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Three-dimensional printing technologies, techniques, and materials currently used dentistry: A comprehensive review

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Abstract

This review evaluated various 3D-printing technologies and materials utilized in dentistry. Digital manufacturing, rapid prototyping, additive manufacturing, and 3D printing have gained precedence over subtractive manufacturing or milling. This cutting-edge 3D printing technology offers precise and advanced manufacturing capabilities for various materials. Technologies have been used to fabricate 3D-printed models. Some problems were associated with 3D-printing technologies: (1) the layer-by-layer image superimposition causes distortion and reduces the mechanical properties of the material; (2) the thickness of the layer affects the final model's smoothness; (3) the lack of trained technicians and clinicians hinders the implementation of 3D printers in regular clinics; (4) most 3D printing machines are not customized for dental use. Even though 3D printers can create a model in a shorter period, acquiring data takes time. To implement 3D printing in dentistry, manufacturers should aim to reduce costs and time, increase surface quality, and improve the reproducibility, reliability, and performance of this technology. Dental practitioners can customize the fabrication of temporary and permanent crowns, occlusal splints, implants, and dental aligners. However, 3D-printing machines are still less accepted than traditional treatment methods.

Keywords: 3D printing, Additive manufacturing, Digital dentistry, Digital technology, Healthcare, Materials.

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1. Introduction

Three-dimensional (3D) printing is an umbrella term utilized for additive manufacturing, rapid prototyping, or digital manufacturing that has significantly impacted various fields, including dentistry [1]. In the early 1980s, Charles Hull pioneered the world of 3D printing by utilizing Stereolithography (SLA) and subsequently obtaining a patent for the SLA process. Another notable development occurred in 1990 when scientist Scott Crump patented Fused Deposition Modeling (FDM) and founded Stratasys, which became the world's first global 3D printing company [2]. Since then, this printing technology has rapidly progressed and nudged its head in almost every technical field.

Digital dentistry encompasses many innovations, ranging from subtractive to additive technologies [1, 3]. In subtractive technology, a computer machine interfaces with a computer-aided design and manufacturing system to precisely mill a dental model such as metal ceramic blocks [4]. In additive technology, products are built in layers with the help of digital data [4-6]. 3D printing technology relies on computer-aided design (CAD) and computer-aided manufacturing (CAM) for automated development of customized digital models [7]. The process of 3D printing starts with designing virtual objects to be fabricated and then converting the information into digital files. The 3D modeling program uses CAD software to guide the 3D printer in following these instructions, resulting in the fabrication of the desired 3D printed objects [8]. The capability of this technique to fabricate customized and complex products has improved its adoption in various dentistry disciplines.

In Dentistry, 3D printing technology finds extensive application across various disciplines, spanning from endodontics to oral and maxillofacial surgery, as well as prosthetic dentistry, orthodontics, and periodontics. It offers distinct advantages over traditional manufacturing and subtractive numerical technologies [9]. The emergence of 3D printing has revolutionized the way complete dentures, implant teeth, surgical guides, and dental restorations are made, as it allows for rapid fabrication with exceptional precision and customization. This manufacturing technology has streamlined complex workflows associated with dental appliance fabrication [10]. For instance, the conventional approach to dental restoration involved milling prior to the widespread adoption of 3D printing. The use of 3D printing for fabricating restorations offers significant advantages over traditional milling processes [11]. In a study conducted by Alharbi et al., it was documented that 3D printing for restoration fabrication yielded lower internal gap values and superior edge quality compared to traditional milling [12]. In recent years, there has been a shift towards using 3D printing technology for the fabrication of dental crowns. Multiple studies have indicated that temporary dental crowns manufactured through 3D printing methods have a proper finish line compared to their counterparts produced using traditional models [13-15].

Furthermore, 3D printers play a pivotal role in the creation of tools and models for orthognathic surgical procedures. These include occlusal splints, repositioning guides, spacers, fixation plates, and anatomical models [16]. These 3D-printed surgical and non-surgical guides provide enhanced predictions of the root canal morphology and underlying bone structure and lower risks of iatrogenic damage compared to conventional endodontic procedures [17]. It has also been instrumental in sinus-lifting procedures, cyst removal surgeries Shepherd, et al. [18] rapid prototyping of anomalous teeth Zaharia, et al. [19] auto-transplantation Li, et al. [20] and implant placement [10].

3D printing technologies also find applications in periodontics for scaffold reconstructions involving bone augmentation, alveolar bone preservation, and periodontal tissue regeneration [18, 21]. The advent of 3D bioprinting has yielded promising results in constructing dental tissues to address the need for reconstructive periodontal and maxillofacial surgeries [11, 22, 23]. These technological advances enable clinicians to customize treatment plans and facilitate the sharing of patients' clinical findings through digital images and records, serving treatment, research, and educational purposes [24-26].

3D printing machines utilize various materials, including photopolymers, metals (such as cobalt chromium and titanium), ceramics, and plastics. Debates and controversies have arisen regarding the choice of materials in 3D printing processes. Materials used for dental restorations should meet specific criteria, including cost-effectiveness, durability, non-toxicity, inertness, and high clinical performance. Additionally, these materials must demonstrate biocompatibility, chemical stability, and dimensional stability to enhance the strength of prostheses [11, 27]. Furthermore, studies have reported that the materials used in 3D printing excel in accuracy and biocompatibility and possess outstanding mechanical and chemical properties [2, 27, 28]. The current materials utilized in 3D printing offer numerous opportunities to enhance clinical workflows, thereby improving the efficacy of dental prostheses through additive manufacturing.

Thus, this review discussed and critically evaluated various 3D printing technologies and materials utilized in dentistry.

2. Materials and Methods (Results/Discussion)

2.1. Three-Dimensional (3D) Printing Technologies and Materials

There are various advantages of 3D printing machines, including rapid production in small batches and customization of dental models [8, 10, 27, 29]. Moreover, this technique proves to be cost-effective, utilizing high-quality materials that benefit both patients and clinicians [2]. However, it is important to note that it also has its share of disadvantages, such as high material costs and time-consuming post-processing.

To delve deeper into this topic, this review comprehensively explores five different 3D printing technologies, including stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), photopolymer jetting, and digital light processing, along with materials and processing systems associated with each. Additionally, it will discuss the manufacturing system and primary applications of 3D printers across various branches of dentistry.

2.2. 3D Printing Techniques in Dentistry

There are various 3D printing technologies used in health care industries as Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Digital Light Process (DLP), Multi Jet Fusion (MJF), PolyJet, Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM). Among these techniques, the five most common are described in this review. Stereolithography, fused deposition modeling, selective laser sintering, photopolymer jetting, and digital light processing are the most common 3D printing techniques mentioned in dental studies. Table 1 summarizes the mechanism and features of each 3D printing technique, while materials used, strengths, limitations, and uses of these 3D printers are described in Table 2.

