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Review article

Advancements in dental implant technology: The impact of smart polymers utilized through 3D printing

Aliasghar Abouchenari [a], Neda Tajbakhsh [b,*], Amirhosein Shahbaz [c], Ghazal Alamdari-Mahd [d,e]

[a] *Department of Material Science and Engineering, Shahid Bahonar University of Kerman, Kerman, Iran*
[b] *Department of Prosthodontics, School of Dentistry, Islamic Azad University, Tehran Dental Branch, Tehran, Iran*
[c] *Department of Materials Engineering, Karaj Branch, Islamic Azad University, Karaj, Iran*
[d] *Faculty of Dentistry, Urmia University of Medical Sciences, Urmia, Iran*
[e] *Cellular and Molecular Research Center, Cellular and Molecular Medicine Research Institute, Urmia University of Medical Sciences, Urmia, Iran*

ABSTRACT

The field of dental implantology has witnessed significant advancements in recent years, driven by innovations in materials science and manufacturing technologies. One such innovation that holds promise for revolutionizing dental implant generation is mixing smart polymers through three-D printing. This evaluation article affords a comprehensive overview of the effect of clever polymers in enhancing the performance and functionality of dental implants. We begin by elucidating smart polymers' fundamental residences, which include their stimuli-responsive conduct, biocompatibility, and mechanical strength. Sooner or later, we discover the evolution and programs of 3D printing, e.g. direct metallic laser sintering (DMLS) and selective laser melting (SLM), in dentistry, highlighting its position in fabricating custom-designed dental implants. Combining smart polymers into dental implants is discussed in element, overlaying surface modification techniques, incorporation of bioactive dealers, and customization for affected person-particular desires. Furthermore, we look at how smart polymers make contributions to enhancing aspects such as osseointegration, peri-implantitis management, and average implant toughness. Clinical insights and case studies are presented to illustrate the real-global applications and results of clever polymer-based dental implants. Ultimately, this evaluation objective is to offer valuable insights for clinicians, researchers, and industry specialists worried about the improvement and utilization of advanced dental implant technologies.

KEYWORDS

Smart polymers
Synthesis
3D printing methods
Dental implanting
Custom dental prosthetics
Direct metal laser sintering

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1. Introduction

Biomaterials have seen a revolution way to smart polymers, which show off stimuli-responsive conduct. Implants that could regulate the dynamic conditions inside the mouth cavity to enhance mechanical electricity and biocompatibility had been made viable by way of their ability to modify their traits in reaction to environmental cues [1, 2]. This flexibility is critical in an area in which an implant's capability to interact with living tissue determines its success [3].

Traditional strategies in the field of dental implantology primarily involved using dentures and bridges, dentures, endosseous implants,

* Corresponding author. *E-mail address:* neda.tajbakhsh65@gmail.com (N. Tajbakhsh)
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subperiosteal implants, and transosteal implants. These strategies served as the mainstay for enamel substitutes for decades [4].
Tracing back to the inception of dental implantology, traditional strategies normally depended on steel-based total implants, which, whilst powerful, presented constrained interaction with the organic surroundings. Over the years, the sphere has witnessed a paradigm shift with the advent of clever polymers, which provide improved osseointegration and bioactivity. This review aim to bridge the historical gap by evaluating those conventional methods with the present-day improvements that have revolutionized dental implant technology [5].
Over the last long time, the sphere of dental implant technology has undergone progressive advances, with the development of clever polymers and 3D printing at the vanguard of this progress. By combining those cutting-edge materials and production methods, dental implants might also now be designed and operated at previously unheard-of tiers of overall performance and personalization [6].
The production process for dental implants has been transformed through the combination of smart polymers and 3D printing generation. Because of its precision and customization talents, 3D printing has made it feasible to create implants that precisely shape the anatomy of the affected person [7]. This degree of customization marks a major development in patient-specific healthcare solutions that was formerly unachievable with conventional production techniques [8].
This article is notable because it thoroughly reviewed the effects of smart polymers used in 3D printing on dental implant technology. Although smart polymers and 3D printing have each been the subject of separate research in the past, this work explores the junction of these two fields and their combined impact on the field. It draws attention to current developments, like the creation of UV-treated implants that offer nearly flawless osseointegration and quicker healing periods.
The main objective of this study is to give a comprehensive understanding of the present and prospective future states of dental implants that are improved by 3D printing and smart polymers. Also, we aimed to focus on the most recent advancements in technology, clinical uses, and materials science that come with such quick development.

