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Application of Polymeric Materials for 3D Printed Dentures: A review

Alaa Raad Ali*, Suha K. Shihab, Sheymaa Alazzawi and Jabbar Gattmah

Department of Materials Engineering, University of Diyala, 32001 Diyala, Iraq

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ABSTRACT

The development of three-dimensional printing technology (3D printing) has revolutionized the dental industry by providing a rapid, dependable, and affordable way to create a variety of dental products, including denture bases. This review article presents in-depth research on polymeric materials and their effect on different properties and aspects of dentures manufactured by 3D printing processes. This study indicated that Poly (methylmethacrylate) (PMMA) is a popular material in the 3D printing process of dentures. Despite its widespread use in dentures, more research is required to overcome some disadvantages like brittleness and poor mechanical qualities by utilizing additives to this material for improvement. The polyether ether ketone (PEEK) has remarkable mechanical and thermal properties and is perfect for dentures. A variety of medical and dental applications can benefit from Acrylonitrile butadiene styrene (ABS) toughness and chemical resistance, our review investigation uncovered several potential applications of ABS for printed dentures. Polylactic acid (PLA) is a biocompatible and biodegradable polymer derived from renewable resources and it has been used in dentures. However, additional study is required to enhance its performance in dentures. Furthermore, it was found that the most appropriate 3D printing technology for denture printing is the vat photopolymerization process. Advances in material qualities are assisting in the durable and biocompatible dental prostheses that meet the evolving needs of patients and doctors. Furthermore, in-depth evaluations of environmental sustainability and biocompatibility are essential for advancing the discipline ethically and responsibly.

1. Introduction

Polymers are the most common material in dental restorations created via 3D printing. In contrast to metals and ceramics, polymers have chemical and physical characteristics like tensile strength and elasticity, which have the potential to offer high performance and durability qualities needed for use as dental restorative materials [1]. The use of polymers in dentistry has grown due to their enhanced biological and mechanical properties, ease of processing, cost-effectiveness, and versatility. Various 3D printing technologies support a wide range of polymeric substances, enabling the fabrication of diverse dental structures.

The denture base is part of the denture that supports artificial teeth and sits on the oral cavity's soft tissues. Biomaterials known as denture base materials (DBMs) are used to create the denture base. DBMs should ideally possess mechanical, physical, chemical, and biological characteristics to function in an intricate and changing oral environment. They should also have excellent aesthetics, adhesion to artificial teeth, cost-effectiveness, precision, and dimensional stability, acceptable thermal characteristics, chemical stability,

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[*] Corresponding author.

E-mail address: suhakshihab@gmail.com

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biocompatibility, high insolubility, and low sorption in oral fluids [2]. Comparing two distinct manufacturing techniques, i.e., conventional and 3D printing, the last offers superior adaptation for studying the complete denture base. Thus, a promising modification for the denture base is provided by the 3D printing technique [3]. The favorite for acrylate structures like poly (ethylene glycol) diacrylate (PEGDA) over epoxide structures may be related to superior printability, while the tendency to utilize SLA (Stereolithography) more commonly than DLP (Digital Light Processing) can be explained by its inherent higher resolution. organic fillers or those that have undergone organic modification are preferred [4].

Polymers are long-chain molecules made up of numerous repeating units, that can be created through addition polymerization or condensation. Methacrylic acid polymer esters are the basis for acrylic resins [5]. Since its introduction in 1937, acrylic resin has been the most widely utilized DBM due to its exceptional qualities. Vinyl styrene, polycarbonates, nylon, ethylene, polyurethane, unsaturated polyesters, polyvinyl acetate, polyether ether ketone (PEEK), and polyether ketone (PEKK) are further polymers that are utilized in trace amounts [6]. According to the ADA's arrangement, denture base polymers are partitioned into various assemblies as shown in Figure 1. There are three main varieties of denture base polymers and relating to how the polymerization procedure is implemented, they may differ from one another in terms of the content and polymerization response [2,7,8].

