Review Article

Fused Deposition Modeling in Dentistry: A Systematic Literature Review of Materials, Process Parameters, Performance Evaluation, and Clinical Barriers

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Abstract

Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), is an additive manufacturing technology that uses filament-based materials to create objects layer by layer. Recognized for its affordability and ease of use, FDM has found widespread applications across various industries, including dentistry. This Systematic Literature Review (SLR) aims to provide a comprehensive overview of the materials, machines, parameters, applications, and tests associated with the use of FDM/FFF technology in dental applications. Through a detailed process of identification and screening, 378 articles of literature were reviewed, and 52 relevant studies were selected for in-depth analysis. The review highlights key trends in the use of FDM in dentistry, focusing on the advancements in materials such as biocompatible polymers and their impact on clinical outcomes. Additionally, the paper discusses machine configurations, operational parameters, and various tests conducted to assess the performance and reliability of FDM-printed dental products. This paper also identifies the key determinants and barriers to the application of FDM in dentistry. This review serves as a valuable resource for dental practitioners and researchers, offering insights into current practices and identifying potential gaps for future research in the field.

Keywords: Additive manufacturing, Dentistry, Fused deposition modeling, Systematic literature review, 3D printing

1 Introduction

Additive manufacturing has grown rapidly as one of the technologies in Industry 4.0. This technology has been successfully used in various industries such as aerospace, automotive, food, and health because of its ease, low cost, and fast production time. In addition, this technology, which uses the addition of materials, also has advantages in making complex shapes, such as human body parts, especially teeth.

Additive manufacturing technologies have been widely studied in the dental field. In 2024, Kim *et al*., [1] studied surgical splints made using Stereolithography (SLA) technology and three types of resin materials, namely Surgical Guide (SG), Dental LT V2 (DLTV2), and Biomed Clear (BMC) (Formlabs, Somerville, Massachusetts, USA). In the same year, Janjić *et al*., [2] studied the effect of print orientation and graphene nanoplate on biaxial flexural strength and cytotoxicity of 3D printable resin for occlusal splints using Stereolithography (SLA) technology. Atam [3] also observed the effect of printing parameters of SLA and Digital Light Processing (DLP) technologies for various orthodontic applications.

Most additive manufacturing technologies used in dentistry are SLA and Selective Laser Sintering (SLS). These technologies use liquid resin materials that are solidified with good resolution to produce detailed products. However, these technologies take longer and are more expensive when compared to Fused Deposition Modeling (FDM) technology that uses filament materials. FDM is an additive manufacturing process that utilizes thermoplastic polymers such as PLA, ABS, polycarbonate, and nylon through melting and solidification during extrusion [4], [5]. FDM is considered cheaper when compared to SLA, SLS, and PolyJet, although it has a lower resolution [6]–[8]. For example, the raw material cost for a single dental model using FDM was \$3.12, compared to \$3.63 (SLS), \$5.18 (SLA), and \$7.84 (PolyJet). FDM showed a higher printing speed for the identical model, requiring 120 min, whereas SLA required 180 min [6]. FDM is generally faster than SLA and conventional fabrication, making it suitable for rapid prototyping and small–batch production [6], [7].

While FDM is generally less precise than SLA, DLP, SLS, and PolyJet, its accuracy is clinically acceptable for many applications, including those in dentistry. Various methods can be employed for improvement, one of which is utilizing machine learning to predict results [9]. Furthermore, adjusting printing parameters is also an alternative to addressing issues that occur with FDM [10]. In dental practice, FDM has been applied to produce surgical guides [11], [12] dental trays/molds [13]–[15], implants [16], crowns [17]–[20] and models [12], [14]–[23].

A literature study on the use of FDM in dentistry was conducted by Lüchtenborg *et al*., [7] in 2021. The study focused more on using materials and novel approaches to dentistry using FDM. Bibliometric analysis has been used in various studies [21]–[25]. This study is an analysis of literature metadata used to provide a general overview of the topics being studied, including health [26]–[28], food [29], and robotics [30].

Meanwhile, a systematic literature review is a method that selects the literature to be studied to be more focused. This systematic literature review has been conducted extensively to explore various topics, including the application of FDM in multiple applications such as robotics [31], medicine [32], and polymers [33]. A general review of AM use for dental applications has been conducted by Oros *et al*., [34], who discussed common applications, technologies, and materials that are most prevalent, and parameters that affect the quality and safe usage of 3D–printed dental applications. However, the discussion on FDM technology remains limited and has not been supplemented with a bibliometric review. This literature study aims to complement and update the study that was conducted by Lüchtenborg *et al*., [7] using bibliometric methods and a more focused systematic literature review, which has never been done before.

This literature study aims to answer several questions related to the application of FDM in dentistry. The research questions and objectives in this literature review are as follows.

RQ1: What FDM materials are used for dentistry?

RO1: Knowledge of materials is essential, especially for additive manufacturing technology. Polymer composite materials have been developed in modern applications for various industries, one of which is in the field of dentistry [4]. So far, the technique used is SLA/SLS using liquid resin material. This material has advantages in strength and surface smoothness obtained after cooling. However, this material is relatively more expensive and must go through post–processing such as UV copying, so it takes longer. FDM techniques with filament materials can provide a faster and cheaper experience in the process, without requiring complicated post–processing. It's just that in terms of strength and smoothness, the SLA/SLS technique is better. Information about the materials known to FDM is essential for a researcher or practitioner to consider when choosing materials.

RQ2: What FDM printers are used for dentistry?

RO2: Not all FDM printers can be used for dentistry due to limitations, such as maximum nozzle temperature, bed size, compatibility with materials, etc. Knowing which FDM printers can be used will help researchers or practitioners in fabrication.

RQ3: What printing parameters are commonly used for dentistry?

RO3: Parameter determination in printing optimization has been done frequently; however, it is still very limited for dental applications. One such study was conducted by Sonaye *et al.*, [10], who discussed the optimal parameters for PEEK dental endosseous implants. Knowledge of printing parameters will help researchers/practitioners determine good parameters or the direction of further research.

RQ4: What are some successful applications of FDM in dentistry?

RO4: The resolution of FDM is smaller compared to SLA/SLS, and the application of FDM is more limited. It is essential to know what applications have and have not been successfully created using FDM, so it can be an alternative technique or direction for further research.

RQ5: What tests have been performed on FDM results in dentistry?

RO5: Dental applications with FDM must first pass a series of tests to be used properly. One of the tests that can be carried out is mechanical testing, such as surface roughness, carried out by Sharma *et al.*, [9]. Knowledge related to this testing will make it easier for researchers/practitioners in their work.

2 Materials and Methods

This study uses the Systematic Literature Review (SLR) method, which consists of three main stages: identification, screening, and determining the number of articles to be reviewed by five reviewers. To minimize bias, each reviewer focused on answering only one RQ and reviewed all papers obtained from the selection process. The SLR was conducted using the Scopus and IEEE databases, with inclusion and exclusion criteria as presented in Table 1. This aims to focus on the theme of the literature study so that a paper that meets the objectives can be obtained.

Table 1: Inclusion and exclusion criteria in systematic literature reviews.

Criterion	Inclusion	Exclusion
Additive manufacturing technique	FDM or FFF	Other than FDM or FFF
Topic	Dental or dentistry	Other than dental or dentistry
Article types	Research article	Other than the research article
Languages	English	Other than English
Open Access	All Open Access	Close access or subscription
Publication stages	Final	Other than the final
Year	2020–2024	Other than 2020–2024

2.1 *Identification*

This systematic literature review was conducted in accordance with the PRISMA guidelines, and the completed PRISMA checklist is provided as supplementary material. The first process in SLR is identifying the topic to be discussed. In this case, the study theme is using FDM technology in dentistry. At this stage, a search was conducted in the SCOPUS database (on March 6, 2025, 10:35 AM GMT+8) and IEEE database, with the initial query for SCOPUS database is TITLE–ABS–KEY((“fused deposition modeling” or “fused deposition modelling” or “fdm” or “fff” or “fused filament fabrication”) and (“dental” or “dentistry”), while for IEEE database, the initial query is (((“Document Title”: “fused deposition modeling” OR “fused deposition modelling” OR “fdm” OR “fff” OR “fused filament fabrication”) OR (“Abstract”: “fused deposition modeling” OR “fused deposition modelling” OR “fdm” OR “fff” OR “fused filament fabrication”) OR (“Author Keywords”: “fused deposition modeling” OR “fused deposition modelling” OR “fdm” OR “fff” OR “fused filament fabrication”)) AND ((“Document Title”: “dental” OR “dentistry”) OR (“Abstract”: “dental” OR “dentistry”) OR (“Author Keywords”: “dental” OR “dentistry”))). In this initial search, 378 articles were obtained, which were then filtered again based on the inclusion and exclusion criteria (Table 1), resulting in 91 articles.