2.2.1. Stereolithography (SLA)

SLA, one of the oldest 3D printing techniques, was invented by Chockalingam, et al. [31]. This technique employs ultra-violet (UV) radiation to cross-link photosensitive resin layers. The software used in this technique divides the 3D model of the object into numerous thin layers, typically with a thickness ranging from 5 to 20 millimeters[32]. This process further involves using a laser to target the surface of a liquid polymer reservoir (vat), with the laser moving vertically as each polymer layer solidifies, ultimately forming a solid object [4, 33]. This technique has two approaches: (1) top-down approach and (2) bottom-up approach.

In the top-down approach, the platform descends into a liquid reservoir, creating a monomer layer between the platform and the bottom[32]. The monomer layer is then exposed to the laser, activating the polymerization reaction. This approach is then stopped locally due to the solidification of free monomers. After each cycle, the platform is checked to ensure resin flow. Conversely, the bottom-up approach involves laser scanning from the top of the reservoir, with the movable platform coated in a thin resin layer. After building the first layer, the platform descends, and the roller adds a new layer [32]. This process is repeated till the object fabrication is complete. Figure 1 illustrates the SLA printing machine's functionality.

Table 1.
Overview of the 3D printing mechanism.

3D printing techniques	Stereolithography	Fused Deposition Modeling	Selective Laser Sintering	Photopolymer Jetting	Digital Light Processing
Materials	Photopolymer resin	Solid thermoplastic filaments	Resin, metal, and ceramic powder	Metal, ceramic, and resin	Photopolymer resin
Description of process	UV light selectively cures liquid photopolymer in a vat	A plastic filament is melted and extruded through the nozzle.	A high-energy source of fuse powder particle	Inkjet printheads are used to jet liquid photopolymers onto a build platform	UV light selectively cures liquid photopolymer in a vat
Estimated cost	Low to moderate	Low	High	High	Low-moderate
Utilization of a Support system	Yes	Yes	No	No	Yes
Average resolution	High	Low	Low	Low	High
Color setting	No	Yes	Yes	Yes	No

Source: Kessler, et al. [5]

Table 2.
Materials used, strengths, limitations, and application of 3D printing techniques.

Printer type	Material used	Strength	Limitations	Application in Dentistry
Stereolithography (SLA)	Photopolymer resin (Epoxy and methyl acrylate monomers)	1. The accuracy is commendable, and the surfaces are smooth. 2. The ability to generate complicated shapes with a high level of resolution. 3. Cost-effective and efficient	1. Fragile materials 2. Heat and sun-sensitive (only photopolymers) 3. Material vat; post-cure	Dental replica model Surgical templates and guides Temporary bridges, restorations, and crowns
Digital light processing (DLP)	Photopolymer resins (resin)	1. The accuracy is commendable, and the surfaces are smooth 2. The ability to generate complicated shapes with a high level of resolution 3. cost-effective and efficient	1. Fragile materials 2. Heat and sun-sensitive (only photopolymers) 3. Material vat; post-cure.	Temporary crown Permanent crown Removable prosthesis
Photopolymer jetting (PJ)	Light curable resin (Biocompatible, VeroDent Plus, VeroDent (natural medically approved photopolymers)	1. High-quality finish and resolution (~16 microns) 2. Multicolor, smoother, finer detailing 3. Hardness-varying multi-material capacities 4. post-modification is not required	1. Expensive 2. Photopolymer materials can only be used 3. Materials decay with time	Dental replicate models Custom trays Implants surgical guides Surgical stimulation models
Fused deposition modeling (FDM)	Thermoplastic filaments (Pastes and wires)	1. Inexpensive prototyping 2. Multicolor outcomes 3. Plastic materials for non-critical loads	1. Anisotropic mechanics 2. Fragile material 3. Rough texture and a few characteristics (layer lines)	Occlusal splits Dental training device Mouth guards
Selective Laser Sintering (SLS)	Metal, ceramic, and polymer powder	1. Cost-effective and affordable printer without a support structure 2. Customized processing for complex parts using various materials 3. High-density outstanding physical properties 4. Productive gas is not required	1. Expensive materials and manufacturing processes 2. Small component size 3. Rough surface and thermal deformation	Custom-made dental prosthesis and implant

Source: Kessler, et al. [5] and Jawahar and Maragathavalli [30].