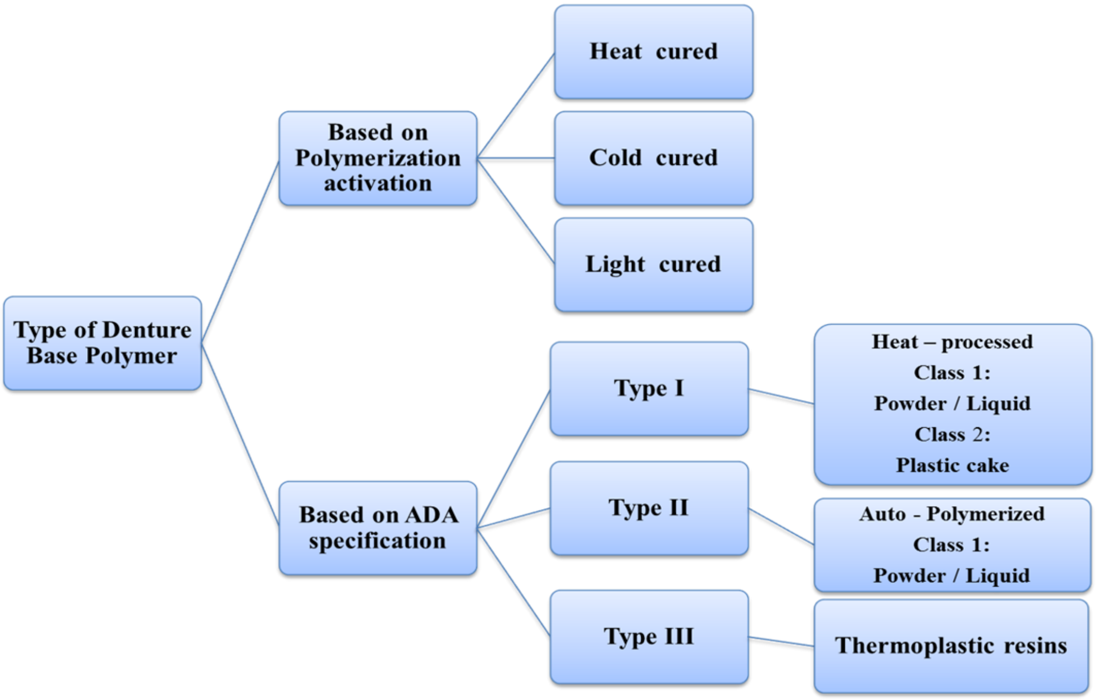

Figure 1. Denture foundation polymer classification by ADA guidelines and based on polymerization activation [9]

3D printing technologies have revolutionized orthodontic practice by producing a wide range of prosthetics for dental restorations using polymer materials, including artificial teeth, denture bases, temporary crowns, bridge and crown facings, and implants [10‹11]. This technology was developed by Charles Hull in 1986 in a process known as vat photopolymerization such as stereolithography (SLA), which was followed by subsequent developments such as powder bed fusion, material extrusion like fused deposition modeling (FDM), material jetting, and sheet lamination [12]. Fig.2 represents the main classification of 3D printing processes.

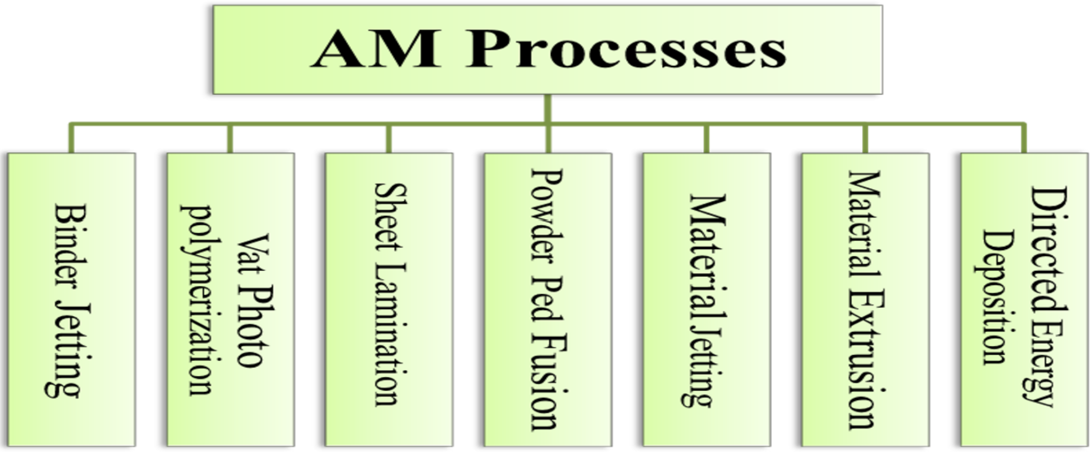

Figure 2. Classification of 3D printing processes based on ISO/ASTM 529000:2015.[13]

The First 3D printing technology is photo-curable printing. The technology is based on photopolymerization and photosensitive liquid resin is utilized as the material [14]. 3D printing, which involves various methods, materials, and equipment, has evolved over the years and can transform manufacturing and logistics processes. In denture manufacturing, 3D printing replaced traditional methods by enabling the fabrication of customized dentures with greater precision and efficiency. This innovative technique involves layer-by-layer deposition of materials based on digital models, allowing the production of complex and patient-specific denture structures. The integration of 3D printing in dentistry offers the potential for improved fit, comfort, and aesthetics in denture design, marking a significant advancement in the field of prosthodontics [15]. A further advantage of 3D printers is that they eliminate the requirement for several laboratory procedures of molding and lengthy steps of conventional heat-cured acrylic resin prostheses [16]. Fig.3 reveals the main steps of the 3D printing process for designing and manufacturing dentures.