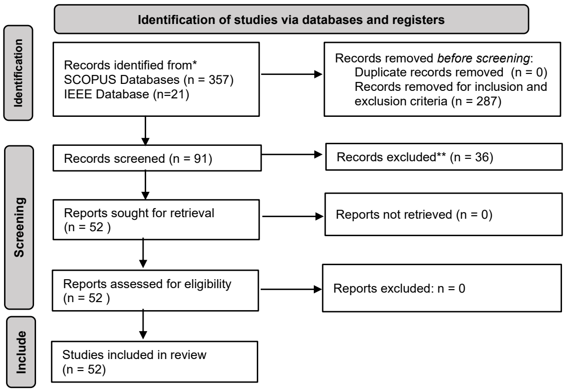

Figure 1: PRISMA Flow Diagram.

2.2 *Screening and determining the number of articles to be reviewed*

All studies included in this systematic literature review were reviewed independently by five reviewers. The screening process (Figure 1) involved quickly reviewing the titles, abstracts, and keywords of the identified articles. This aims to ensure that the articles obtained align with the desired topic focus. Based on the screening process carried out, several articles were found that had the same keywords, namely FFF. FFF is an acronym for Fused Filament Fabrication, which is often used in additive manufacturing and is the focus of this study. Meanwhile, in dentistry, the term FFF is used as an acronym for Free Fibula Flaps, a reconstructive surgical procedure to replace lost soft tissue and bone. Due to the similarity in the keywords, articles with the term FFF for Free Fibula Flaps were not used. In addition to the similarity in keywords, several articles that turned out to be review articles and editorial pages were also found. Review articles were excluded from the synthesis to prevent duplication of evidence. However, they were consulted to provide background context and to identify relevant primary studies.

After the screening process of the title, abstract, and keywords is complete, the articles are then downloaded for further reading. In this stage, there are no articles that cannot be downloaded, and after further reading, all articles can be used. The total number of articles that have gone through this screening stage and will undergo a literature review process is 52 articles. Only the most relevant outcome per study was extracted based on relevance to clinical application. Additional variables extracted included author, publication year, country, study design, dental application, FDM material type, printing parameters, and funding sources when available. Missing or unclear information was recorded as not reported. In addition, the metadata for these 52 articles will also be analyzed using the Bibliometric review.

2.3 *Appraisal design*

The methodological quality of the included articles was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Systematic Reviews and Research Syntheses [35]. This checklist was applied to evaluate methodological validity, potential sources of bias, and the quality of reporting of the systematic reviews included in this study. The appraisal process was conducted independently by five reviewers. Only full–text articles that met the eligibility criteria and were included in the review (n = 52) were appraised. Each article was evaluated based on the 11 JBI appraisal items.

2.4 *Data extraction*

The data were systematically extracted and managed using Google Sheets. The information collected from each selected article included printing materials, application areas, process parameters, testing and evaluation methods, post–processing procedures, comparisons with other 3D printing technologies, and comparisons with alternative materials.

Studies were grouped based on dental application and FDM material type to ensure comparability within each synthesis category. Given the heterogeneity of study designs and outcome measures, no quantitative synthesis was conducted. Therefore, effect measures were presented descriptively, including reported accuracy values, mechanical properties, and qualitative performance comparisons. No data transformation was required. Missing summary statistics were reported as not available. Results were synthesized using summary tables, graphs, and narrative descriptions.

3 Result and Discussion

This SLR analysed 52 articles on the application of FDM in dentistry. The findings summarise recent research trends, commonly used FDM materials, printing parameters, 3D printer brands, dental applications, and evaluation methods for FDM–printed outcomes. Most included studies were experimental or in vitro, with limited clinical validation, which restricts the generalisability of the findings. Substantial heterogeneity in study design, materials, printing parameters, evaluation methods, and reported outcomes precluded meta–analysis. In addition, this review has methodological limitations, including restriction to selected databases and English language publications, the absence of formal risk of bias and certainty of evidence assessments, and the potential for subjective interpretation during qualitative synthesis despite independent review by multiple reviewers.

3.1 *Bibliometric review*

A Bibliometric review was conducted to determine the quantity of article data that had been obtained. As shown in Figure 2, 52 articles from 33 sources, published between 2020 and 2024, exhibit an annual growth rate of 18.92% and an average citation per document of 10.79. This indicates a sustained and increasing research activity in the field of FDM applications in dentistry.

Timespan 2020:2024
Sources 33
Documents 52
Annual Growth Rate 18.92 %
Authors 258
Authors of single-authored docs 1
International Co-Authorship 25 %
Co-Authors per Doc 5.4
Author's Keywords (DE) 185
References 2210
Document Average Age 3.56
Average citations per doc 10.79

Figure 2: Main information on the literature used.

Figure 3 illustrates the publication trends from 2020 to 2024, presenting both the number of publications and the average citations per year. Figure 3 illustrates an increasing trend in the number of publications, particularly in 2023 and 2024, alongside a decline in the average number of citations per year. This decrease is mainly due to the higher proportion of recently published articles, which have had limited time to accumulate citations. As a result, the lower average citation values reflect a temporal effect rather than a decline in research impact, while the growing number of publications indicates continued interest and expansion of the research field.

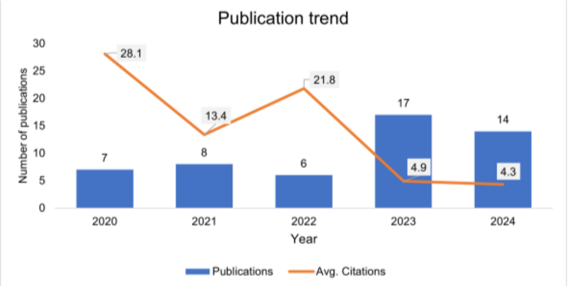

Figure 3: Publication trend (2020–2024).

The most papers associated with FDM and dentistry are Materials and Polymers, with 7 and 6 articles sourced from MDPI publishers. We can also see other publishers such as Wiley, Springer, and Elsevier, with the same focus (Table 2). This shows that the reviewed articles have good enough quality to be studied.

Table 2: Source of articles.

Total Articles	Source	Publisher	H–Index	SJR	IF
7	Materials	MDPI	161	0.521	3.2
6	Polymers	MDPI	159	0.519	4.9
2	Advances in Science and Technology Research Journal	Politechnika Lubelska	14	0.227	1.3
2	Applied Sciences (Switzerland)	MDPI	162	0.521	2.5
2	Clinical and Experimental Dental Research	Wiley	12	0.321	2.2
2	Clinical Oral Investigations	Springer	108	1.321	3.1
2	Dental Materials	Elsevier	143	2.321	6.3
2	Heliyon	Elsevier	47	0.521	3.6
2	Journal of Dentistry	Elsevier	123	1.521	5.5
2	Journal of Prosthetic Dentistry	Elsevier	97	1.221	4.8

Figure 4 presents the keyword co–occurrence network generated using VOSviewer. A total of 23 thematic clusters were identified, each represented by a distinct color, reflecting major research domains within the field. The network reveals prominent clusters related to digital workflow and additive manufacturing technologies, material systems and mechanical performance, and clinical dental applications. Smaller and less interconnected clusters correspond to biological response and safety evaluation, post–processing, and regenerative or bioactive material applications. The limited overlap between technology and biology-oriented clusters highlights a persistent gap between manufacturing feasibility and biological as well as clinical validation in current FDM dental research.