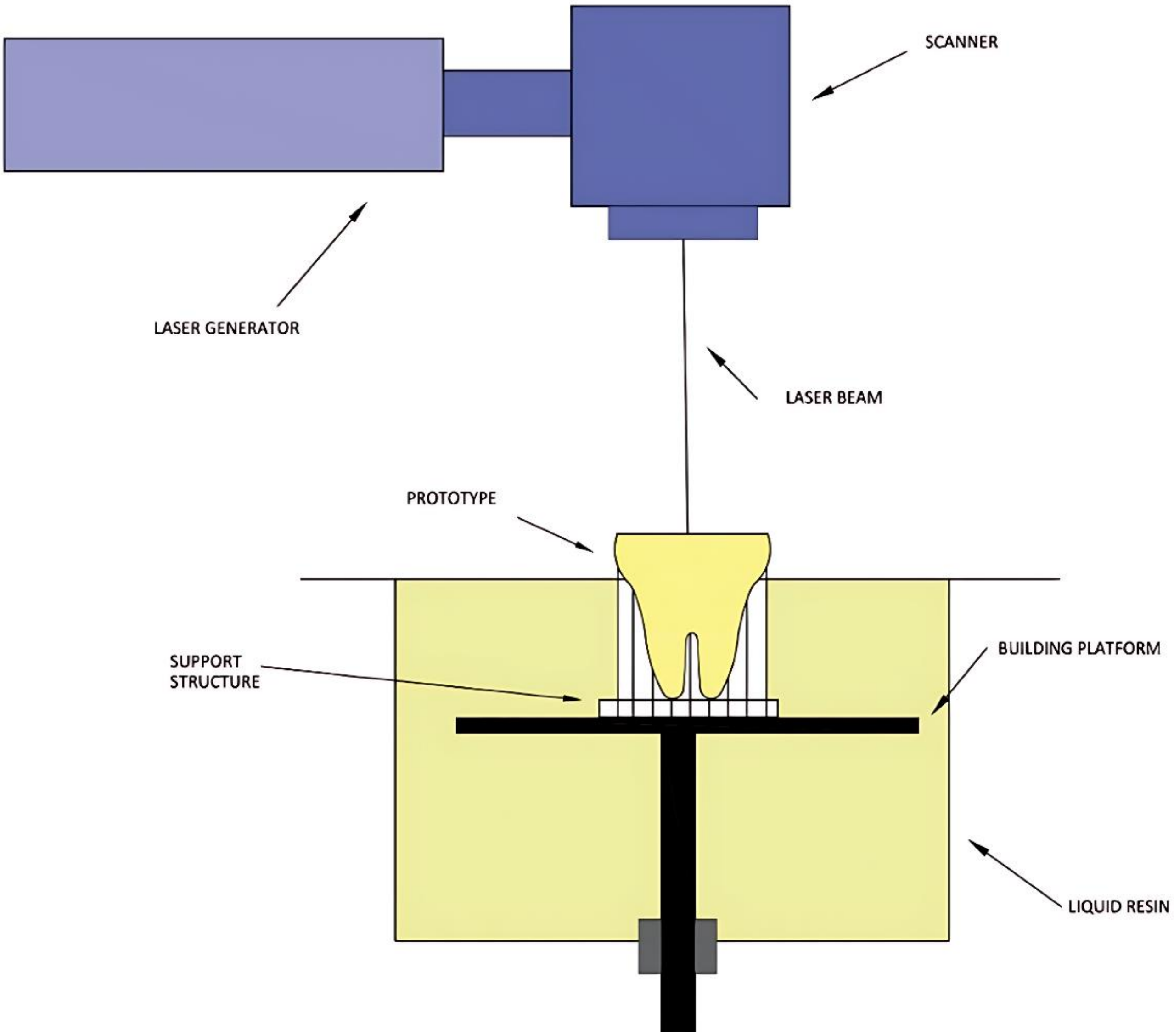

Figure 1.
Schematic representation of stereolithography.

There are various advantages of a top-down approach. Firstly, integrating laser rays reduces the risk of exposure to the operator. Secondly, curing resin in the depth of the reservoir prevents the inhibition of photopolymerization by oxygen. Additionally, the resin is automatically replenished, and layer-by-layer printing results in a smooth surface due to the continuous contact of the building platform with the reservoir. Moreover, high-precision measurements from patient scanning data enable long-term appliance production [34, 35]. However, it is important to note that there are limitations to the SLA process. This includes the potential leaching of remaining unreacted resin monomers from printed appliances, which may induce cytotoxicity and reduce appliance durability. Other limitations include perceived temporal and mechanical instabilities of photocurable resins, a lack of color, and the presence of partially activated polymers [36].

2.2.2. Digital Light Processing (DLP)

DLP is a photocuring technology that is similar to the SLA printing process. It involves using liquid photosensitive resins that undergo photocuring to create layer-by-layer 3D printed models [6]. A key component in DLP is the digital micromirror device (DMD), which consists of a matrix of small mirrors. These mirrors enable light transmission from the laser projector to the projection lens [37]. Below the projection lens lies the construction chamber, where an image of the object is generated on the building platform. The movement of the build platform, whether ascending or descending, is determined by the position of the UV source, as depicted in Figure 2 [5, 38, 39] . The build platform moves vertically in increments equal to the thickness of each layer, allowing for the curing of each layer until the entire part is completed [6, 38, 40]. Various configurations are employed to create adjustable layers, each capable of producing a two-dimensional sketch of the layer through light on the curing surface [6, 37, 38].

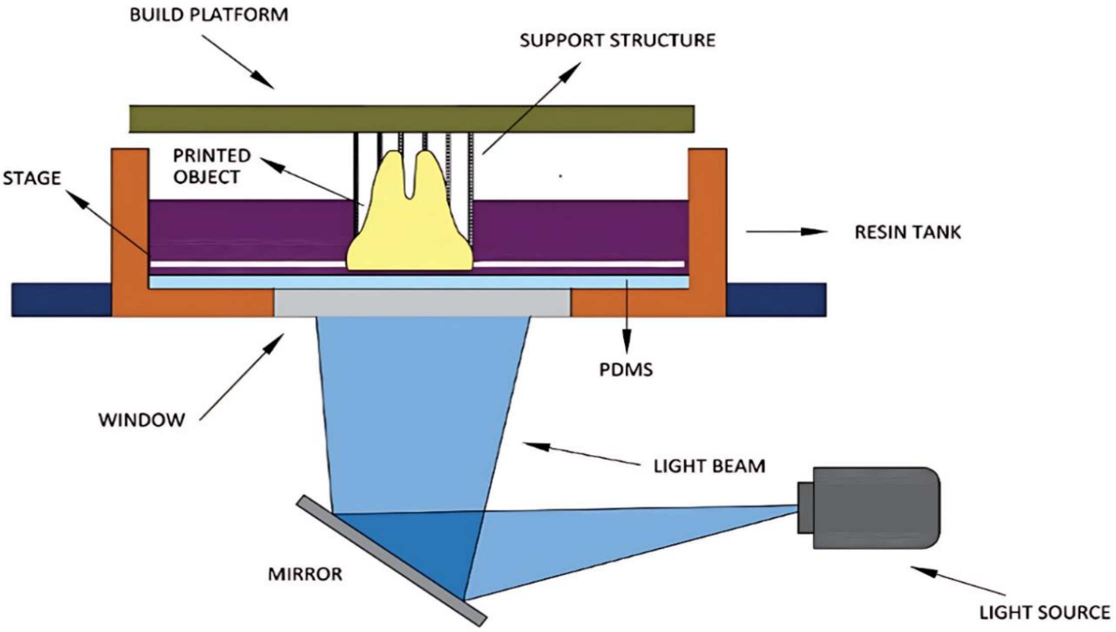

Figure 2.
Schematic representation of digital light processing.

SLA and DPL exhibit similarities and differences, primarily centered around the UV light source. SLA employs a UV laser beam, whereas DLP utilizes UV light emitted by the projection source [10, 41, 42]. In SLA, the resin is cured point-by-point with a laser beam, whereas DLP cures each resin layer using a steady light source [28, 38]. These different curing procedures make SLA more accurate and of higher quality than DLP, although DLP prints faster. The light source intensity can be adjusted in the DLP 3D printer and fixed in the SLA printer. This implies that the operator can control the impact of light on the resin material. In summary, DLP excels at quickly printing larger components with fewer details, while SLA prints accurate parts with intricate details [2, 27, 41].

2.2.3. Photopolymer Jetting (PJ)

PJ is a versatile and precise 3D printing process commonly used to produce high-quality, multi-material, and multi-color prototypes [43, 44]. PJ machines typically feature multiple material reservoirs, each containing a different type of photopolymer resin. These resins vary in properties such as color, rigidity, or flexibility. Like inkjet printers, PJ systems use print heads to deposit tiny droplets of photopolymer resin onto the build platform or previous layers [28, 45]. These droplets are selectively positioned to create one layer of the printed object. PJ printers use photoactive resin to charge deflation plates and cure them with ultraviolet radiation (Figure 3) [43, 44, 46].