2. Smart polymers

2.1. Understanding smart polymers

Polymers are renowned for their ease of property modification, making them a versatile platform for a myriad of applications. Smart polymers, including hydrogels, microgels, and composite networks, are at the forefront of technological advancements in medication delivery, sensor development, and actuator design. The collaboration between polymer scientists and multidisciplinary professionals is propelling polymer science into a future where it addresses critical societal challenges in the environmental and health sectors [9, 10].
The function that distinguishes clever polymers from ordinary polymers is their capability to react to environmental stimuli with a sizeable and often reversible exchange in their physical homes. This responsiveness isn't always present in ordinary polymers, which usually preserve steady homes no matter environmental changes [2]. Smart polymers can adapt, self-modify, and respond to external factors, making them flexible for various packages where environmental sensitivity is needed [11]. Regular polymers lack this dynamic functionality and are used on the whole for his or her static cloth houses. In essence, the smartness of those polymers is attributed to their capacity to behave upon external stimuli, which units them aside from conventional, non-responsive polymers [12].
Smart polymers are helpful in biological applications, inclusive of tissue engineering and protein folding, because of their top-notch asset adjustments in reaction to environmental shifts. Their untapped potential for dynamic interactions between organic and chemical systems opens the door to progressive answers for complex demanding situations [13]. Through incorporating molecular popularity factors, these polymers come to be quite sensitive to stimuli, enabling particular management over their homes. Clever polymers with super wettability, classified with the aid of their constructing components, find various packages in tissue engineering, drug delivery, and biosensor improvement [14].
Smart polymeric hydrogels, which dynamically adjust their houses in response to chemical, physical, or biological stimuli, are specifically promising for biomedical applications. Their capability to exhibit reversible solubility-insolubility in aqueous media or shape hydrogels while cross-related makes them suitable for drug transport and immunoassays. Those polymers consist of artificial editions like poly(N-isopropyl acrylamide) and methyl-methacrylate polymers, natural options like alginate, chitosan, and carrageenan, and hybrids along with collagen-acrylate and poly(ethylene glycol-co-peptides) [15].
The emergence of stimuli-responsive polymers (SRPs) holds awesome promise for biomedical programs, with several industrial and scientific makes use of. Of particular hobby are clever polymeric hydrogels, which dynamically adjust their homes in response to modifications in their environment, maybe chemical, physical, or biological. Amongst SRPs, temperature-responsive polymers have garnered attention for his or her numerous biomedical packages [16]. Stimuli-responsive polymers, additionally known as clever polymers, adapt their shape or physical characteristics in response to mild adjustments in environmental stimuli. Examples of such stimuli include pH, ionic energy, temperature, mild, and magnetic or electric fields, which have observed packages in biopharmaceutical fields [17].
Also amongst clever polymers, SMPs are prominent via their precise capability to go back to a predetermined form in reaction to stimuli like warmth, mild, or electric fields. This two-degree system entails programming the polymer at a high temperature to a temporary shape and then improving its original shape upon publicity to an appropriate stimulus. Efforts in SMP studies focus on improving traits such as response time and recovered shape strength to make their industrial programs [18]. Efforts in SMP studies purpose to beautify characteristics consisting of reaction time and recovery from power to develop their packages across numerous industries [19].
Qi and Wang [20] overviewed the techniques used to prepare SMPs, blends, and composites become given in a few chapters. Those procedures blanketed single-step polymerization of monomers and prepolymers with cross-linkers and chemical cross-linking of thermoplastic polymers. The preparation strategies for SMPs, a class of clever polymers prominent by using their ability to regain their authentic form following deformation, are blanketed inside the referred to chapter. Because of this characteristic, they may be extremely useful in many programs, consisting of aeronautical and medicinal components. Thermoplastic Polymers with chemical cross-linking process forms covalent bonds between polymer chains. A network

structure is created by adding cross-linkers during the polymerization process [21]. This network structure establishes the permanent shape of the SMP, which is essential for the shape-memory effect. The material can be distorted when heated above a certain transition temperature, and it will retain this transient shape when cooled. The substance will regain its normal shape when reheated [19, 22].

Monomer/prepolymer single-step polymerization using the cross-linkers method involves polymerizing monomers or prepolymers in a single step by combining them with cross-linking agents. A thermoset polymer with a set shape can be produced using this method. The cross-linking agents aid in establishing the polymer's permanent shape, which can be stimulated to revert to its original form following deformation [20, 23]. Smart Biodegradable Polymers with electrical conductivity are polymers intended for use in biological fields. Their electrical conductivity is outstanding. Applications include tissue engineering, drug delivery, surgical implants, electronic medical devices, and cancer treatments. Sustainability and long-term stability are guaranteed by biodegradability [24, 25].