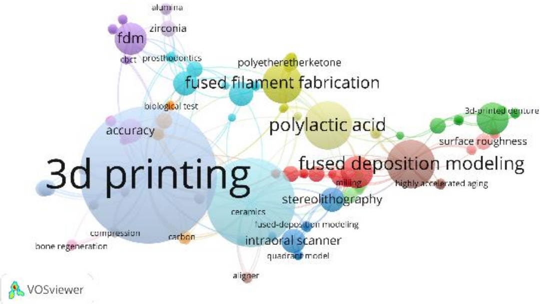

Figure 4: Network visualization of FDM in dentistry.

3.2 *Material used*

Table 3 shows the widely used materials in 3D printing for dentistry. As one of the most frequently used materials in FDM, PLA has also been used in dentistry [11], [15], [17], [20], [36]–[43]. In addition to regular PLA, various PLA developments are used in dentistry research. Liu *et al.*, [44] have used medical–grade PLA, a PLA development material prepared explicitly for applications in the medical and healthcare fields. PLA material with Biocompatibility was also studied by De Angelis *et al.*, [45], who developed PLLA combined with 10% hydroxyapatite (HA). In addition, Lümkemann *et al.*, [46] conducted a study using PLA HT, an improved PLA material for higher temperature resistance than standard PLA.

In 2023, when environmental issues began to develop, Nagata *et al.*, [19] used environmentally friendly virgin and recycled PLA materials. This environmental issue was also used by Mousa [47], who used Z–PLA, a PLA material with a smooth surface and low shrinkage. Not only that, Ime *et al.*, [48] also used PLA/PHA, which offers better durability and ease of printing and is easily biodegradable. In addition to features, material color is also an option in research. Grzebieluch *et al.*, [49] used metallic silver PLA, while Ishida *et al.*, [18] used natural PLA.

In addition to PLA, ABS is also a material often used in FDM because it offers better strength. In research in the field of dentistry, ABS is also often used [50]–[52]. De Freitas *et al.*, [53] conducted a study using ABS Premium+ filament, which offers advantages in terms of good impact and thermal resistance, as well as better durability compared to regular ABS. Better capabilities than regular ABS are also utilized by Anadioti *et al.*, [54], who use ABS–M30. This filament is 25–75% stronger than regular ABS and offers versatility, ease of use, and durability. Not only that, ABS is also available in medical grade, which has been used by Jaber *et al.*, [55].

Table 3: Materials used in this study.

Material	Notes
Polyether	Medical–grade PEEK [56]–[58]; PEEK [16], [56], [59–61], PEEK + Amorphous magnesium phosphate (AMP) [62]; PEEK Biosolution [56], PEKK–A [61]; Polyether for impression material [14]
ABS (Acrylonitrile Butadiene Styrene)	ABS Filament Premium+ [53], ABS [50–52], ABS–M30 [54]; Medical–grade ABS [55].
Poly (ε-caprolactone) (PCL)	PCL+ buffering agents (CaCO3, Na2HPO4, NaHCO3, TRIS, and MgCO3) [63]; PCL+ poly(vinyl alcohol) (PVA) or poly(ethylene glycol) (PEG) [13], [64], PCL + 20% β–TCP [45]
PLA (Polylactic Acid)	medical grade PLA [44]; PLA [11], [15], [17], [20], [36–43]; Metallic silver PLA [49]; virgin and recycled PLA [19]; Z-PLA [47]; PLA/PHA [48]; natural PLA [18]; Renfert PLA HT Filament [46]; PLLA +10% hydroxyphatite (HA) [45]
Other materials	Arfona Tray ([14]; Polylite PETG [65]; Polywood [66]; PMMA (Polymethylmethacrylate) [67], [68], $ZrSiO_4$ [69]

In addition to PLA and ABS, another material that is often used in dentistry is Polyether. This filament is stronger and more resistant to high temperatures than ABS and PLA, making it suitable for dentistry. In their research, Rues *et al.*, [14] used polyether material for molds. One of the polyethers commonly used in dental research is PEEK [16], [56], [59]–[61]. Han *et al.*, [57], Han *et al.*, [58], and

Miura *et al.*, [56] used medical–grade PEEK, which has biocompatible properties, making it suitable for use in dentistry. Biocompatibility is important in dental research. In 2023, Bokam [62] researched the combination of PEEK and Amorphous magnesium phosphate (AMP) so that it can integrate with tissue. Polyether filaments used in FDM are not only PEEK but also PEKK. A comparison of polyether materials such as PEEK and PEKK has been carried out by Paszkiewicz *et al.*, [61]. The study concluded that PEKK, after heat treatment, has advantages in mechanical properties and less bacterial adhesion to the surface than PEEK.

Research related to dentistry is not only related to teeth, but also to drug delivery. The material commonly used for this application is Poly(ε–caprolactone) (PCL). In 2024, Schüler *et al.*, [63] used PCL material and buffering agents ($CaCO_3$, Na_2HPO_4, $NaHCO_3$, TRIS, and $MgCO_3$); and de Angelis *et al.*, [45] in 2023 used PCL + 20% β–TCP material. Meanwhile, Berger *et al.*, [13] and Berger *et al.*, [64] used the same material, namely PCL + poly(vinyl alcohol) (PVA) or poly(ethylene glycol) (PEG).

Other filaments used in dentistry include Arfona Tray [14]; Polylite PETG [65]; Polywood [66]; PMMA (Polymethylmethacrylate) [67], [68], and $ZrSiO_4$ [69]; however, these materials are still not widely used. Research on dental filaments is a rapidly evolving field with substantial potential for further development. Lüchtenborg *et al.*, [7] also discussed the opportunities for future materials, one of which is the use of multi–materials, which currently cannot be done by SLA/SLS and can only be done by FDM technology. Figure 5 presents a summary of the materials used in FDM printing. The figure was generated based on the materials reported in the studies included in this SLR, as summarized in Table 3. The most frequently used material is PLA, including its various derivatives, followed by polyether, ABS, PCL, and other materials. The predominance of PLA in the included studies reflects its favorable combination of biocompatibility, printability, and accessibility, which has facilitated its widespread adoption in dental FDM research. However, the limited use of other polymers highlights important research gaps, particularly the scarcity of studies exploring multi-material FDM and high-performance polymers for functional dental applications. Furthermore, conflicting findings regarding optimal printing parameters across different materials suggest that FDM performance is highly material dependent, underscoring the need for application specific material selection and standardized optimization protocols. Future research should therefore expand beyond PLA centered investigations to address material diversity, process material interactions, and their implications for clinical translation.

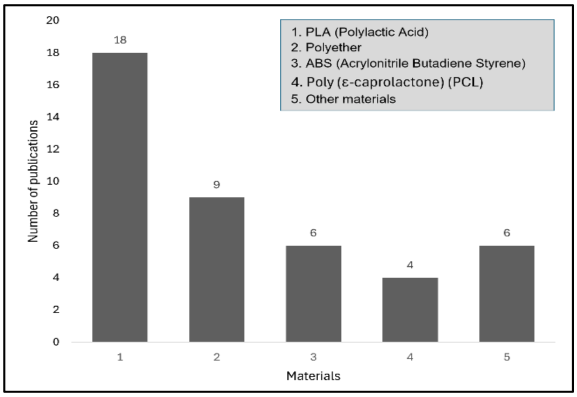

Figure 5: Distribution of FDM materials used in the included studies.

3.3 *FDM printer*

FDM fabricates products by extruding materials through a nozzle and joining them to manufacture three dimensional objects [70], [71]. In the application of FDM in dentistry, several stages are involved, ranging from material selection to clinical use. Figure 6 illustrates the FDM workflow for dentistry, beginning with the choice of material and the creation of a CAD model, which can be obtained from self–designed drawings, intraoral scans, CBCT data, or other sources. This is followed by the slicing process, performed using various software, the printing process with FDM technology, and subsequent post–processing through different available techniques. Finally, before clinical use, the printed objects undergo testing, which may include mechanical evaluation, material characterization, biological assessment, or other relevant tests.