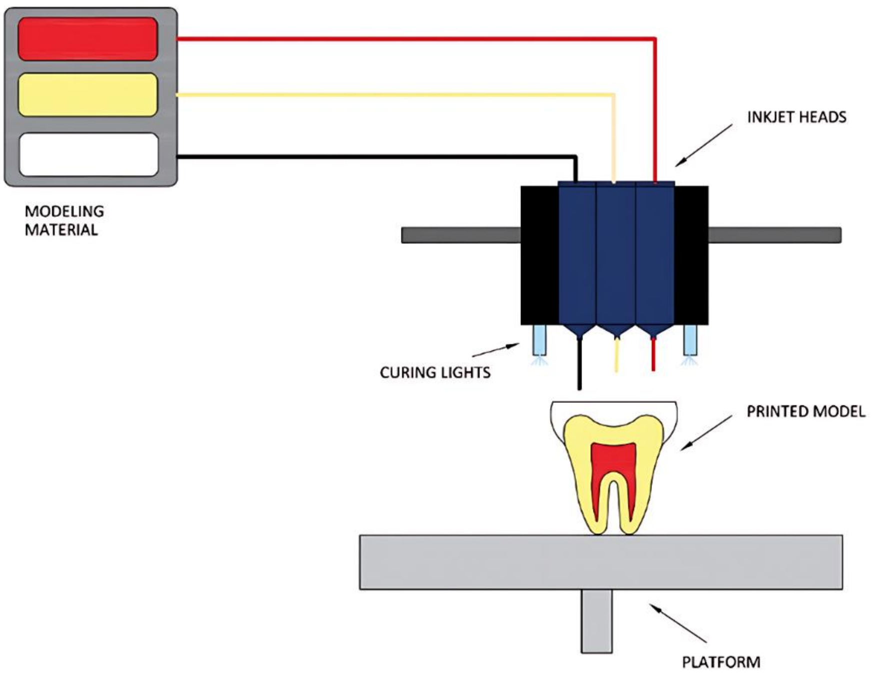

Figure 3.
Schematic representation of Photopolymer Jetting.

PJ technology offers more precise control over resin composition than SLA, primarily due to dispensing each ink drop. This capability allows for the adjustment of materials, facilitating the creation of diverse objects with high-resolution material gradients [9]. Various materials, such as casting resins, waxes, and silicone-like rubber materials, can be used for PJ printing. The popularity of PJ technology in dentistry is increasing due to its ability to produce parts with diverse colors and physical properties. Moreover, loading print heads with different materials during the same process enables the construction of complex objects. However, the equipment and materials used in PJ printing are expensive, and the support materials can be tenacious and challenging to remove [44].

2.2.4. Fused Deposition Modeling (FDM)

FDM 3D printing, also known as Fused Filament Fabrication (FFF), is a 3D printing technique that involves constructing a 3D model by layering molten polymers onto a building platform. In 1989, Scott Crump devised and patented an FDM technique of thermoplastic polymer ribbons that served as mechanical filaments to the extrusion printer [47]. The FDM process requires energy input in the pre-deposition phase to melt the polymer into a state suitable for application through a thin head or print nozzle. The molten material is then onto the construction platform, which undergoes cooling and solidification in successive layers (Figure 4) [7, 48].

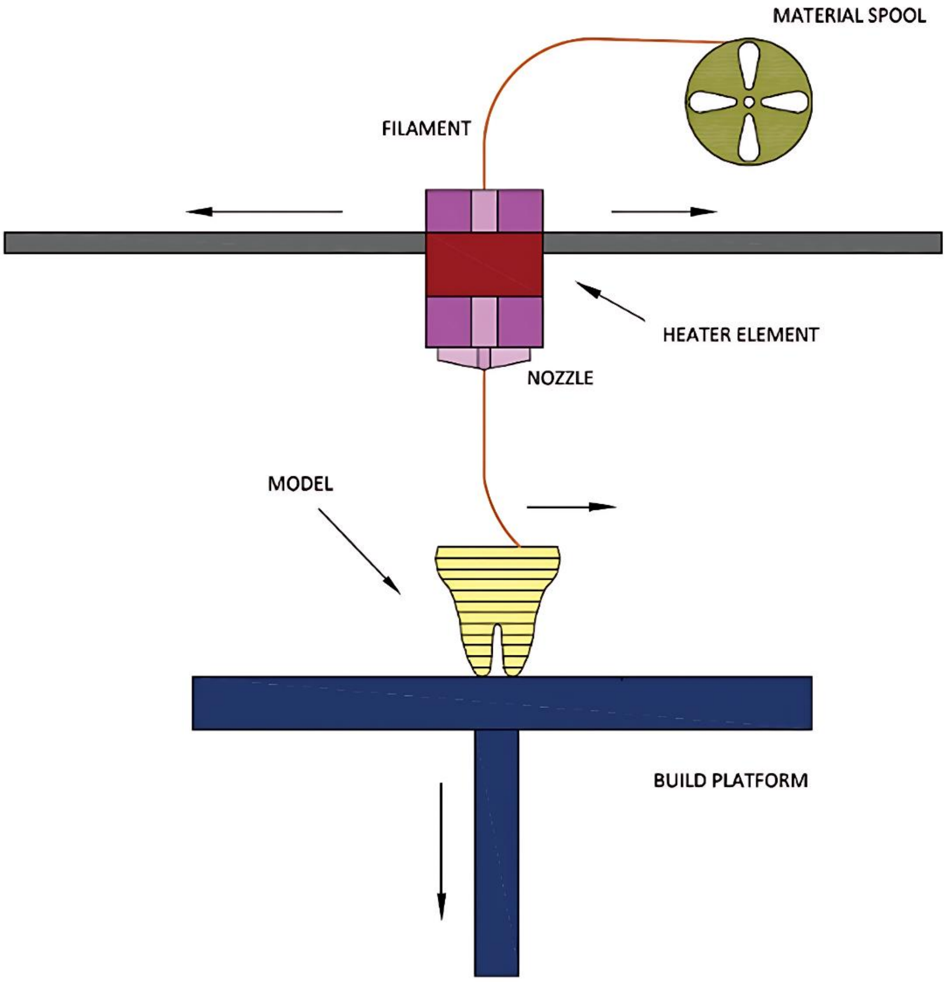

Figure 4.
Schematic representation of fused deposition model.

FDM is a global technology platform that offers customizable, low-cost 3D printing for homes and offices [4, 47]. Various polymers, including polyvinyl alcohol (PVA), polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), thermoplastic elastomers (TPE), nylon and polyethylene terephthalate modified glycol (PETG) are commonly used for FDM printing. These materials can easily manufacture intricate structures with predictable and cost-effective outcomes [3].