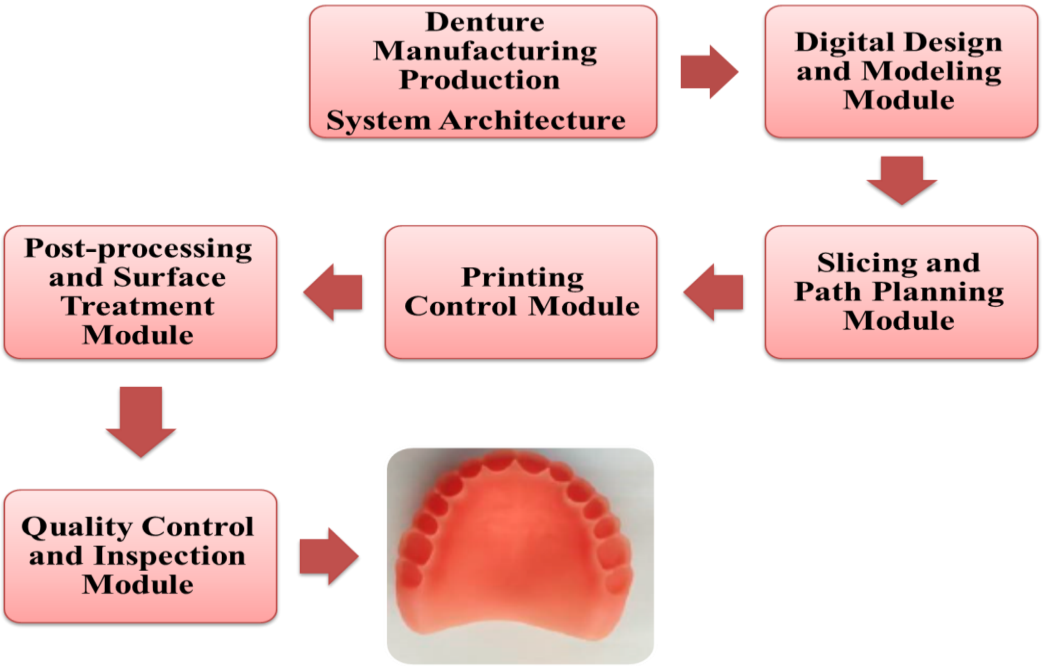

Figure 3. 3D printing for design and manufacturing denture [17]

The range of dental-grade polymers that can be used in 3D printing dentures has significantly increased. This includes stronger, more aesthetically pleasing, longer-lasting biocompatible materials. Printed dental materials are quickly evolving with research focusing on the creation of additive manufacturing (AM) printing settings to fine-tune the mechanical properties of commonly used materials [18]. Post-curing is a crucial process in 3D printing that significantly impacts the final properties of printed parts. It involves exposing the printed parts to controlled UV light for a specific duration to ensure complete curing and achieve optimal mechanical properties. Post-curing enhances the strength, durability, temperature resistance, and surface finish of the prints. Different methods like sunlight curing, UV light curing, and using UV lamps or curing stations can be employed for post-curing, with UV light sources offering consistent and reliable results in just minutes [19]. When compared to conventional dental resins, 3D printing resins are shown similar biocompatibility and enhance the general clinical fulfilment of the produced material resins. This biocompatibility can be increased further through post-processing steps such as curing and washing. It was revealed that the minimal post-curing time to achieve ideal results is 30 min, as further curing will have no significant effect on the properties of the printed material [20]. Also, the flexural strength of the 3D printed denture base resin was affected by the printing orientation but not the curing time and the values increased with the increasing angles of the layer orientation from 0° to 90°. Further, surface hardness was altered with the printing orientation and curing times [21]. One of the studies states that 90° printing orientations and 30-minute curing times produced the highest mechanical and physical properties [22]. To attain the best possible aesthetics and patient satisfaction, certain 3D-printed dentures may need post-processing procedures like surface finishing or polishing. Regulatory approval is necessary and it is a constant struggle to ensure that 3D-printed dental devices are approved and comply with regulations [23]. The impact of artificial aging and printing orientation on the hardness and indentation modulus of different 3D-printed dental resins was investigated using the DLP printing method. It was exhibited that 90° printed specimens have higher hardness while no significant effect was observed for orientation on the indentation modulus for all 3D-printed materials. Also, it was noted that the hardness values of the used 3D printed materials were considerably affected by artificial aging [24]. Further, one important step is Cone beam CT scans that were used to measure the artificial teeth and complete dentures. A 3D CAD program was then used to create a picture of the entire denture, which was then used to cut and produce the acrylic denture base. Resin cement was then used to affix the fake teeth to the denture base. For the occlusal surface, the average deviation from the primary 3D picture was 0.50 mm. Consequently, a full denture can be produced with the CAD/CAM system. [25].

To better understand polymeric materials used in denture 3D printing, a thorough examination and analysis of the literature should be conducted. The goal of the review is to present a thorough overview of the characteristics, effectiveness, and uses of these polymeric materials while considering pertinent elements like mechanical strength, biocompatibility, and aesthetics. The review aims too to provide important insights into the developments, difficulties, and possible future paths in the field of materials engineering concerning the use of polymeric materials for 3D-printed dentures.