Knowledge of FDM printers is essential to determine the needs of researchers/practitioners. Table 4 provides an overview of the printer models used and their specifications. For the most significant build volume owned by AON–M2 used in the study [60], with a size of 450x450x450 mm. Meanwhile, the maximum speed is 300 mm/s or equivalent to 18,000 mm/min, which is found in the AON–M2 printer [60], Ultimaker 2 Extended+ [39], and Ultimaker 2+ Connect [49].

Table 4: Printers used identified in this study.

3D Printer Model	Build Volume (mm)	Max Speed (mm/s)	Max Nozzle Temp (°C)	Max Bed Temp (°C)	Resolution (microns)	Dual Nozzle Feature
AON–M2 [60]	450 x 450 x 640	300	470	200	20	Yes
Apium M220 [58]	205 x 155 x 150	150	540	160	50	No
Apium P220 [57]	205 x 155 x 150	150	540	160	50	No
Craftbot Plus Pro [72]	300 x 200 x 250	200	300	110	50	No
Creality Ender 3 [51]	220 x 220 x 250	180	255	110	100	No
Creatbot PEEK–300 [16]	300 x 250 x 300	120	500	120	40	Yes
Cubicon Style Plus A15D [17], [37]	150 x 150 x 150	200	260	120	50	No
FlashForge Adventurer [36]	150 x 150 x 150	100	240	100	100	No
FlashForge Creator Pro [41], [48], [53]	227 x 148 x 150	100	240	120	100	Yes
Flow IDEX [65]	460 x 300 x 300	200	300	120	50	Yes
Fortus 450mc [54], [73]	406 x 355 x 406	200	300	200	178	No
INTAMSYS Funmat HT [56], [61]	260 x 260 x 260	150	450	160	50	No
Lingtong III [44]	300 x 300 x 400	150	260	120	100	Yes
LulzBot TAZ 6 [67]	280 x 280 x 250	200	300	120	50	No
MakerBot Method [40]	190 x 190 x 196	200	300	100	20	Yes
Markforged X7 [72]	330 x 270 x 200	100	300	140	50	No
Moment M350 [38]	350 x 350 x 400	150	300	120	50	Yes
Prusa i3 MK3 [12], [47], [55], [72], [74]	250 x 210 x 200	200	300	120	50	No
Prusa Mini LCD [45] (46)	180 x 180 x 180	200	280	100	50	No
Qidi Tech X–Max [68]	300 x 250 x 300	150	300	120	50	Yes
r.Pod Arfona [75]	200 x 200 x 200	100	260	100	100	No
Raise3D E2 [50]	330 x 240 x 240	150	300	120	50	Yes
Raise3D Pro 2 [11], [13], [14], [20], [64]	305 x 305 x 300	150	300	120	50	Yes
Simplex, Renfert [46]	150 x 150 x 150	100	260	100	100	No
Sunlu S8 Pro [42]	310 x 310 x 400	150	260	100	100	No
Ultimaker 2 Extended+ [39]	223 x 223 x 305	300	260	100	20	No
Ultimaker 2+ Connect [49]	223 x 220 x 205	300	260	100	20	No
Wanhao Duplicator 6 [76]	200 x 200 x 180	150	300	120	20	No
Zortrax M200 [52]	200 x 200 x 180	100	290	110	25	No

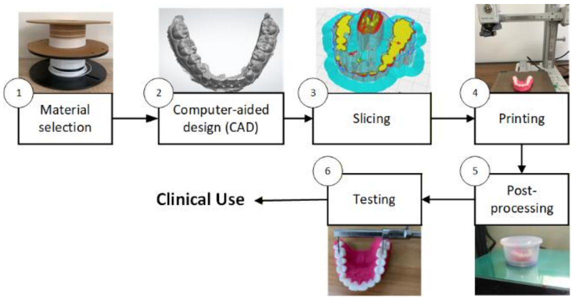

Figure 6: FDM workflow for dentistry.

Printing for dental applications does not require enormous print sizes. However, larger dimensions allow for more prints per print. Furthermore, maximum speed also offers the potential for efficiency in dental printing.

The highest maximum nozzle temperature is 540 °C, owned by the Apium M220 [58], and P 220 [57]. This maximum nozzle temperature is essential, considering the polyether material requires high nozzle and bed temperatures. While PLA can be printed at temperatures ranging from 190 to 230 degrees Celsius, ABS can be printed at temperatures of 250–280 degrees Celsius, and PEEK can be printed at temperatures of 370–450 °C. Therefore, if the maximum temperature of the 3D printer is only up to 300 degrees Celsius, printing with PEEK material will be difficult. The same applies to the bed temperature. If the bed temperature is not high enough, the PEEK material will not adhere well to the bed, potentially causing printing failure. AON–M2 [60] and Fortus 450 mc [54], [73] hold the highest maximum bed temperature at 200 °C. Meanwhile, good resolution is owned by the AON–M2 printer, Ultimaker 2 Extended+ [39], Ultimaker 2+ Connect [49], and Wanhao Duplicator 6 [76] with 20 microns.

Additionally, the dual nozzle feature is one of the attractions of the FDM printer, as it enables the printing of more than one material directly. This is necessary for printing dental products that require two colors or two different types of materials simultaneously, such as dental models (white for teeth and pink for gums). However, using a dual–nozzle 3D printer tends to be more time–consuming, as it requires changing the filament during the printing process. Some printers that have this feature are AON–M2 [60], Creatbot PEEK–300 [16], FlashForge

Creator Pro [41], [48], [53], Flow IDEX [65], Lingtong III [44], MakerBot Method [40], Moment M350 [38], Qidi Tech X-Max [68], Raise3D E2 [50], and Raise3D Pro 2 [11], [13], [14], [20], [64]. In this literature review, several studies were also obtained that used other printers as a comparison. Some of the printers used and their technologies can be seen in Table 5.

3.4 *Print parameters*

Printing in dental applications may have different parameters than other applications. Based on the literature study, some parameters used in dental–related research are nozzle temperature, layer thickness, filler density, build plate temperature, print speed, and nozzle diameter (Table 6).

Table 5: Other printers used.

No	Technology	Printer
1	DLP	Nextdent D–150 [41]; Pro4K80 and D20+ [65]; Rapidshare D30II [75]; Phrozen Shuffle Lite [49]; Moonray sprintray [55]; Cara print 4.0 pro [38]; Planmeca creo []
2	SLA	Form2 (Formlabs) [41], [48], [54], [73]; form 3 [77]; form 3B [65]; Nobel 1.0, xyz printing [18]; DW028D, DWS [18]; Anycubic photon [50]; Photon Mono 4k [51]
3	LCD	Sonic 4K [65]
4	Multi–jet	ProjetDP3000, 3D Systems [18], Projet 6000 [54]
5	PolyJet	Connex 500 [73]
6	SLS	EOSINT P 395 [73]

Table 6: Parameters used.