For surgeons seeking cost-effective and rapid prototyping solutions, FDM printers can be the ideal option. For instance, the UPplus2® (FDM) 3D printer produces ABS plastic models with dimensional accuracy comparable to that of other well-established, expensive rapid prototyping manufacturing technologies such as SLS -Sinteristation2000 (DTM, USA), SLS- EOSINT P380 & SLS 2200 (EOS GmbH, Munich, Germany) [49]. However, its use in dentistry is still limited. This is primarily because FDM utilizes thermoplastic materials, which are brittle in nature. The final product obtained by FDM possesses high surface roughness and provides fewer details compared to other 3D printing techniques.

2.2.5. Selective Laser Sintering (SLS)

SLS is an advanced 3D printing technique used to construct three-dimensional components. It achieves this by selectively fusing layers of powdered materials, including plastics, metals, or ceramics, with a high-powered laser [50]. This process entails depositing a thin layer of powder onto a build platform and subsequently sintering it with a laser in a precise layer-by-layer approach, as seen in Figure 5. One distinct feature of SLS is that the un-sintered powder surrounding the object serves as a self-supporting material, obviating the requirement for supplementary support [38]. SLS is known for its material versatility, enabling the production of robust and intricate parts. This has led to widespread adoption in various industries, including aerospace, automotive, and healthcare [51]. SLS is particularly valued for its ability to prototype and manufacture functional components in small batches rapidly.

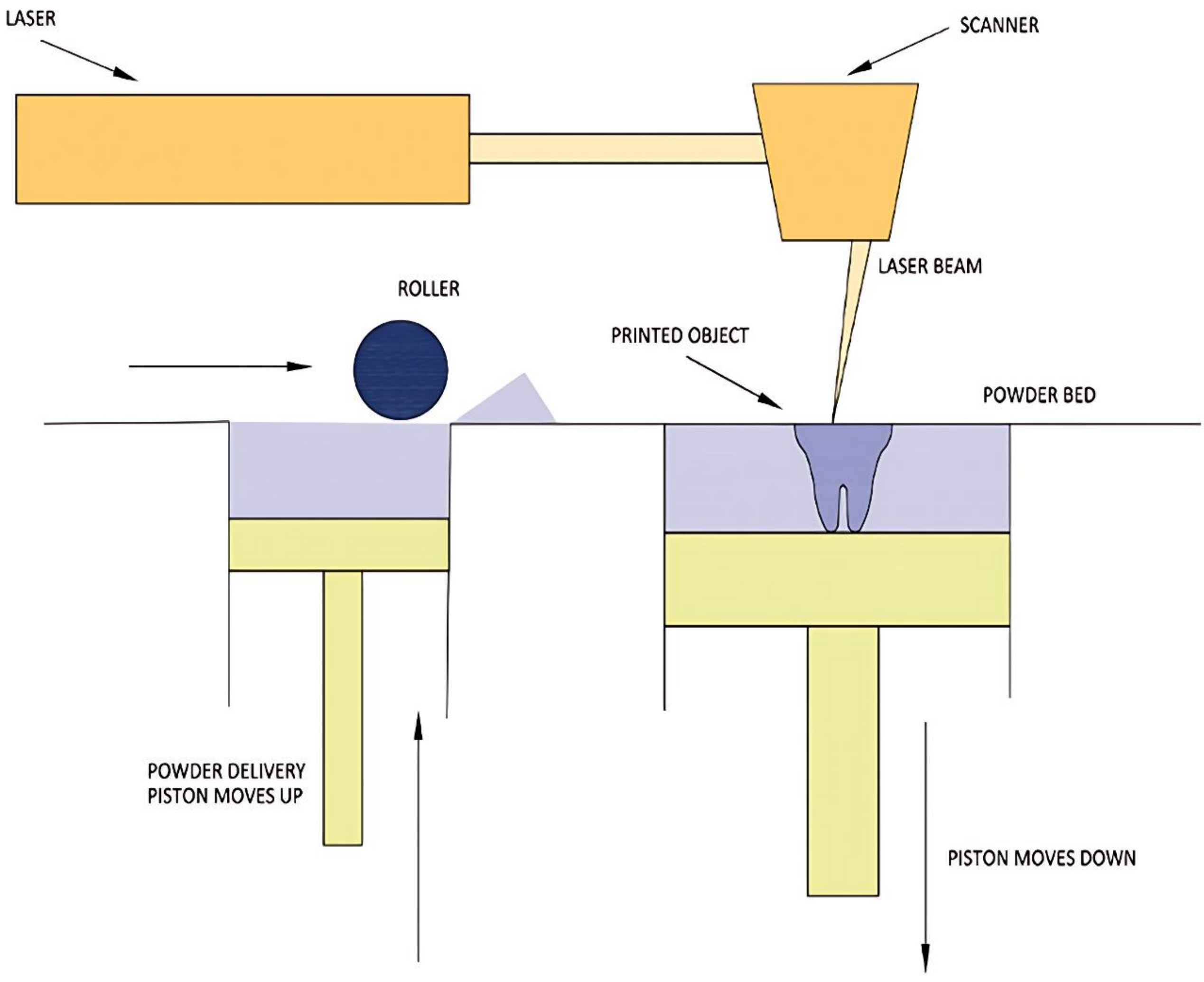

Figure 5.
Schematic representation of selective laser sintering.

SLS technology is currently employed to print partial dentures, denture structures, and implant bridge structures [19]. It can also be integrated with milling processes to achieve precise connections. The key attributes that make SLS material suitable for industrial applications include excellent mechanical properties, versatility in material selection (such as nylon, polystyrene, and metal), and the absence of support structure requirements [7, 52].

However, SLS does have its limitations. One significant drawback is its high cost, which limits accessibility primarily to professional 3D printing companies. Additionally, the resulting rough surface finish can lead to water absorption and, consequently, impact the mechanical properties [34, 53].

2.3. Materials Utilized in 3D Printing

Various materials are employed in 3D printing, each possessing unique properties, advantages, limitations, and applications. Below, we discuss applications of commonly used materials in dentistry and their mechanical and physical properties, as shown in Table 3.

Table 3.
Overview of mechanical and physical properties of materials.

