in both the medical and dental fields, our study is limited by its focus solely on prosthodontics, orthodontics, and endodontic dentistry. Consequently, this scoping review does not encompass other potential applications of 3D printing, particularly in areas related to advanced biomaterials, such as collagen-based constructs, artificial bone replacement materials, 3D-printed ceramics, and cell culture research. Additionally, the potential use of 3D printing for bone graft materials, which holds significant promise for regenerative dentistry, was not thoroughly explored. Future research should aim to conduct a more comprehensive analysis of these foundational scientific aspects and explore the potential of 3D-printed biomaterials for bone regeneration and tissue engineering. Expanding the scope of investigation in this direction will contribute to a more holistic understanding of the transformative potential of 3D printing in clinical practice.

#### 3.5.1. Real-World Case Studies

In clinical practice, 3D printing facilitates the creation of surgical guides, custom prosthetics, and orthodontic appliances, showcasing its versatility and precision. For instance, the integration of digital intraoral scanning with 3D-printed surgical guides has significantly enhanced the accuracy of implant placements, particularly in complex anatomical cases. Studies have shown notable improvements in the precision of implant placement and reduced surgical time when using 3D-printed surgical guides [105,106]. Furthermore, 3D-printed prosthetics have enabled the fabrication of restorations with superior fit and aesthetics, leading to higher patient satisfaction rates. Nonetheless, while these case studies highlight the immediate benefits of 3D printing, longitudinal studies are essential to evaluate the long-term efficacy and durability of 3D-printed dental solutions.

#### 3.5.2. Patient Outcomes

The patient-centric approach facilitated by 3D printing has the potential to revolutionize patient outcomes in dentistry. Customized treatment plans, enabled by 3D printing, allow for the fabrication of dental devices that are tailored to the unique anatomy of each patient [107]. This customization leads to enhanced comfort, improved functionality, and better aesthetic results. For example, 3D-printed orthodontic aligners offer a comfortable and discreet alternative to traditional braces, resulting in improved patient compliance and treatment outcomes. However, concerns regarding the biocompatibility of 3D printing materials and the long-term effects on patient health require further investigation. Clinical research focused on evaluating patient-reported outcomes and long-term clinical performance is imperative.

In the future, the utilization of 3D printing technology to develop bone graft materials holds great potential for regenerative applications [108]. Particularly in cases of immediate anterior tooth extraction, employing 3D-printed bone substitutes and provisional dentures can effectively address bone resorption issues while simultaneously meeting aesthetic demands. This approach facilitates prompt prosthetic rehabilitation, minimizing patient discomfort and enhancing clinical outcomes.

#### 3.5.3. Regulatory Considerations

As 3D printing becomes increasingly integrated into dental practice, regulatory frameworks must evolve to ensure patient safety and product quality. Medical device regulations pertaining to 3D-printed dental products must address quality control, material safety, and performance standards [29]. The need for clear guidelines is especially pronounced for patient-specific devices, where customization introduces unique challenges to regulatory

compliance. Standardization efforts are essential to maintain consistent quality across 3D-printed dental products. Regulatory bodies must establish frameworks that balance innovation with rigorous safety standards.

#### 4. Conclusions

This scoping review highlights the transformative potential of 3D printing in dentistry, particularly in prosthodontics, orthodontics, and endodontics. The findings reveal significant advancements in precision, customization, and efficiency, demonstrating how 3D printing has revolutionized the production of dental prostheses, aligners, and surgical guides. However, key challenges remain, including material durability, cost-effectiveness, and the standardization of workflows.

The primary novel contribution of this study lies in its holistic analysis of 3D printing applications across multiple dental disciplines, providing a comprehensive synthesis that bridges existing knowledge gaps. Unlike previous reviews that focus narrowly on isolated applications or single specialties, our scoping review presents a multidimensional perspective that encompasses prosthodontics, orthodontics, and endodontics. This approach enables the identification of overarching trends, technological advancements, and persistent challenges.

In prosthodontics, this study uniquely addresses the integration of stereolithography (SLA), digital light processing (DLP), and selective laser melting (SLM) technologies, evaluating their distinct advantages and limitations. The comparative analysis of 3D-printed prostheses versus milled restorations highlights critical differences in accuracy, durability, and clinical applicability. By presenting evidence from both traditional and advanced manufacturing techniques, our review establishes a robust framework for assessing the feasibility of adopting 3D printing as a mainstream method in dental prosthesis fabrication. Future studies must address critical challenges including material performance, surface quality, and long-term clinical reliability. Investigating the development of advanced photocurable resins, improving precision, and understanding the biomechanical properties of 3D-printed prosthetics will be essential. By systematically exploring these areas and potentially developing hybrid approaches that combine traditional techniques with emerging 3D printing technologies, researchers can optimize the clinical application and cost-efficiency of digital dental restoration methods.

In orthodontics, this review stands out by systematically evaluating the accuracy and patient satisfaction associated with 3D-printed aligners and diagnostic models. It critically examines the mechanical properties and dimensional stability of various materials, addressing the persistent issue of deformation and wear resistance. By consolidating findings from diverse studies, our review underscores the need for standardized protocols and the development of new high-performance resins to enhance the longevity of orthodontic appliances. Although 3D-printed aligners and diagnostic models have improved treatment precision and patient comfort, material properties such as durability and wear resistance require further refinement. Large-scale, multi-center clinical trials are essential to validate the long-term efficacy of 3D-printed orthodontic solutions and assess their impact on diverse patient populations. Research into standardizing digital workflows and streamlining the integration of 3D printing with existing orthodontic protocols is also necessary.

This study contributes significantly to the field of endodontics by examining the use of 3D-printed surgical guides and training models, which have shown promise in enhancing procedural accuracy and educational effectiveness. While the existing literature has explored individual applications, our comprehensive review elucidates the integration of these technologies into clinical practice, highlighting the potential for improving surgical outcomes through precise and minimally invasive approaches. The integration of advanced

imaging technologies, such as CBCT with customized 3D-printed tools for complex cases requires further development. Future research should also focus on designing minimally invasive tools and biocompatible materials that can improve the success rates of challenging treatments such as root canal navigation and apical surgery.

By systematically mapping the current landscape and identifying critical gaps, this scoping review serves as a foundational resource for guiding future research and clinical innovation. Addressing these challenges will expand the clinical applicability of 3D printing, improve patient care, and promote the adoption of advanced manufacturing technologies in modern dentistry.

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