Parameter	Typical Ranges	Notes	Range
Nozzle temperature	190 °C –480 °C	Commonly set at 210 °C for PLA; up to 480 °C for PEEK.	68–93 [63]; 110 [45]; 145 and 100 [13]; 175 [45]; 180 [78]; 190 [42]; 200 [40], [42], [44]; 210 [20], [36], [40], [42], [74]; 215; 220 [12], [69]; 225 [19]; 230 [38]; 235 [53]; 240 [50]; 245 [72], [75]; 250 [51], [67], [74]; 230–255 [74]; 340 [61]; 360 [61]; 380 [60], [61]; 410 [62]; 420 [59]; 480 [57], [58]
Layer thickness	0.06 mm –0.4 mm	Common values: 0.1 mm, 0.2 mm; often set at 100 µm (0.1 mm) or 200 µm (0.2 mm).	0.05 [50]; 0.1 mm [37], [38], [44], [48], [49], [60], [69]; 0.12 (50); 0.16 mm [36], [51]; 0.17 [39]; 0.2 mm [13], [57], [58], [64], [68], [72], [74], [76]; 0.26 mm [63]; 0.28 [68]; 0.3 [60]; 0.41 mm [63];
Infill density	25%–100%	Varies based on application; 100% for high strength applications.	20% [50]; 25% [43]; 40% [68]; 50% [43]; 65% [68]; 75% [43]; 90% [68], [74]; 100% [20], [51], [72], [74]
Build plate temperature	60 °C –140 °C	Typically, around 100 °C; 40 °C for less demanding materials.	130 [57], [58], 40 [13], [75], [78]; 30 [13]; 110 [53], [72]; 50 [36]; 100 [50], [51], [60], [67]; 160 [62]; 60 [12]; 140 [61]; 45 [76]
Print speed	30 mm/s–80 mm/s	Common speeds around 30 mm/s, up to 60 mm/s or 80 mm/s for some setups.	600 mm/min [60], [76]; 900 mm/min [61]; 1500 mm/min [61]; 1800 mm/min [50], [61], [62], [78]; 2000 mm/min [57], [58]; 2100 mm/min [59]; 3000 mm/min [36], [42]; 3600 mm/min [20], [53]; 4500 [42]; 4800 mm/min [51]; 6000 mm/min [42]
Nozzle diameter	0.25 mm, 0.3 mm, 0.4 mm, 0.6 mm	Diameter affects detail and flow rate.	0.1 mm [75]; 0.3 mm [44]; 0.33 [63]; 0.4 [36], [37], [43], [57]–[59], [61], [69], [74], [76]; 0.51 [63]; 0.6 [43], [60], [78]; 0.8 mm [43], [74]

Nozzle temperature is one of the parameters that has quite an influence on additive manufacturing printing. In the literature review, the nozzle temperature ranges fairly widely, namely 68 to 480 degrees Celsius. Low temperatures are usually used for PCL materials, as done by Schüler *et al.*, [63], with a nozzle temperature range of 68–93 degrees Celsius. Meanwhile, PLA has a temperature range of 190–220, and ABS has a temperature range of 220–250. Nozzle temperature parameters that can withstand high temperatures are typically sought, allowing for the use of various filaments, which can exceed 300 degrees Celsius.

Layer thickness is also a parameter that is often used in additive manufacturing. Usually, this parameter will affect the process time and surface smoothness. In this literature study, the layer thickness is quite diverse, from 0.05 mm [50] to 0.41 mm [63]. Infill density is a parameter that usually affects strength and cooling time. The greater the infill density, the stronger it is, and vice versa. In dental applications, the infill density is usually 100% [20], [51], [72], [74], so the resulting product has maximum strength. However, the infill density can be reduced in applications that do not require too much strength, such as models. So that the printing process becomes faster and cheaper, Richter *et al.*, [50] in 2022 used an infill density of 20%.

Print speed is a parameter that can affect the manufacturing time, accuracy, and surface smoothness. Usually, printers have speed limits, so not all printers can run at high speeds. On the other hand, some materials require low speeds because they have low shore hardness. Based on the results of the literature review, the lowest speed used in dental research is 600 mm/min [60], [76], and the highest is 6000 mm/min [42].

Other parameters used are the build plate temperature and the nozzle diameter. The build plate temperature must be set so that the printed object sticks to the build plate. The temperature also depends on the material used; for PLA, the build plate temperature usually ranges from 45–60 degree Celsius [36], while PEEK is much higher than that [57], [58], [61]. What needs to be remembered is that not all printers have a heated bed, and even if they do, the maximum temperature must be considered. Meanwhile, the nozzle diameter usually affects the flow rate and the details produced. Spintzyk *et. al.,*. [75] used the smallest nozzle diameter of 0.1 mm, while Nakonieczny *et al.,* and Hamed & Abbas [43], [74] used the largest diameter of 0.8 mm.

3.5 *FDM applications in dentistry*

The application of FDM technology in dentistry has gained attention across various domains (Table 7). A significant portion of the printed objects are test specimens, serving as references for the development of more advanced applications. These specimens are typically designed to evaluate key aspects such as mechanical properties, biological interactions, and material performance under specific conditions. Several types of test specimens have been explored in the literature. Among the most commonly used are dog–bone-shaped specimens [47], [51], [61], [62], [64], [72], [74], which are often utilized to assess the mechanical properties of materials, including tensile and flexural strength. Other test specimens include those designed to evaluate microbial adhesion [36], which are crucial for understanding the biological interactions of dental materials. Further specimens have also been developed, for example: testing specimens for mechanical properties, especially temporary restorations [37]; flexural strength [61] and Vickers Microhardness test specimens [78]; torsional fatigue specimens [72]; Cad models [42], [54], [56], [60]; 3–point flexural specimens [68]; Compressive Properties of Rigid Plastic Test Objects [43]; cylindrical shapes for biological research [61]; and disk samples [57], [58].

Table 7: Objects that have been made with FDM.

Object	Notes
Scaffolds	Composite scaffolds [63]; LayFomm scaffold [76]
Tooth caps	Customized fluoride–releasing tooth caps [13]; tooth caps [64]
Surgical guides	Surgical guides [11]; surgical guides used in oral implant placement [12]
Testing specimens	Dog-bone shaped specimens [47], [51], [61], [62], [64], [72], [74]; specimens designed for evaluating microbial adhesion [36]; testing specimens for the mechanical properties specifically interim restorations [37]; flexural strength [61] and Vickers microhardness tests specimens [78]; torsion fatigue specimen [72]; CAD model [42], [54], [56], [60]; 3–point bending specimens [68]; Compressive properties of rigid plastics test specimens [43]; cylindrical shape for biological research [61]; disk samples [57], [58]
Membranes	Unidirectional–release permeable membranes [64]
Dental trays	Dental trays [64]; impression tray [14], [15]
Implants	Modified porous poly–ether–ether–ketone (PEEK) implants [59], dental implant [16]; modified implant abutment holder [44]
Crowns	Temporary crowns [17]; model crowns [18]; provisional crowns [19]; dental crown [20]
Models	A maxillary model of a patient with partial edentulism [65]; dental models [19], [38], [40], [45], [48–50], [55], [67], [73], [77]; aligner model [46]; maxillary models [47]; scaffold models [39]; Presurgical Dental Models [52]; CBCT–derived mandibular casts [66]; maxillary arch casts [53]
Prosthetics	Dental prostheses mold (specifically including crowns, couplings, bridges, and dentures) [69]; Provisional Fixed Dental Prostheses [41]; non–metal clasp removable partial denture (RPD) [75]

The next most widely researched objects are models and prosthetics, several maxillary models of patients with partial edentulism [65]**;** dental models [19], [38], [40], [45], [48]–[50], [55], [67], [73], [77]; aligner model [46]; maxillary models [47]; scaffold models [39]; Presurgical Dental Models [52]; CBCT–derived mandibular casts [66]; maxillary arch casts [53].

Models and prosthetics are not used directly on the patient, so they do not require high strength. The same goes for surgical guides and dental trays. Research related to surgical guides was conducted by Pieralli *et al.*, [12], who used them in oral implant placement in 2020. Dental trays were conducted by Berger *et al.*, [64] in 2022, and impressions were conducted by Priyadharsini *et al*., and Rues *et al*., in 2023 and 2024 [14], [15].

Dental research can also be done to make tooth caps, as done by Berger *et al*., [64] in 2022, and even Berger *et al*., [13] have been able to create customized fluoride-releasing dental covers. Scaffolds 45,51] and membranes [64] are also among the applications that FDM can make.

High strength in dental research is necessary, especially in the development of implants and crowns, which are currently being manufactured. Implants and crowns have unique shapes depending on the case, thus requiring technology that can perform easy and cheap fabrication processes. Some applications that have been made related to implants and crowns include modified porous PEEK implants [59], dental implants [16], modified implant abutment holder [44]**,** temporary crowns [17], model crowns [18], provisional crowns [19], and dental crowns [20].