Materials	3D technologies mainly used	Fabricated dental products	Physical property	Mechanical property
Metal (Co-Cr, Ti)	SLA, DMLS	Surgical guides, metal coping, metal crowns, Co-Cr restorations	• Highly biocompatible • Potentially causes allergy • Adequate bonding property	• High mechanical properties High tensile strength • Limited abrasive resistant
Ceramics (Glass ceramic, Zirconia, Alumina)	SLA, SLS, PJ, and FDM	Crowns, restorations, Dental models, study models, visual prototypes, temporary restorations, root canal piles, crown and bridge restorations, implants abutments, bone cement materials	• Biocompatible • Osteoconductive • High internal stress • High volume shrinkage • Suffers crack after sintering	• High mechanical strengths • Low electrical conductivities • High dielectric constant • High chemical resistances • High thermal stabilities
Composite	SLA, FDM, and DLP	Crowns, study models, wax patterns, surgical guide, dentures, implant abutments	• Limited color stability • Biocompatible • High water sorption and water solubility	• High flexure, tensile strength. • High durability • High peak strength
Polymers (PCL, PMMA, PLA, PLGA, and UV resin)	SLA, DLP	Surgical guides, implant guided surgical model, aligners, gingival mask, biological framework, resin pattern	• Biocompatible • Highly porous • Dimensionally accurate with minimal changes required. • Adequate surface roughness • Color stability is high	• High flexure strength (30-50 mins of curing time) • High surface hardness • Adequate durability

Source: Tian, et al. [2] and Shaikh, et al. [42]

2.3.1. Metals

Metals are mainly used in the SLS additive method to craft metallic structures from materials like titanium, cobalt-chromium (CoCr), and nickel alloys [54]. Among these, cobalt-chromium and titanium alloys are the most used. Studies have reported that the objects made by titanium alloy exhibit higher accuracy, ductility, and tensile strength than other metals. However, the high cost of titanium limits its utilization. Conversely, CoCr alloy is porous in the raw state with an irregular surface. Polymers bind the metal powder during the sintering procedure to achieve the appropriate density of metals [55]. Numerous studies support using cobalt-chromium alloy in dental restoration fabrication owing to its high mechanical and tensile properties [56]. Additionally, dental restoration fabricated by Co-Cr alloy reduces the post-processing stress and improves the mechanical properties [23]. Unfortunately, drawbacks such as powder adhesion, thermal and residual stress, and other complications associated with the SLS technique can impact product performance and quality [46].

Both CoCr and precious metals are potential raw materials, and additive manufacturing techniques like direct metal laser sintering (DMLS) can overcome the challenges of casting and milling hard materials like CoCr [57] . DMLS technology eliminates shrinkage during casting and CoCr hardness during milling by not using active force during structure creation. Despite their high cost, DMLS fabrication methods produce low unrecyclable waste, making precious metals suitable for digital production.

2.3.2. Ceramic

Hydroxyapatite (HA) and tricalcium phosphate (TCP) stand out as the most popular ceramic biomaterials [58]. Additive manufacturing offers the flexibility to utilize these ceramics as feedstock in various forms, including bulk solid-based, slurry-based, or powder-based, with printing techniques such as stereolithography, two-photon polymerization, inkjet printing, direct ink writing, digital light processing, and selective laser sintering [58]. The need to manufacture high-performance ceramic components with complicated shapes that are difficult or impossible to fabricate via traditional methods is fabricated by 3D printing of ceramic materials. Direct ceramic manufacturing has fewer processing parameters than laser metal deposition [59].

In other 3D printing technologies like FDM, a thin spool filament is employed to bind ceramic powders together to produce the green ceramic form. Subsequently, these green forms are sintered to achieve high mechanical strength [60]. Conversely, technologies like SLS and selective laser melting (SLM) utilize ceramic powder or pre-sintered ceramic for 3D printing. Nonetheless, it has been observed that direct use of ceramic powder makes porous dental prostheses, making it challenging to post-process to high density. Hence, in SLS, ceramic materials only produce glass ceramics to fabricate bioactive tissue scaffolds. Moreover, SLS techniques utilize porcelain slurry to achieve a dense ceramic prosthesis [30]. Printing techniques involving powder-bed jetting and vacuum infiltration have produced dense alumina-reinforced ceramic (crude zirconia ceramics) with high tensile and mechanical strength [61].

Furthermore, dense alumina-reinforced ceramic prostheses have been fabricated using photo-initiated resins loaded with alumina via SLA printers, a widely used technology known for producing highly accurate prostheses [59]. However, using ceramic as a material in additive manufacturing has certain drawbacks. Firstly, anisotropic shrinkage has been reported during the sintering of green-state ceramic. Secondly, the nature of the SLA fabrication process can result in a staircase effect. Nonetheless, ceramic materials have demonstrated promise in the fabrication of tissue scaffolds [59].

2.3.3. Composites

Composite materials, which combine two or more distinct substances to create a new material with enhanced properties, find diverse applications in 3D printing for dentistry. These materials are typically classified based on the matrix and reinforcing material. The matrix material provides structure and bonding, while the reinforcing material improves its mechanical qualities. Yang et al. investigated many 3D printing methods for fiber-reinforced polymer composites [62]. Composite 3D printing uses nylon-based thermoplastics with continuous fibers such as fiberglass, carbon fiber, high-temperature high-strength fiberglass, and Kevlar. For example, high-strength, high-temperature fiberglass is utilized in 3D-printed welding fixtures, thermoform and thermoset molds [20]. Fiberglass can 3D print industrial tools, fixtures, and working parts due to its fourfold strength and elevenfold rigidity compared to acrylonitrile butadiene styrene (ABS). Carbon fiber, on the other hand, stands out as the strongest and stiffest reinforcement fiber, with nearly double the strength-to-weight ratio of aluminum. Deforming until the fibers fail individually makes Kevlar suitable for multi-motion and interface applications [20].

He et al. employed optical microscopy and micro-CT to study the detrimental effects of voids in printed 3D continuous fiber-reinforced polymer composites. However, feasibility proved to be a challenge [63]. Berman proposed a new technology for thermoplastic matrix carbon-fiber-reinforced plastic (CFRP) additive manufacturing technology. The results were somewhat limited due to material combinations and volume fraction fluctuations, necessitating further testing to determine mechanical qualities, including shear and bending strength [64].

2.3.4. Polymers

Thermoplastics are the most utilized polymer in 3D printing [51]. Polymers play a crucial role in creating various dental components such as surgical guides, implant restorations, and custom-made impression trays. Some of the polymers in 3D printing include polymethyl methacrylate, polylactic acid, ultraviolet resin, and polycaprolactone [41].

Among these, acrylonitrile butadiene styrene (ABS) and the environment-friendly greener polylactic acid (PLA) polymer are the most commonly used polymers in 3D printing [51]. PLA is favored for its high tensile strength, ductility, resilience, and non-toxic properties [8]. Additionally, biodegradable polyester with bioactive tricalcium phosphate (TCP) holds promise as a material for dental tissue scaffolds.

Intriguingly, additive techniques that were initially employed as support materials for the build are now being used as building materials for intricate prosthodontic wax-ups [60]. Another group of additive manufacturing polymers is photoinitiated resin. SLA equipment cures this polymer layer by layer with UV light or laser [32] . These polymers have greater color, stiffness, and component modification flexibility. It mixes them with biocompatible and bioactive components like bioactive glass [32]. Studies have revealed that they distribute additional chemicals evenly and are bioactive [33]. Light-cured resins can even replace the manual wax-up step in lost wax casting, creating equally exact final structures once invested into a mold for printing images.