2. Methods

The literature review aimed to provide an in-depth analysis of the use of polymeric materials in 3D-printed dentures, focusing on their mechanical, biological, and clinical properties. The initial search was conducted to capture a broad spectrum of studies from 2010 to 2024, covering various aspects of polymers in dental applications. Our review focused on both conventional denture base materials and those used in 3D printing technologies.

To ensure a comprehensive overview, we followed a systematic search strategy, which involved the following steps:

1. Database selection
   The databases used for the literature search included PubMed, Scopus, and Embase, as they cover a wide range of dental, materials science, and engineering journals. These databases are highly regarded for their extensive peer-reviewed content on biomedical and materials science topics.
2. Search terms
   The search terms used included combinations of keywords related to the research focus: "Polymers in 3D printed dentures", "3D printed resins for dentures", "Digital dentures", "Acrylic resins", PEEK dentures". These terms ensured that the search captured literature on both traditional and emerging polymeric materials used in dental applications.
3. Initial search and screening
   The initial search returned over 200 articles. These articles were screened by title and abstract to assess their relevance to the study’s focus on polymeric materials in 3D-printed dentures. Articles that discussed polymers in unrelated medical fields or focused solely on traditional manufacturing techniques without discussing 3D printing or polymers in dental prosthetics, were excluded.
4. Inclusion and exclusion criteria
   To refine the selection further, we established the following inclusion criteria:
   - Articles published between 2010 and 2024
   - Studies on clinical and in vitro performance of polymeric materials used in 3D-printed and conventionally fabricated dentures
   - Research that provided data on the mechanical, biological, and aesthetic properties of these materials
   - Studies written in English.

   Exclusion criteria included:
   - Articles not related to denture base materials
   - Studies that lacked original research data or presented incomplete information
   - Duplicate studies or those that repeated findings from previous work without adding novel insights
5. Final selection of articles
   After the initial screening, a total of 120 articles were selected for full-text review. Each article was evaluated based on its methodology, results, and relevance to the research objectives. Finally, 90 articles were included in the review, representing the most relevant studies on PMMA, PEEK, ABS, PLA, and other polymers used in 3D printing for dentures.

3. Polymeric Materials in 3D Printing of Denture

The denture material should achieve a high degree of polymerization (conversion) to minimize the amount of unreacted monomer that may leak out. This is because unpolymerized monomers can irritate the soft tissues of the mouth. Improved biocompatibility, cytotoxicity, and mechanical and physical capabilities are directly correlated with the types of materials used [26].

3.1. Poly (methyl methacrylate) (PMMA)

Methacrylate is the basis for the majority of dental resins in dentistry because of their affordability, ease of processing, and attractive appearance [27]. Gel, powder, or liquid form is frequently used to supply denture base materials [1]. The powder is composed of acrylic or copolymer heads, pigments (mercuric sulfide, cadmium sulfide, or dyes), an initiator such as benzoyl peroxide, and opacifiers, of which titanium dioxide is the most efficient. They also contain plasticizers, inorganic particles like glass fibers and beads or zirconium silicate, and dyed synthetic fibers to stimulate the blood vessels beneath the oral mucosa [28]. On the other hand, the liquid is made up of Methyl methacrylate, a monomer, as well as accelerators, inhibitors, plasticizers, and agents that cross-link molecules [29].

Since 1937, PMMA, commonly referred to as acrylic resin, has been the prosthetic dentistry material that has been most thoroughly studied and used [30]. It is used in the creation of dentures and teeth and has several benefits over alternative materials, including chemical stability in the mouth, acceptable appearance, and accurate fit. PMMA can also be produced and ease of processing, and it can be adjusted, repaired, and modified in a clinical setting. Furthermore, only reasonably priced processing equipment is required [14]. Resin, nylon, epoxy resin, and polypropylene are not as good as acrylic resins (PMMA) in terms of mechanical and physical properties. However, PMMA has some intrinsic drawbacks, including a high rate of shrinkage when exposed to light, a high degree of brittleness, poor mechanical qualities, and little antibacterial activity, which have impeded the wide-ranging clinical application [31, 32].

In a study to improve the properties of acrylic dentures by filling them with fibers and nanotubes, This addition led to a better increase in the properties of PMMA compared to the incorporation of nanoparticles due to the surface area that the fibers and nanotubes have about their size [33] .

PMMA is the general material used to fabricate partial complete dentures. However, it cannot achieve all the mechanical desires of fabricated dentures. Therefore, the researchers used reinforcement of denture materials such as silver, titania (TiO_2), zirconia (ZrO_2), alumina, and ceramic to improve the mechanical properties of denture base resins [34].

In another study, hybrid composites comprising PMMA, nanoparticles of zirconium oxide (ZrO_2), and glass fiber possess the greatest stability between flexural and impact strength and are endorsed as a reinforcement for essential materials to manufacture dentures [35].