Expanding the utility of smart polymers involves designing materials that mimic natural structures while integrating stimuli-responsive units. Reversible super wettability switching, responding to external stimuli like pH and temperature, has garnered attention for applications such as industrial oil recovery and self-cleaning. Among smart polymers, thermoresponsive polymers stand out for their ability to quickly alter structure in response to temperature changes, categorized as upper or lower critical solution temperature (UCST or LCST) [9, 26]. Some applications of smart polymers are shown in Fig. 1.

2.2. Characteristics and properties

2.2.1. Stimuli-responsive behavior

Creating smart polymers selectively is sensitive to biomolecules and switchable wettabilities remain challenging due to weak feedback from bimolecular recognitions. Rethinking conventional molecular design can enable controlled recognition signals, enhancing sensitivity to stimuli and facilitating intelligent technology development [28].

Early applications of smart polymers, such as immunoassays utilizing poly(N-isopropylacrylamide) (PNIPAAm) conjugation, demonstrated their potential for biomolecule detection. Despite initial promise, challenges in time and cost hindered widespread adoption [29]. When a polymer is cross-linked to create a gel, it becomes Smart and collapses and re-swells in water in response to changes in its critical condition caused by a stimulus. The collapse of the gel releases any drugs that are placed into it in a burst.

For another example, one of the initial uses of a smart polymer biomolecule combination is the immunoassay. It was predicated on an antibody's conjugation to poly(N-isopropylacrylamide) (PNIPAAm). To detect an antigen, such as a biomarker of hepatitis or AIDS, which was being checked for at the time in all blood banks, the smart bioconjugate was then added to a blood test sample. Subsequently, a second labeled antibody was introduced, which was specifically made to form an affinity link with the same antigen [30].

Hoffman et al. [31] confined the cells and enzymes in smart gels, and the enzymes (or the enzymes inside the cells) might be turned "on" and "off" by causing the gel to inflate and collapse cyclically.

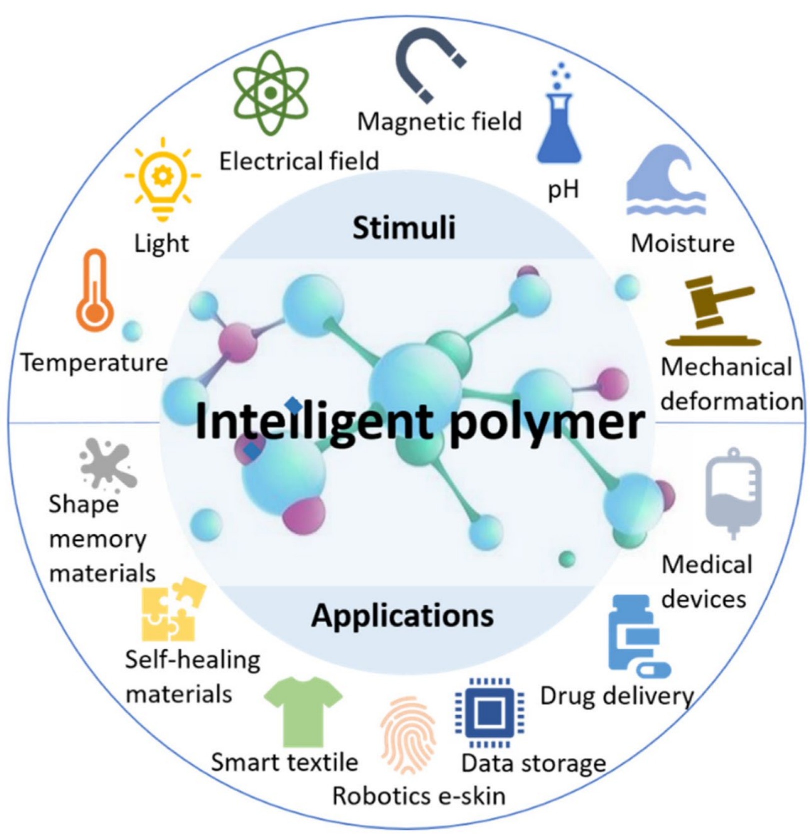

Fig. 1. Some smart polymers benefit in different fields [27].

Smart polymeric materials, whether synthetic or natural, exhibit significant changes in their properties in response to small environmental variations such as temperature, pH, light, and chemicals. These stimuli-sensitive materials find widespread applications in various biological fields, including tissue engineering, drug delivery, bioseparation, biosensor development, microfluidics, and protein folding. By replicating the intelligence of biological systems, these materials offer efficient control over intricate processes like immune responses, fostering a dynamic interaction between biology and chemistry [32].