Another widely utilized polymer in 3D printing is polymethyl methacrylate (PMMA) [50]. This material is valued for its cost-effectiveness, stability, and ease of manufacturing. Its utilization in dentistry is limited to the fabrication of denture bases, bone cement, and retainers. Even though PMMA is utilized in prosthetic dentistry to fabricate denture bases with excellent performance, there is limited research regarding its interaction with the oral environment. Compared to other polymers, PMMA exhibits the ability to maintain its color and durability for up to 10 years [5]. However, further investigation is warranted due to the limited number of studies on the biocompatibility and mechanical properties of PMMA.

2.4. Application of 3D Printing in Dentistry

Over the past decade, 3D printing has been utilized in various aspects of dentistry, including dental education and surgical procedures. Its applications encompass the construction of guided treatment procedures in orthodontics, prosthodontics, oral and maxillofacial surgery, and endodontics. The recent advancements and applications of 3D printers are discussed below.

2.4.1. Periodontics and Oral and Maxillofacial Surgery

The introduction of cone beam computer tomography (CBCT) has ushered in a new era in 3D printing, revolutionizing diagnosis, treatment planning, and operation guidance while simultaneously reducing postoperative complications [64, 65]. This technological advancement has particularly benefitted procedures in the maxillofacial region, including implant insertion in complex or esthetic regions, sinus lift, and orthognathic surgeries [49].

In case of traumatic or cancerous maxillofacial abnormalities, removal of defects as well as a substantial amount of tissue may be necessary. Depending on factors such as defect size, trauma severity, and the patient's financial condition, post-surgical rehabilitation may require oral, nasal, and orbital maxillo-facial prostheses [49]. Leveraging intra-oral scanners for precise area scanning has streamlined the fabrication of these prostheses, making the process more efficient, accurate, and patient-friendly. Prostheses produced using additive manufacturing (AM) technologies exhibit superior accuracy and fit the defect area better than conventionally fabricated ones [16].

Patients with maxillary or mandibular deformity, severe malocclusion, or facial esthetic alterations often undergo orthognathic surgical procedures [16]. Utilization of 3D-printed models in these cases enhances patient communication and surgical treatment outcomes [18, 66]. Digital surgeries are gradually replacing traditional orthognathic surgeries as they provide better intraoral access during surgery and are more accurate [14]. 3D printing technologies offer many advantages, particularly in improving facial symmetry and the functional effect of maxillofacial plastic surgery.

2.4.2. Orthodontics

The evolution of digital dentistry has streamlined and improved the planning of procedures in dental laboratory and clinical settings. Notably, integrating 3D printing in orthodontics has rendered orthodontic methods more adaptable and flexible to changing treatment needs. This adaptability is exemplified by the capability to adjust alignment at any stage based on updated intraoral scans[52].

One particularly exciting development facilitated by 3D printers is the creation of Invisalign aligners, offering a promising alternative for patients with mild malocclusion [52, 67]. Direct 3D printing of orthodontic clear aligners is the future of 3D printing and orthodontics. These aligners, which can be removed while eating and drinking, represent the future of 3D printing in orthodontics. While creating these aligners, orthodontists can obtain patients' oral impressions through intraoral scanners. Subsequently, 3D printers like stereolithography and FDM are employed to produce models for thermoforming the aligners, all while maintaining the material's quality. Mohamed, Khader, and Ali proposed that manual workflow can be reduced with 3D printing [68]. Moreover, digital manufacturing techniques have reduced the orthodontic treatment and planning steps [11].

2.4.3. Crown and Bridge Preparation

Dental crowns and bridges represent some of the most fabricated dental prostheses by 3D printing. Dental crowns, specifically, serve to protect the underlying tooth structure of endodontically treated teeth while also helping in masticatory functions [41]. In dental practice, both laboratory technicians and dentists have increasingly turned to technologies such as SLA and DLP to fabricate provisional crowns. This choice is driven by factors such as cost-effectiveness and minimal material wastage. Furthermore, these techniques are capable of rapidly producing various materials with remarkable reproducibility [41, 69].

The precision of dental provisional and fixed crowns is paramount, as ill-fitting crowns can lead to issues such as microleakage of adhesives, periodontal diseases, plaque accumulation, and dental caries. Notably, provisional crowns fabricated by 3D printing have exceptional fit and accuracy, surpassing those fabricated via traditional milling methods. In an in-vitro study by Chaturvedi et al., a provisional crown fabricated by 3D printing exhibited improved proximal ends and edges, ultimately resulting in a better fit than traditionally manufactured crowns [70].

2.4.4. Dentures

The development of CAD/CAM systems has significantly transformed the fabrication of dental prostheses [42]. The traditional approach to creating prosthetic devices involved using alginate or polyvinylsiloxane impressions. In contrast, CAD/CAM technology offers a more advanced and streamlined process.

Using CAD/CAM for prosthetic construction typically involves three key phases [71]. In the initial phase, intraoral and extraoral scanners are used to capture virtual impressions of patients' oral structures and register their occlusion. In the second part, computer software designs the prosthesis. This step can be executed by dental laboratories and clinics, allowing dentists to evaluate the prefabricated dentures during this phase. In the third and final phase, the prosthesis is fabricated either by additive or subtractive manufacturing methods [71].

Integrating 3D printing with computer optimization and digital modeling has become a valuable approach in the design and fabrication of dentures. In recent years, the primary materials used for 3D printing denture bases and teeth are methacrylate-based photopolymerizable polymers [72]. Laboratory technicians or dentists utilize 3D printing to create separate denture-based and artificial teeth. These printed components are then attached together using a photocurable bonding. This approach stands in contrast to traditional denture processing methods such as compression molding and injecting molding. The use of 3D printing offers several advantages, such as more effective clinical modification, reduced patient discomfort, and a potential decrease in long-term bone resorption. These advancements contribute to the improved quality and customization of dentures in dental practice [5, 40, 72].

2.4.5. Endodontics

Guided endodontics treatment is an umbrella term where intraoral scanners and 3D printers guide clinicians on the depth of the cysts, periapical abscesses, and/or bony lesions [3]. The major advantage of 3D scanners is guiding clinicians to plan calcified pulp root canal openings [14]. This process involves acquiring data, a 3D image of the calcified canal and pulp chamber, a virtual drilling path, and a template followed by printing [4]. The printed templates help clinicians direct the canal treatment with calcified and curved roots. Similarly, 3D printed guides are utilized in guided endodontic microsurgery to guide the drill to the targeted root-end resection and osteotomy [17].