More studies were performed to improve PMMA composite resin's mechanical, thermal, and antibacterial qualities. It was obtained that 1% of TiO_2 would be a useful addition [36-38]. The findings have also shown that, in comparison to the other groups, the PMMA-reinforced composite resins (TiO_2-1 percent-PEEK-1 percent) had the most optimized properties. These composites showed tremendous potential as functional dental replacement material because of their superior mechanical strength, high level of antibacterial activity, and minimal cytotoxic effects [36]. This makes them extremely promising for use in dental applications.

In a study to enhance the thermal polymerized PMMA resins used in the denture industry by adding varying concentrations of AgNPs, the highest impact strength was observed in samples consisting of heat-cured acrylic resins modified with 1 wt% AgNPs followed by samples consisting of heat-cured acrylic resins modified with AgNPs. 0.5 wt% AgNPs while the samples consisting of heat-cured acrylic resin modified with 2 wt% AgNPs, revealed relatively lower impact strength compared to the rest of the samples which confirms that with increasing concentration of AgNPs, a subsequent decrease in tensile strength was observed from the final polymer material [39]. Also, it was found that adding silicon dioxide nanoparticles (SiO_2NPs) to acrylic (3D printed resin), greatly enhanced the material's mechanical characteristics, including hardness, flexural strength (FS), and impact strength (IS), while Ra remained relatively unchanged [40]. Acrylic resins are easily scratched or distorted because they lack a high degree of hardness [41]. Compared to injection molded resins, acrylic resins experienced greater volume changes during the polymerization process, and they were tested for 28 days. This can significantly affect its stability when chewing. It was found differences in surface and mechanical properties between different brands of 3D printed resin and conventional heat-polymerized PMMA [42]. However, further studies are needed to evaluate other surface and mechanical properties before recommending 3D printing as a standard manufacturing technique for the fabrication of complete dentures[43]. PMMA has lower heat conductivity than metallic denture bases. PMMA has a poor thermal conductivity (5.7×10^{-4} C/Cm), which prevents heat generated during denture production from escaping and causing surface crazing [9،14]. Additionally, the patient's capacity to sense the temperature of the meal may be compromised by the low conductivity; as a result, extremely hot liquids may reach the pharynx or esophagus without the patient feeling anything and may burn the sensitive soft tissues [4, 7].

Although PMMA has been used in prosthetic restorations with consistent clinical results, scientists are still studying more about how PMMA interacts with the oral environment, and they have found some possible negative effects on cells [44, 45]. As a denture base material, PMMA can retain its color better than polyamide-12. The translucent nature of PMMA resins and their ease of coloring to resemble the tissues they replace confer upon them excellent aesthetic qualities. The material needs to be sufficiently transparent to resemble the tissues it is replacing in appearance. The plastic must be colorless and pigmentable or colorable; after manufacturing, the material's color and appearance cannot be altered [46].

Different curing techniques can be used to classify PMMA used in dentures. The main curing methods are heat application, light exposure, chemical reactions (self-curing), or using microwave energy [47]. Heat-curing PMMA results in a stronger denture base material than those cured by light or chemical methods, offering additional advantages such as better color stability, and reduced residual monomer levels [48]. In comparison to heat-polymerized resin, 3D-printed denture base resin has less flexural strength, elastic modulus, impact strength, and surface hardness [49]. The use of nanoparticles (NPs) is one of the most promising strategies that researchers have investigated to reinforce 3D-printed resin [50]. The incorporation of nanosized fillers into PMMA has been thoroughly studied in dentistry to improve the properties of dental materials [51].

Numerous 3D printing factors may influence the characteristics of the resin utilized for denture base applications, which can be categorized into uncontrollable elements like material composition, light wavelength, and light power, as well as controllable factors including printing orientation, post-curing time, and post-curing temperature [52-58]. An examination conducted by one of the studies assessed the impact of printing orientation and post-curing time on the mechanical and physical properties of the 3D-printed denture base resin. The outcomes indicated that the post-curing durations and printing orientations scrutinized in this investigation did indeed influence the characteristics of the printed PMMA NextDent resin energy [47].

Malvika Nagrath et al. [59], demonstrated the capability of 3D printed dentures using PMMA material to save identical mechanical properties as compared to the conventional fabrication methods. PMMA 3D-printed resin material is vital for the production of removable dentures. Nonetheless, more investigation and evolving materials are requisite to prolong their applicability in dentures [60]. Methacrylate-based photo polymerization resins were used by (Joo-hee Lee, n.d.) to make dentures via 3D stereolithography. This technique was found to provide sufficient fracture resistance for the prosthetic denture [61]. In a study, it was verified that the nan composite consists of PMMA incorporated with nanoparticles of TiO_2 using stereo-lithography under UV illumination to manufacture complete dentures and has antibacterial properties, especially on Candida species [62,63].

One study discovered that PMMA composites with three distinct reinforcements-aluminum nitride, titanium oxide, and barium titanate could be printed using SLA technology [64]. The combination of zirconia microparticles into the PMMA 3D-printed denture resin verified the possibility of augmenting the denture's biological and mechanical properties using the liquid crystal display technique (LCD) compared to conventional techniques. Conversely, compared with the bulk 3D-printed denture base resin, the mechanical properties weakened while the biological properties amended [65].