Zhang and Huang [33] introduced hydrogels as a smart polymer by emphasizing their vital role in biological applications, highlighting their classification based on molecular composition into natural and synthetic polymers. While synthetic polymers offer customization and strength, natural polymers boast biocompatibility. Designing hydrogels to respond to environmental stimuli like light, temperature, and pH is crucial for applications such as drug delivery and tissue healing, where precise triggers are needed. However, challenges in hydrogel design include integrating synthetic and natural polymers, developing multifunctional systems, and incorporating novel materials for customized medical solutions.

Ganguly and Margel [34] examined the potential of magnetic hydrogels (MHGs) in biomedical applications. It draws attention to their magneto-responsive qualities, which can be used for anti-cancer therapies based on hyperthermia and regulated drug delivery. They concluded that MHGs are tunable porosity and internal morphology and are promising for diffusion-related smart devices and therapies that benefit from non-contact hyperthermia heating.

2.2.2. Biocompatibility

Biocompatible smart polymers have garnered significant interest in biomedical applications. These polymers, whether natural or synthetic, exhibit adaptability to the human body and its fluids, known as biocompatibility. They find applications in various biomedical domains, from bone filler materials to controlled drug delivery systems [35]. Life itself is inherently polymeric, with proteins, carbohydrates, and nucleic acids serving as the basic components of living organic systems. To mimic biopolymers, synthetic polymers have been developed for various industrial and scientific purposes [36].

The biocompatibility of smart polymers refers to their ability to perform with an appropriate host response in a specific application. These materials are designed to engage with organic systems without eliciting any unfavorable outcomes, inclusive of toxicity or immune rejection [17, 37]. For dental implants, this means that clever polymers can alter their behavior to suit the dynamic situations within the oral hollow space, enhancing their compatibility with the natural environment of the mouth. This pliability is critical for implants, which must no longer simplest bodily suit well but additionally be chemically inert to avoid infection or rejection using the body [35]. Moreover, the surface properties of clever polymers can be engineered to encourage cellular attachment and increase, selling osseointegration, which is the technique of bone bonding tightly to the implant. This is vital for the long-term balance and functionality of dental implants [37].

In summary, the biocompatibility of clever polymers in dental implants is a key attribute that ensures these substances may be correctly and successfully used inside the human frame, responding appropriately to the body's environment and contributing to the general success of the implant [38].

Some studies have been that specialize in numerous components of clever polymers, consisting of their layout, characterization, and programs in the biomedical area. These substances are being explored for their capability in cell therapy, 3D printing for precision medicine, and as companies for tablets, proteins, and cells due to their responsive nature to environmental stimuli [37]. Additionally, the special requirements for scaffold materials used in biomedical devices, such as biocompatibility, biodegradability, and mechanical properties, are being addressed in the development of smart biomaterial devices. These materials aim to meet the stringent demands of biomedical applications [39]. Table 1 presents a summary of the biocompatibility tests, results, and other details for some polymers.

2.2.3. Mechanical strength

Over the past few decades, there has been a growing interest in smart materials that have found diverse applications in biotechnology, medicine, and engineering [46] because these polymers show many characterizations such as biopolymer connection, synthetic polymers, and reversibility.

Smart polymers undergo reversible transitions in their macroscopic structure, solubility, surface characteristics, and molecular assemblies in response to environmental stimuli [47]. However, classifying smart synthetic polymers poses challenges due to their diverse physical and chemical properties [48].

Table 1. Summary of biocompatibility and performance metrics for smart polymers (SPs) in biomedical application.

Polymers	Applications	Biocompatibility	Results	Details information	References
Collagen	Biological scaffold	Cell proliferation and immune response	Supports cell growth without adverse reactions	Cell viability >90%	[40, 41]
Hyaluronic acid	Medical application and skin tissue engineering	Skin tissue compatibility	Promotes wound healing, compatible with human tissues	Rapid epithelization rate	[42, 43]
Polyether ether ketone (PEEK)	Orthopedic and dental implants	Cytotoxicity, sensitization, and irritation	Non-toxic, non-irritant, and non-sensitizing	Low inflammatory response	[44, 45]

In biomedical applications, SMPs are utilized for their adaptability, particularly in bio-medical parts. These materials, combined with low-temperature polymers and thermoplastic elastomers, demonstrate potential for applications such as synthetic muscle fibers, offering promising solutions for various industries [50].

The exponential growth of interest in smart polymers since the 1990s, driven by complex industrial demands, has seen over 6000 scientific works and 500 reviews published, with biotechnology and biomedicine being prominent fields for their applications [2].