Various artificial tooth models replicating human teeth are created with CBCT or CT scans, followed by printing. These models help students and academicians understand tooth morphology and internal anatomy [17]. Replicas of donor teeth can be created by rapid prototyping before auto-transplantation. This replica is utilized to prepare alveolar sockets at the recipient site, thereby reducing the extra waiting period before the placement of artificial teeth. Stem cells, injectable calcium phosphate, pulp scaffolds, and growth factors can be delivered using 3D printing. 3D printing has improved endodontic treatment processing time, safety, and predictability [17]. 3D printers have increased the preparedness of the operators before performing complex endodontic therapies.

2.4.6. 3D printing in Dental Education

Three-dimensional printing has provided an up hand in the field of dental education [24-26]. 3D-printed teeth made of silica replicate natural teeth and serve as a teaching model for dental students [73]. A wide range of dental procedures, such as pulp-capping, caries excavation, veneer, and crown preparation, can be taught in vitro by utilizing models created by 3D printers [73]. These models have overcome the drawbacks of learning from extracted teeth, such as contamination and ethical considerations [4]. Dental institutions can easily create 3D replicates with access to CBCT and a 3D printer. In maxillofacial surgeries, these models are extensively utilized for preoperative planning [73]. Overall, 3D printing has significantly improved the efficiency, safety, and predictability of endodontic treatments, providing clinicians with valuable tools and resources for complex procedures. It has also enhanced operator preparedness, particularly for challenging cases in endodontics.

2.5. Advantages, Limitations, and Challenges

The paradigm shift of 3D printing eliminates complex procedures in conventional techniques by reducing manufacturing costs and energy consumption [30]. Additive technology offers advantages over conventional digital manufacturing methods, such as having the ability to use various materials and equipment [61]. This makes additive technology an interesting area for research and offers an entirely new range of potential dental applications. Only a few big companies manufacture 3D printers; however, several start-up businesses are already creating precise equipment at lower costs because many patents have recently expired [61]. Previous research papers showed that SLA fabrication was uncommon due to high material and machine costs [63]. A few advantages of 3D printing are described below.

Flexibility. Some machines can print multiple materials simultaneously without misplacing the structure during development [50]. While this has primarily been limited to the fabrication of organic or multicolored materials, future technological advancements may allow the fabrication of multi-component dental prostheses and their substructure for challenging prosthodontic cases in a single machine in a single stretch, which would fully realize digital workflow.

Minimal waste. Subtractive manufacturing can remove up to 96% of the original material, and this waste is essentially non-recyclable [41]. In contrast, additive manufacturing machines often utilize only the materials necessary to build and waste less than 40%. Additionally, 95% to 98% of the waste might be recycled in upcoming production cycles [9]. This is critical in cases where the raw material's total weight and size are a concern because it lowers the cost of the raw material overall and per unit. While subtractive manufacturing relies on preformed blocks of material, additive manufacturing limits the final product's size by the machine's building chamber, usually larger than the milling machine's preformed disks [9].

There are various limitations to applying 3D printing technologies in regular practice: (1) *Staircase effect*: layer-by-layer 3D printing can cause a staircase effect on the final product unless the layering thickness is reduced to a minimal resolution [29]. However, this will significantly increase the time the 3D printer takes to construct the structures; (2) *Manufacturing of materials*: some advancements have been made in the fabrication of ceramic structures (made of zirconia and alumina), but the porous structures created by the additive technique require a significant amount of post-processing, resulting in shrinkage [42]. As a result, 3D printing cannot create the homogeneity that subtractive manufacturing has achieved and does not bypass the shrinkage issue that arises when milling pre-sintered material blocks [2] (3) *Reproducibility*: even though many additive machines have been introduced, the printed material still lacks reproducibility [2]. When reproducibility and accuracy issues are sought, production speed becomes a problem; (4) *Support structure*: 3D printers like SLS and FDM require a supporting structure while printing [24] . This cumbersome step is performed either during the initial fabrication stage or during pre-processing and must be removed immediately after printing is finished.

Also, various challenges have been reported while implementing 3D printing in regular dental practice: (1) *Ethical and legal considerations*: ethical considerations and regulations regarding 3D printing differ globally. For instance, countries like the United Kingdom, the United States of America, and other developed worlds have regulations regarding materials utilized in 3D printing; however, no regulations apart from manufacturer's indications are labeled in the developing world. Higher medical authorities should contact doctors and manufacturers to set protocols and guidelines to overcome this challenge; (2) *Skilled technicians and Dentists*: even though 3D printing has been introduced in dentistry long back, limited or no training has been provided to dental technicians and clinicians for operating 3D printing. Manufacturing companies should create consortia to help dentists and technical staff improve their knowledge about this machine; (3) *Dentists and*

Patients Confidence: another factor leading obstacle to implementing 3D printers is the lack of confidence of dentists. This low confidence level in treatment with modern machinery could also be seen in patients. Hence, testimonies of patients treated with crowns or bridges made by 3D printers should be circulated to overcome these obstacles.

2.5.1. Limitations of This Review

This review intended to bring on debate and discuss, from a panoramic point of view, the use of 3D printing technologies and materials in dentistry. Therefore, no strong methodology was used to develop this article compared to systematic studies. Moreover, although the authors worked on this review without any influence, conflict of interest, or favoritism for specific equipment or materials, some bias can be present.

3. Conclusion

Within the limitations of this review, it was possible to summarize the characteristics, applications, and classifications of 3D printing in dentistry, including challenges and limitations to implementing 3D printing in regular dental practice. Overall, this review highlighted the importance of 3D printing in dentistry and its applications in various dental areas. Although 3D printing significantly reduces complex surgical procedures into simpler forms by directing clinicians with guided templates, various problems are associated with 3D printing technologies: (1) the layer-by-layer superimposition of images causes distortion and reduces the mechanical properties of the material, restricting the long-term utilization of dental appliances, such as crowns and occlusal splints; (2) the thickness of the layer affects the final model's smoothness, which requires high surface trimming and smoothing to be aesthetically pleasing to the patient; (3) the lack of trained technicians and clinicians hinders the implementation of 3D printers in regular clinics; (4) most 3D printing machines are not customized for dental use.

Due to the aforementioned drawbacks, 3D printing machines are still less accepted than traditional treatment methods. Future research on printers should focus on reducing these issues with printing principles. Notably, 3D printers require a support system like CAD/CAM and digital files to acquire data, which ultimately increases the cost of the equipment, making it challenging to adopt in regular clinical practice. Even though 3D printers can create a model in a shorter period, acquiring data takes time; hence, these printers are not recommended in emergencies. However, to implement 3D printing in dentistry, manufacturers should aim to reduce costs and time, increase surface quality, and improve the processes of reproducibility, reliability, and performance of this technology. With these changes, it could be anticipated that 3D printers could be utilized more sophisticatedly.

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