Additionally, fused deposition method (FDM) was also used to manufacture PMMA [66]. More research is necessary, though, because there haven't been many studies on biocompatibility and 3D-printed PMMA compositions.

3.2.Polyether Ether Ketone (PEEK)

In 1979, the Du Pont firm invented Polyetheretherketone or PEEK. It is a thermoplastic polymer with excellent performance [67]. PEEK has a good resistance to chemicals, radiation, and hydrolysis (excluding sulphuric acid and a high in-vitro biocompatibility (non-cytotoxicity)). [68,69]. PEEK is a biocompatible thermoplastic polymer used in various industries, including dentistry. It has a semi-crystalline microstructure with superior thermal properties. PEEK also offers several benefits, including low modulus that is like natural bone, resistance to corrosion, and lightweight nature[70]. Also, it was observed that PEEK material has mechanical characteristics that make it suitable for use in biological fields. Different forms of PEEK have already been used in various surgical domains, including maxillofacial surgery, spine surgery, and orthopedic surgery [71].

PEEK is a robust material that can be used for dentures fabricated using 3D printing. It is lightweight and helps to improve patient comfort. PEEK implants made using 3D printing technology therefore offer increased patient satisfaction and safety [72]. Fabricated PEEK dentures using the FDM process have a stronger chewing power that is distributed across the mucosa and the inside of the denture, and the mechanical properties and fit satisfied clinical requirements [73]. PEEK is considered one of the materials used to restore lost tissue in the face and mouth because of its properties. It is scientifically approved and safe for applications of orthodontic wires, dental implants, and fixed and removable partial dentures.[74]. A previous study revealed that artificial saliva solutions with varying pH values did not affect the mechanical properties of PEEK at 25 °C [75]. Another study showed that the inclusion of titanium dioxide considerably improved the hardness parameter of PEEK, although it remained inferior to that of natural tooth structure [76]. Schwitalla et al. illustrated that PEEK samples reinforced with various fiber fillers could resist the axial pressure exerted during mastication. In addition, they concluded that it is considered one of the appropriate materials for reinstating lost tissues in the mouth owing to the assets it retains as being precisely suitable and safe for denture applications [74]. One research indicated that beverage solution has an insignificant effect on the flexural strength of PEEK dentures [77] . It was noticed that PMMA resin with TiO_2-1% and PEEK-1% composite exhibited a specificthe resolution, and finished surface signifying this efficient material would be an appropriate resin in the 3D printed denture industry [37].

In reality, PEEK materials are utilized in the dentistry profession as well as PEEK abutments for the creation of gingiva before crown restoration. Recently, PEEK/ceramic crowns and removable dentures were proposed in the field of dental prosthodontics and it was reported the possibility of using this material in 3D printing methods could raise scientific concern and their future improvement likewise [71].

3.3.Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile butadiene styrene (ABS), a common thermoplastic, has better chemical resistance and favorable impact strength, compared to pure polystyrene [78]. ABS is a sturdy, lightweight material that is oil-based and recommended to be printed at temperatures ranging from 230–250˚C for the extruder and 80–105 ˚C for the print bed [56]. ABS performs well overall and has a high resistance against impacts. By increasing the filling content, stiffness and limited strength are correspondingly increased, according to an analysis of the stress-strain (σ–e) curves. It also has a greater flexural modulus than that of pure ABS, but the flexural strength decreased with Boron Nitride BN content which proves to be a promising thermal filler material for AM applications where electrically insulating materials are required [79]. The properties of ABS can be adjusted based on the ratio of its three monomers. As, its density can be between 1.05 mg/m^3 and 1.07 mg/m^3, which corresponds to a tensile modulus of 2.5 GPa to 2.7 GPa [80]. Moreover, ABS has slightly different mechanical properties such as tensile strength in the range of 15 MPa to 38 MPa. These differences are due in part to the different processing temperatures and printing parameters used to produce the parts, the slightly different monomer proportions in the ABS structure, and the orientation of the part being tested. [81].

The production of a composite material that can be used for 3D printing by combining different amounts of hydroxyapatite with ABS and industrial drawing is anticipated to lead to the eventual use of this material in dental implants. [82].

In clinical dentistry, using ABS is still limited compared to PMMA and PEEK. Some clinical studies have demonstrated the potential for ABS to be used in removable partial dentures due to its impact resistance. Despite this, ABS is not yet a mainstream choice in clinical practice due to its lack of long-term data regarding wear resistance and biocompatibility [53].