A summary of the materials used in FDM and their applications is presented in Figure 7. Figure 7 illustrates a Sankey diagram that shows the relationship between FDM materials and their specific applications in dentistry. In the diagram, wider flows indicate materials that are more widely utilized for multiple purposes, such as PLA in dental models, presurgical models, specimens, and others. In contrast, specialized materials like PETG are linked to more specific applications, such as implants. This mapping highlights the diversity of materials employed in dentistry and their corresponding applications.

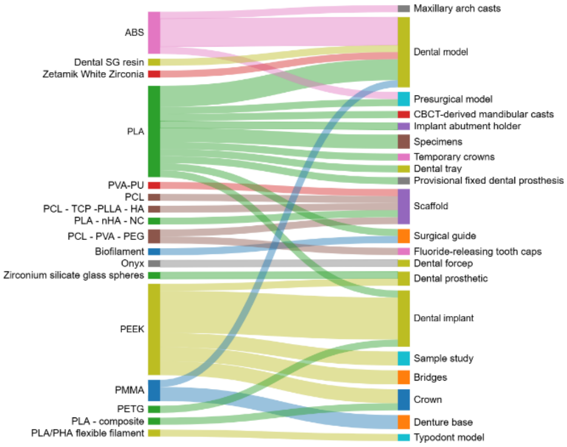

Figure 7: Sankey diagram illustrating the relationship between FDM materials and the applications.

3.6 ***Testing***

Some of the tests conducted in the literature are mechanical (Table 8), material characterization (Table 9), biological (Table 10), and dimensional (Table 11). Mechanical testing is performed to determine the mechanical properties of the printed object using FDM. Mechanical testing that is often conducted includes tensile and flexural strength, both of which are necessary in dental research.

Usually, after knowing the mechanical properties, researchers will try to find out how the screening was obtained by conducting material character tests (Table 9). The material character test is often done with SEM, a test to see the microscopic structure.

Biological testing (Table 10) is performed to determine the biocompatibility of the printed object. The most performed biological tests are in vivo and in vitro studies to evaluate biological performance and interactions. Several studies assessing FDM fabricated thermoplastics for dental applications provide indirect evidence of cytotoxicity through cell viability, adhesion, proliferation, or in vivo tissue responses in animal models, without standardized cytotoxicity testing (e.g., ISO 10993–5) or analysis of material degradation byproducts. Although these findings consistently indicate acceptable initial biocompatibility, they remain insufficient to substantiate long-term biological safety in the intraoral environment.

Evidence related to oral environment degradation also reveals a substantial gap. Only a limited number of studies simulate oral conditions using artificial saliva, PBS immersion, or pH–cycling, and these evaluations primarily focus on short–term functional stability (e.g., active–agent release or macroscopic structural integrity). Consequently, the true degradation behavior of FDM thermoplastics under complex intraoral conditions remains poorly characterized. Meanwhile, wear behavior of thermoplastics in the oral cavity is not addressed in the reviewed studies. The absence of wear-related data directly limits the clinical translation of FDM materials for long-term intraoral applications. Future studies should integrate cytotoxicity, oral–environment degradation, and intraoral wear evaluations to ensure the safety, durability, and clinical reliability of FDM fabricated materials in dental practice.

Dimensional tests (Table 11) are also an essential factor in dentistry for evaluating the accuracy of objects. The most frequently performed test is the truth assessment, which aims to evaluate the accuracy of the impression model compared to its original dimensions.

Table 8: Mechanical test.

Testing Procedure	Description/Method	Objective	Result
Tensile Testing	Static tensile tests according to EN ISO 527:2012 standards.	Determine tensile strength and elongation properties.	~45–70 MPa [13], [64] ; ~65–90 MPa [62] ; ~40–65 MPa [79] ; ~50–80 MPa [51] ; ~60–85 MPa [58] ; ~70–95 MPa [74] ; ~55–75 MPa [39] ; ~60–100 MPa [61] ; ~45–65 MPa[50] ; ~70–90 MPa [72]
Flexural Strength Test	Three-point bending method to assess the flexural strength of specimens.	Measure flexural properties of materials.	~50–85 MPa [67] ; ~70–95 MPa [37] ; ~60–80 MPa [69] ; ~55–90 MPa [45] ; ~60–100 MPa [51] ; ~80–120 MPa[78] ; ~65–95 MPa [58] ; ~90–130 MPa [56] ; ~55–75 MPa [68] ; ~80–140 MPa [61]
Impact Strength Test	A standardized procedure to measure the impact strength of materials by determining the energy absorbed during fracture under sudden loading.	Evaluate the material's resistance to sudden impacts and its durability in real-world applications.	~2–5 kJ/m² [67] ; ~4–9 kJ/m² [61]
Compression Test	Assessment of compressive strength under specified conditions.	Evaluate materials' compressive capacities.	~150–250 MPa [20] ; ~140–220 MPa [51] ; ~120–200 MPa [43] ; ~160–260 MPa [39]
Fatigue Testing	Evaluation of the material's ability to withstand cyclic loading over time.	Assess durability under repetitive stress.	Inferior to conventional tools [16]; Improved fatigue resistance [72]
Shore D Hardness Testing	Hardness measurement using a Shore durometer for polymer and composite samples.	Assess the hardness properties of materials.	~75–85 [37] ; ~70–88 [51] ; ~85–90 [72]

Table 9: Material characterization test.

Testing Procedure	Description/Method	Objective	Ref.
Scanning Electron Microscopy (SEM)	High-resolution imaging to observe microstructures and surface morphology of samples.	Analyze surface characteristics at a micro–scale.	[13], [20], [39], [45], [56], [57], [63], [72]
X–ray Diffraction (XRD)	Analysis of material crystalline structures and phases using X–ray diffraction patterns.	Determine material composition and crystalline orientation.	[64]
Differential Scanning Calorimetry (DSC)	Thermal analysis to identify phase transitions and thermal properties.	Understand thermal behavior and stability of materials.	[13], [39], [61], [62]
Fourier Transform Infrared Spectroscopy (FTIR)	Chemical characterization of materials by measuring the absorbance of infrared light.	Identify functional groups and molecular structure.	[39]
Dynamic Mechanical Analysis (DMA)	Assessment of material viscoelastic properties under varying temperatures and frequencies.	Evaluate mechanical performance under dynamic conditions.	[62]
Surface Roughness Measurement	Measurement of the surface texture using a rugosimeter or optical techniques.	Assess surface finish and quality of printed materials.	[16], [18], [36], [37], [42], [57], [58], [60], [67], [77]
Surface Wettability Measurement	Contact angle measurement to determine how wettable the surface is.	Evaluate the interaction of materials with liquids.	[16], [36], [57], [67]
Gravimetric Analysis	Measurement of mass change during material absorption or exposure to fluids.	Assess water absorption and solubility properties.	[13], [39], [61], [69]
Histological Analysis	Examination of tissue samples to evaluate the response to the implanted materials.	Investigate biological responses at the cellular level.	[59], [76]

Table 10: Biological test.

Testing Procedure	Description/Method	Objective	Ref.
Cytocompatibility Test	Testing cellular compatibility using cultured cells on material surfaces.	Assess the biocompatibility of materials at the cellular level	[58]
Microbial Colony Count	Quantification of viable microbial cells after incubation on different materials.	Evaluate antibacterial properties against oral bacteria.	[77]
Compatibility with Oral Bacteria	Testing how materials interact with common oral bacterial strains.	Assess potential for microbial adherence.	[64]
In Vivo and In Vitro Studies	Biological assessments in living organisms (in vivo) and controlled laboratory settings (in vitro).	Evaluate biological performance and interaction.	[13], [57]–[59], [64], [76]
Biocompatibility Assessment	Evaluate the tissue response and integration of materials in biological systems.	Determine safety for use in medical applications.	[16], [76]
Use of Profilometer	An instrument used to measure surface roughness or texture by analyzing the contour of a surface at a microscopic level.	To assess the surface quality and roughness of dental materials or models, which refers to the texture or unevenness of a material's surface	[57], [58], [60], [73]

Table 11: Dimensional test.