3.4. Polylactic Acid (PLA)

Polylactic acid (PLA) is another well-known thermoplastic derived from renewable resources that is biocompatible, but it has a lower glass transition temperature. PLA has attracted the attention of the scientific community due to its biocompatibility, biodegradability, ease of processing, and thermal stability. It is a water-insoluble and bio-friendly polymer unlike ABS, which releases an odor during printing [83, 84]. PLA filaments and photosensitive liquid resins were used to produce 3D-printed aneurysm models with hollow skulls and rigid walls [85, 86]. PLA scaffolds are generally used to at least hold within the body cavity and possibly also create a lumen. Because of its outstanding physicochemical properties, PLA is an ideal option for producing scaffolds. For surgical modeling applications, PLA is, therefore, a better fit for desktop fused deposition printing [87]. To maximize the hold of the PLA filament and ensure a flawless printing experience, a basic measurement was developed namely 3D's custom-made extruder bolt. This can improve the efficiency of PLA printing and allow the experiment to run smoothly [88,89]. PLA can also be used for other kinds of printing processes, like stereolithography and resin curing [81], which allow for the creation of more intricate part architectures than are typically achievable with extrusion processes. While PLA is biocompatible, the addition of photopolymers to the resin solution which is required for cross-linking monomers to form polymers in the presence of ultraviolet light-raises some concerns about toxicity in stereolithography-printed PLA. The class transition temperature Tg of the material could be raised to a level appropriate for intra-oral use by combining PLA and PMMA. Thermoplastic injection PMMA/PLA blend has a higher flexural modulus and equivalent flexural strength to traditional heat polymerized PMMA, making it a potential substitute material for denture bases [90]. A whole denture design is produced via the FDM method and CAD software which improves the efficient fit of the finished denture as compared to the traditional method. A PLA full denture produced by an FDM printer revealed a practically valued substitute, and the procedure fulfills the accuracy requirements. [91].

Further, the mandibular complete denture printed by fused deposition modeling from PLA material was evaluated. The results displayed a virtuous fit in the FDM denture with low cost and efficiency. Furthermore, 3D printing can be used to print out thorough dentures and as a source for clinical applications [92,93] .

In another study, an evaluation of the microstructural and mechanical properties of polymeric materials over dentures manufactured by 3D printing was performed. The polymers offered high surface roughness and exceptional values for hardness and compression properties. Moreover, the ABS material didn’t display satisfactory retaining to specify its usage as an overdenture while PLA material can be selected to custom as an attachment to keep overdentures [94].

4. The gaps and limitations in the existing research

1. **Limited Long-Term Clinical Studies:** While several studies focus on the mechanical and physical properties of 3D-printed denture materials in vitro, there is a lack of long-term clinical trials that evaluate the durability and patient satisfaction with these materials over extended periods. For instance, PMMA, although widely used, is known to become brittle over time in the oral environment. However, the absence of extended clinical trials on reinforced PMMA (e.g., with TiO_2 or ZrO_2 nanoparticles) means that the long-term efficacy of these reinforcements remains unclear. This limits clinicians' confidence in adopting newer material formulations until such trials are conducted.
2. **Diversity in Denture Design and Patient Populations:** The current research often lacks diversity in the range of denture designs tested and the patient populations studied. For example, many studies focus on standard full dentures, but there is limited research on the performance of 3D-printed partial dentures or implant-supported dentures, which are increasingly common in modern prosthodontics. Furthermore, most studies do not account for variations in patient age, oral health conditions, or specific needs such as those of edentulous patients with compromised bone structure. This reduces the generalizability of findings and creates a gap in understanding how these materials perform in a broader range of clinical scenarios.
3. **Standardization of Testing Protocols:** One of the significant limitations in the field is the lack of standardized testing protocols across different studies, making it difficult to compare results. For example, some studies measure flexural strength and impact resistance under different environmental conditions or use varying specimen geometries, leading to inconsistent results. This lack of standardization hinders the ability to draw meaningful conclusions about which materials (e.g., PMMA vs. PEEK) perform best under specific clinical conditions
4. **Limited Exploration of Novel Polymer Combinations:** Most research focuses on established materials like PMMA, PEEK, and ABS, while novel polymer combinations or advanced composites receive less attention. For instance, the potential of hybrid composites such as PMMA reinforced with nanomaterials (e.g., graphene, carbon nanotubes) remains underexplored. This limitation hampers the development of new materials that could address current shortcomings, such as improving the fracture resistance of dentures.
5. **In-Depth Analysis of Biocompatibility:** While biocompatibility is often referenced in studies, most focus on short-term in vitro tests, which fail to capture the material’s interaction with oral tissues over extended periods. For instance, although Polyether Ether Ketone (PEEK) shows high initial biocompatibility, long-term clinical data on its interaction with oral tissues, especially in patients with specific oral conditions (e.g., dry mouth or periodontal disease), is sparse. This lack of long-term biocompatibility data makes it difficult to fully endorse PEEK as a substitute for traditional materials like PMMA in routine clinical practice. Furthermore, biocompatibility issues may arise with novel materials like reinforced PMMA composites, which may have nanoparticles (e.g., TiO_2) that could trigger immune responses over time.
6. **Scaling Up Production and Cost Considerations:** The scalability of using advanced materials like PEEK and the economic feasibility of producing dentures using these materials remain significant challenges. PEEK, for example, has excellent mechanical properties, but its high cost limits its application to premium

dental prosthetics, making it inaccessible to a broader patient population. Studies on the production costs of PEEK-based dentures using 3D printing are still lacking, making it difficult for clinicians to adopt these materials on a larger scale. Additionally, production techniques for some materials, such as Polylactic Acid (PLA), may not yet be optimized for mass production, further constraining their use in clinical settings.