Testing Procedure	Description/Method	Objective	Ref.
Interobserver and Intraobserver Reliability	Assessment of measurement consistency between different observers (interobserver) and the same observer across different instances.	To assess the consistency of measurements among observers.	[66]
Trueness Assessment	Comparing 3D printed maxillary models to original human skull dimensions using nine linear measurements taken with a digital caliper.	To evaluate the accuracy of printed models compared to the original dimensions.	[11], [14], [47]–[49], [52], [53]
Precision Assessment	Comparing dimensions among three printed models for consistency in dimensional accuracy.	To determine the consistency of printed models' dimensions.	[11], [14], [47], [49], [53]
Marginal Fit Measurement	Fitting identical provisional crowns onto fabricated models using micro–computed tomography to evaluate marginal fit at specific points.	To assess the fit of provisional crowns on printed models.	[19], [40]
Model Distortion Measurement	Careful examination of printed models for distortions in terms of widening and twisting.	To evaluate deviations in model shape and structure.	[49]
Horizontal Accuracy Testing	Comparing horizontal dimensions of models to a reference base model using stereolithography (STL) data.	To determine the horizontal dimensional accuracy of printed models.	[48]
Vertical Accuracy Testing	Comparing vertical dimensions against a reference model to determine vertical fit precision.	To determine the vertical dimensional accuracy of printed models.	[48]
3D Analysis	Superimposition of STL data sets using Geomagic software to visualize accuracy through color–coded maps of deviations.	To visually represent model accuracy via deviation mapping.	[48]

3.7 *Other technologies comparison*

In this study, several publications compared FDM with SLA and DLP technologies. Although a small number of studies also included SLS and PolyJet, these technologies were each reported in only one study and were therefore not synthesized in the present analysis. The compared objects varied across studies, and the evaluation parameters also differed, including accuracy, precision, mechanical strength, and flexural strength. Due to this methodological heterogeneity and the variability of outcome measures, a meta–analysis of the comparative data was not feasible.

Table 12 presents a qualitative synthesis of the studies comparing FDM with other 3D printing technologies included in this SLR. Green indicates that a specific 3D printing technology demonstrated superior performance compared with others for the reported parameter. Yellow indicates that the technology showed inferior performance compared with alternatives but remained clinically acceptable. Red indicates that the technology was not considered clinically acceptable in the respective study.

FDM is one of the most widely adopted additive manufacturing technologies, primarily due to its cost-effectiveness and ease of use compared to other techniques. However, there are certain considerations to be mindful of when applying FDM in the field of dentistry. Table 13 provides an overview of other commonly used 3D printing technologies in dental applications.

Table 12: Comparative performance of FDM, SLA, and DLP in dental applications.

Product	Printer		
	SLA	**DLP**	**FDM**
Surgical guide [44]	trueness and accuracy	trueness and accuracy	🟥
Clear aligner models [49]		precision	trueness
Impression rays [14]		accuracy	accuracy
Dental models [48]	trueness and precision	trueness and precision	🟨
Dental models [55]		accuracy	🟨
Screw–retained implant [38]		accuracy	🟨
Impression trays [15]		🟨	retention strength and dimensional stability
Dental models and surgical guides [51]	precision		mechanical strength
Dental models [19], [40]	accuracy		accuracy
Dental prostheses [41]	flexural strength	flexural strength	🟥
Surgical guide [12]	accuracy		accuracy
Presurgical model [52]		trueness	trueness
CAD model [54]	accuracy		accuracy

Table 13: Other technologies comparison.

Technology	Description	Advantages	Comparison
Stereolithography (SLA)	Use a laser to cure the liquid resin layer by layer.	High accuracy and smooth surface finish.	Outperforms FDM in precision, especially in dental applications.
Fused Deposition Modeling (FDM)	Extrudes heated thermoplastic filaments to form objects.	Cost-effective and easy to use, but with lower accuracy.	Results in greater distortion compared to SLA and DLP.
Selective Laser Sintering (SLS)	Use a laser to sinter powdered material into solid structures.	Good mechanical properties and support complex geometries.	Provides comparable accuracy to SLA, suitable for functional parts.
Multijet Printing (MJP)	Sprays droplets of resin onto a platform layer by layer.	High accuracy and multi-material capabilities.	Higher initial costs but better accuracy than FDM.
PolyJet	Like MJP, it allows printing with multiple materials.	Produces intricate details and varying material properties.	Typically provides better detail than FDM in dental applications.
Conventional Milling	Uses rotating cutting tools to remove material and shape objects.	High precision and excellent surface finish.	Generally, it offers superior accuracy compared to 3D printing methods.
Casting	Involves pouring liquid material into a mold to create objects.	Suitable for mass production and complex shapes.	Can produce high-quality finishes, though less flexible for rapid prototyping.
Injection Molding	Injects molten material into a mold to form objects.	Efficient for high-volume production.	Best for mass production, but not suitable for small batches.

3.8 *Determinants and barriers of clinical adoption of FDM in dentistry*

Based on the analysis and synthesis of the included studies, a translational framework for FDM in dentistry was developed to illustrate the key domains influencing clinical implementation and the associated barriers (Figure 8). The framework integrates materials, printer systems, manufacturing parameters, validation and testing, and clinical applications, emphasizing that successful translation depends on the interaction of these domains rather than on the printing technology alone. While PLA dominates current research due to its printability and suitability for indirect use, the limited availability of dental grade filaments, anisotropic mechanical behavior, and inconsistent biocompatibility testing restrict the adoption of high performance and composite materials. In addition, the widespread use of consumer grade printers introduces variability in resolution, thermal control, and reproducibility, which is further amplified by material and application dependent manufacturing parameters and inconsistent post–processing practices.

Validation and testing across the literature remain predominantly in vitro and are rarely aligned with relevant ISO dental standards, limiting regulatory readiness and clinical confidence. Consequently, FDM has reached clinical maturity primarily for indirect and low risk applications. The majority of FDM fabricated products reported in the selected papers remain at the experimental or prototype stage. Some products have demonstrated compliance with specific standards; however, this compliance is limited primarily to mechanical and material level testing, such as mechanical testing (ISO 10477, ISO 178/ASTM D790, ISO 14937, EN ISO 527, and ISO 10993), flexural testing (ISO 6872), and material characterization (ISO 10477 and ISO 868). To date, none of the reviewed FDM applications has progressed to formal human clinical trials. Although a small number of studies have reached the in vivo stage, these investigations were limited to animal models, primarily rodents, and have not yet been translated to human clinical evaluation.

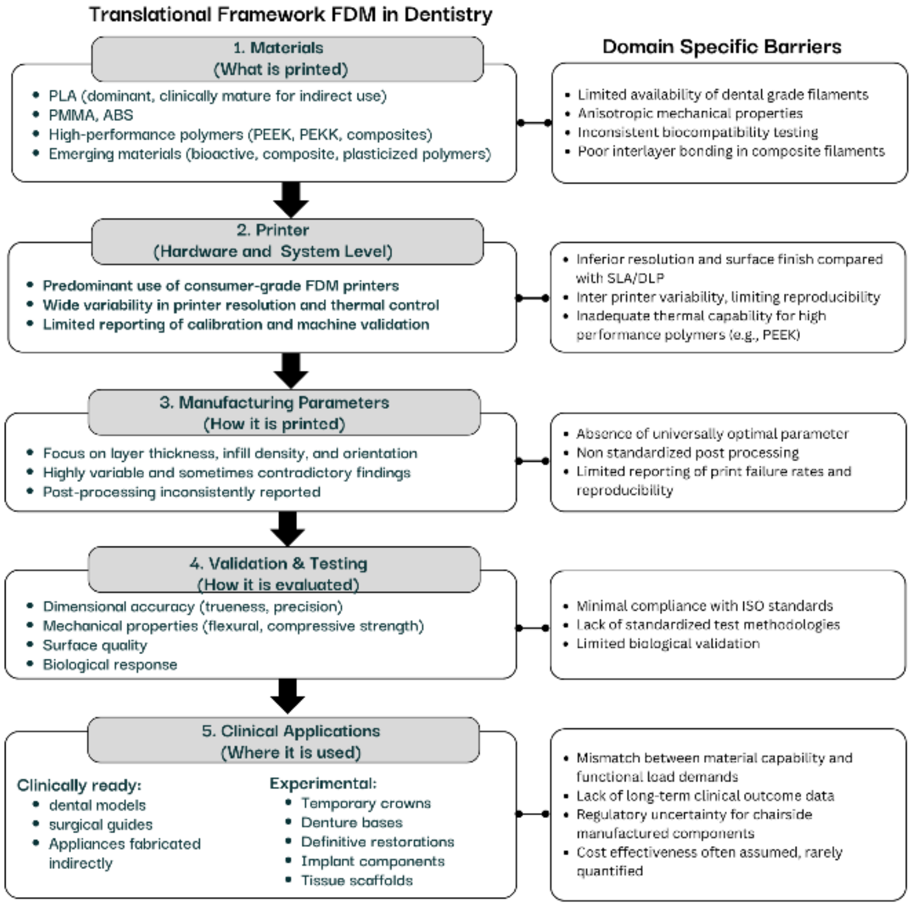

Figure 8: Translational framework for FDM in dentistry.

In contrast, several FDM fabricated products have been used in clinical workflows despite the absence of formal clinical validation. These applications mainly include dental models and other chairside auxiliary devices that are not placed directly in the oral cavity or used as definitive dental restorations. While such products do not comply with specific ISO clinical standards, they have been clinically accepted due to their demonstrated dimensional accuracy and functional adequacy for clinical use. Across all domains, translational barriers including lack of standardization, limited long term clinical evidence, regulatory uncertainty for chairside manufactured components, and the absence of robust cost effectiveness analyses continue to constrain broader clinical adoption.

The evidence from the included studies was integrated into trends, performance thresholds, critical gaps, and contradictions, highlighting both the maturity and limitations of FDM applications in dentistry to address the need for analytical synthesis. Table 14 shows the qualitative synthesis of FDM evidence in dentistry.

Table 14: Synthesis of FDM evidence in dentistry.

Aspect	Synthesis based on SLR
Trends	PLA is the dominant FDM material, widely used due to biocompatibility, low cost, and ease of printing. Research has shifted from feasibility and accuracy validation toward process optimization and material development.
	FDM has reached clinical maturity for indirect, low-risk applications, particularly dental models, surgical guides, and orthodontic workflows.
	Increasing interest in high–performance polymers (e.g., PEEK, PEKK) and composite filaments, although evidence remains largely experimental.
Performance Thresholds	Dimensional accuracy: Most studies report deviations within clinically acceptable limits for models and guides, although consistently inferior to SLA/DLP.
	Mechanical performance: FDM materials are suitable for low to moderate load–bearing applications, but not yet equivalent to milled or resin–based alternatives for definitive restorations.
	Clinical readiness: Clear differentiation emerges between applications that are clinically ready (models, guides) and those that remain conditional or experimental (definitive restorations, implant components).
Critical Gaps	Lack of standardized testing protocols for dimensional, mechanical, and biological evaluation limits cross–study comparability.
	Limited multimaterial and functionally graded FDM studies in dentistry.
	Scarcity of longterm clinical trials and in vivo evidence, particularly for load-bearing applications.
	Cost analysis is largely absent, despite frequent assumptions that FDM is more economical than conventional or other AM technologies.
Contradictions in the Literature	Conflicting findings regarding optimal layer thickness, infill density, and print orientation, with no universally optimal parameter set.
	Some studies report improved mechanical performance with reduced layer thickness, while others show minimal or material–dependent effects.
	Variability in outcomes suggests that FDM performance is highly material–and application–specific, rather than driven by printer technology alone.

4 Conclusion

Based on this systematic literature review, a total of 52 studies were analyzed to provide a comprehensive overview of the materials, equipment, process parameters, applications, and testing methods associated with FDM in dentistry. The bibliometric analysis demonstrated a growing research interest in this field, with an annual publication growth rate of 18.92% and an average of 10.79 citations per document, indicating both increasing productivity and scientific impact.

Despite this growth, several important research gaps remain. Material development emerged as a key driver for advancing FDM in dentistry, particularly the need for biocompatible, high performance, and application specific filaments suitable for medical and dental use. In parallel, manufacturing processes and parameter optimization, including post processing strategies, require further investigation, as material properties and clinical requirements necessitate tailored fabrication protocols. Moreover, the validity and reliability of FDM fabricated dental objects must be systematically evaluated under standardized conditions to ensure reproducibility and clinical safety. At present, the lack of harmonized manufacturing and testing standards represents a significant limitation to broader clinical adoption.

This systematic literature review focuses exclusively on studies addressing the application of FDM technology in dental contexts, restricted to open-access publications in SCOPUS and IEEE that were written in English and released up to 2024. Consequently, a considerable number of relevant investigations may not have been incorporated into the selection process. Moreover, the review does not provide direct cost estimations, as pricing structures vary across regions and could introduce potential bias. Most current studies rely on the assumption that additive manufacturing, particularly FDM, is more cost effective than conventional or other AM technologies, without providing detailed economic evaluations. Robust and transparent cost analyses are therefore needed, as they may play a decisive role in facilitating the clinical translation of FDM in dental practice.

In the development of research on FDM for dental applications, several key themes have emerged. First, the issue of material selection and biocompatibility remains critical. Advanced dental materials with high strength and proven biocompatibility are required. However, options such as PEEK, PLA, and composites have not yet been sufficiently investigated, particularly regarding their long-term safety. Second, dental specific process parameters, including layer thickness, infill density, and build orientation, are still underexplored, despite the continuous introduction of new printing parameters by manufacturers and the emergence of novel materials. The potential integration of multimaterial printing is also anticipated in future developments. Third, advances in post processing technologies may provide effective solutions to meet the specific demands of dental applications. Fourth, the adoption of multiaxis FDM, which could overcome current geometric limitations, remains largely unexplored. Finally, experimental testing should be aligned with international standards to enhance the readiness of this technology for market acceptance.

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Author Contributions

I.I.: conceptualization, reviewing investigation, writing an original draft, data analysis; H.M.: conceptualization, reviewing, investigation, writing an original draft; S.I.A.: reviewing, investigation, methodology, data curation, project administration; I.B.: reviewing, research design; S.B.B.: data analysis, supervision; S.S.: data analysis, supervision; W.P.S.: editing, visualization; A.E.T.: research design; S.F.D.: reviewing, investigation, editing; A.A.: conceptualization, supervision; H.H.: conceptualization, editing, funding acquisition, supervision. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online here.

List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AMP	Amorphous magnesium phosphate
BMC	Biomed Clear
CAD	Computer-aided design
CBCT	Cone Beam Computed Tomography
DLP	Digital Light Processing
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FTIIR	Fourier Transform Infrared Spectroscopy
HA	Hydroxyapatite
ISO	International Organization for Standardization
JBI	Joanna Briggs Institute
LCD	Liquid Crystal Display
MJP	Multijet Printing
PBS	Phosphate-buffered saline
PCL	Poly(ε-caprolactone)
PEEK	Poly-ether-ether-ketone
PETG	Polyethylene terephthalate glycol
PHA	polyhydroxyalkanoate
PLA	Polylactic Acid
PLLA	Poly-L-lactic acid
PMMA	Polymethylmethacrylate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PVA	poly(vinyl alcohol)
RPD	Removable Partial Denture
SEM	Scanning Electron Microscopy
SG	Surgical Guide
SLA	Stereolithography
SLR	systematic literature review
SLS	Selective Laser Sintering
STL	stereolithography
USA	United State of America
UV	Ultraviolet
XRD	X-ray Diffraction
$ZrSiO_4$	Zirconium Silicate

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