7. **Environmental Impact of Materials:** The environmental sustainability of polymeric materials used in denture fabrication has been under-researched because of the limited information regarding their ecological footprint. The main environmental concerns involve the sourcing, production, and disposal of these materials, particularly regarding their biodegradability, recyclability, and overall lifecycle impact. PLA, for instance, is biodegradable and derived from renewable resources, making it an environmentally friendly option. However, its weaker mechanical properties make it less suitable for dentures, necessitating additional reinforcements that may negate its eco-friendly benefits. Furthermore, most materials like PMMA and PEEK are non-biodegradable and derived from petroleum-based sources, contributing to long-term environmental concerns when used in mass production. However, PEEK's durability and longevity, particularly in dental applications, suggest that it may need to be replaced less frequently than other materials, potentially reducing its overall environmental footprint. Research into the recyclability of PEEK is still limited, but advancements in this area could help offset some of its environmental drawbacks. Research into the recyclability and life cycle of these materials is currently minimal, limiting our understanding of their environmental footprint.
8. **Patient-Centric Outcome Measures:** Most studies focus on the mechanical and physical properties of materials, with fewer addressing patient-centered outcomes such as comfort, aesthetics, and functional performance (e.g., speech and chewing efficiency). For instance, while PMMA is widely used due to its affordability and ease of adjustment, its brittleness may cause frequent fractures, leading to lower patient satisfaction in the long term.PEEK, despite its superior mechanical properties, may have aesthetic drawbacks due to its less natural appearance compared to PMMA, potentially impacting patient acceptance. Few studies measure these softer, patient-centered outcomes, which are crucial for understanding the real-world success of 3D-printed dentures.

These specific limitations affect the current state of research by limiting our ability to fully understand the long-term clinical performance, patient outcomes, and environmental impact of the materials used in 3D-printed dentures. Addressing these gaps through targeted research would significantly advance the field and lead to the development of more effective and sustainable denture materials.

5. Conclusion

The introduction of 3D printing technology has brought significant changes to several industries, such as dentistry, by providing new methods for creating dental prosthetics. This review article thoroughly investigates the utilization of polymeric materials in 3D printing for dentures with a focus on their mechanical, biological, and clinical properties. Our evaluation covers a variety of polymeric materials, including Poly (methylmethacrylate) (PMMA), Polyether Ether Ketone (PEEK), Acrylonitrile Butadiene Styrene (ABS) Polylactic, and Acid (PLA) among others. Polymeric materials are essential in the creation of dental restorations using 3D printing due to their special properties like biocompatibility, strength, and ease of processing. The key findings of this study are summarized as follows:

1. **PMMA** remains the common most and best-used material in denture fabrication due to its affordability, aesthetics, and ease of processing. However, it is limited by its brittleness and suboptimal mechanical properties, which have been partially addressed by reinforcement with nanoparticles (e.g., TiO_2, ZrO_2).
2. **PEEK** offers superior mechanical and thermal properties, high biocompatibility, and resistance to wear, making it an ideal candidate for advanced dental applications. However, its high cost and limited long-term clinical data on biocompatibility remain barriers to widespread adoption.
3. **ABS** is a promising material due to its toughness and chemical resistance, but its use in clinical denture applications is still limited. Further research is needed to assess its biocompatibility and long-term performance.
4. **PLA** is biocompatible and biodegradable, making it environmentally friendly. However, its mechanical properties are not yet sufficient for denture fabrication, necessitating further research into reinforcement techniques and composite formulations.

The use of 3D printing technology allows for the creation of personalized dentures that have better fit, comfort, and aesthetics, leading to higher levels of patient satisfaction. Additionally, improvements in material properties and post-processing methods are helping in the production of long-lasting and biocompatible dental prosthetics, catering to the changing requirements of both clinicians and patients. However, despite the encouraging progress made in this field, there have been several gaps and limitations identified in the current research. The absence of long-term clinical studies is a hindrance to fully evaluating the performance of 3D-printed dentures and patient satisfaction over prolonged periods. Additionally, the limited range of denture designs and patient demographics may limit the applicability of research findings, indicating a need for studies that include diverse demographic groups and oral health conditions. It is important to have standardized testing protocols in place to make it easier to compare studies and guarantee the accuracy of results. It is also important to continue researching new combinations of polymers and advanced polymers composite materials to meet specific needs and improve the quality of 3D-printed dentures. Additionally, thorough assessments of biocompatibility and environmental sustainability are crucial for moving the field forward responsibly and ethically. To sum up, the evaluation of polymer materials utilized in 3D printing for dentures highlights the notable progress and possible obstacles in the industry. Collaborative research endeavors can help address gaps and limitations, leading to the creation of denture solutions that are safe, long-lasting, and tailored to patients' needs. This, in turn, can enhance the quality of dental treatment and improve patient results**.**

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