In terms of mechanical strength, smart polymers play a crucial role in the development of smart gadgets, sensors, and actuators. Through editing their macroscopic or meso-structural arrangement or altering their chemistry, these substances may be made aware of environmental stimuli. Mechanical modeling at molecular and continuum scales is essential for engineering the microstructure of clever polymers to gain favored features and design cutting-edge devices [50].

Melly et al. [52] have targeted their research on SMPs and other clever polymers with the purpose of engineering materials that could autonomously perform specific features in response to outside stimuli. This approach is pivotal for the development of systems that can be greater adaptive and responsive across diverse fields. Their dialogue delves into the current advancements in SMP blends and composites, highlighting the consequences of reinforcement, cutting-edge shape-memory capabilities, and responsiveness to oblique thermal stimuli. The intention is to beautify power and durability without compromising the intrinsic shape-memory traits, by way of employing blending or composite techniques to bolster mechanical residences [51, 52].

The form recovery price of SMPs shows a form restoration fee of 98% or higher, which is a vital measure of their capability as clever substances [53]. Increasing energy and sturdiness while maintaining form memory by way of mixing or composite-making substances to enhance mechanical features. These developments are key to creating versatile materials for diverse applications, aiming to improve performance and functionality [54].

Design of elastin-like polypeptides (ELPs)-based functional hydrogels such as methacrylate group-modified lysine-rich ELPs are investigated. These ELPs experience photo-crosslinking and a phase shift brought on by temperature. Methacrylation and ELP-MA concentration can be changed to modify properties (mechanical strength, pore size, swelling ratio). When implanted in mice, ELP-MA hydrogels exhibit good biocompatibility, indicating potential for use in smart material applications. These developments in smart polymers could lead to creative solutions across a range of industries [44].

The tensile strength of SMPs has been reported to exhibit a tensile strength ranging from 2 to 50 MPa, depending on their chemical composition and the nature of the stimuli applied [55].

Elongation at break of polymers can stretch significantly before breaking, with elongation at break values between 200% to 400% for certain compositions [56].

Smart polymers, or stimuli-responsive polymers, can change their physical properties, such as elasticity and stiffness when triggered by external factors like temperature, pH, or light. Young's modulus is a measure of a material's stiffness and is defined as the ratio of stress to strain within the elastic limit of the material [57].

For smart polymers, Young's modulus is particularly relevant because it can change as the polymer transitions between its different states. For example, a temperature-responsive polymer may have a lower Young's modulus (be more elastic) below its transition temperature and a higher Young's modulus (be stiffer) above this temperature. This changeable stiffness is what makes smart polymers useful in applications where materials need to adapt their mechanical properties dynamically [58]. Young's modulus of SMPs can vary widely, from as low as 0.01 GPa for soft gels to over 3 GPa for rigid thermoset polymers [59].

3. 3D printing in dentistry, evolution, and applications

3.1. Historical context and technological progression

3D printing has revolutionized dentistry over the last decade, enabling a shift to digital workflows and personalized treatment plans [60, 61]. This technology has been integrated into various dental specialties, including oral surgery, orthodontics, endodontics, prosthodontics, and periodontics, enhancing clinical treatment, education, and research [62].

The advancements in 3D modeling and imaging technologies have expanded the applications of 3D printing in creating drill guides, models, and implants, contributing to its significance in dentistry [63].

Despite its success, the technology faces challenges such as material costs and regulatory compliance, which need to be addressed for its continued adoption [61, 64].

The potential of 3D printing extends to the development of 4D printing, promising more personalized care through image-based devices for regeneration and repair [65, 66]. Some applications of this technique are shown in Fig. 2.

Nyirjesy et al. [67], as a head and neck oncologic surgical reconstruction, has been transformed by developments in computer-aided design/computer-assisted manufacture (CAD/CAM) and three-dimensional (3D) printing, primarily in the use of bony free flaps. 3D anatomic modeling has improved conventional free-hand techniques, and state-of-the-art technology enables full virtual planning (VP), including with patient-specific implants for greater functionality. Future developments in patient-specific craniofacial restoration may involve the use of biological scaffolds that are 3D printed, drug-eluting implants, and bioactive implants.

Shaikh et al. [68] presented it is possible to produce customized dental implants, surgical guides, anatomic models, aligners, crown and bridge constructions, endodontic guides, and periodontal surgery guides, 3D printing technology is completely changing the way dental treatments are customized. Through the use of modern imaging techniques and computer-aided design (CAD) data, oral surgeons may precisely plan and perform difficult surgeries in a shorter amount of time. Furthermore, 3D printing is enabling preclinical skill development and patient education in dentistry, indicating a paradigm change in favor of more individualized and efficient dental care [68].

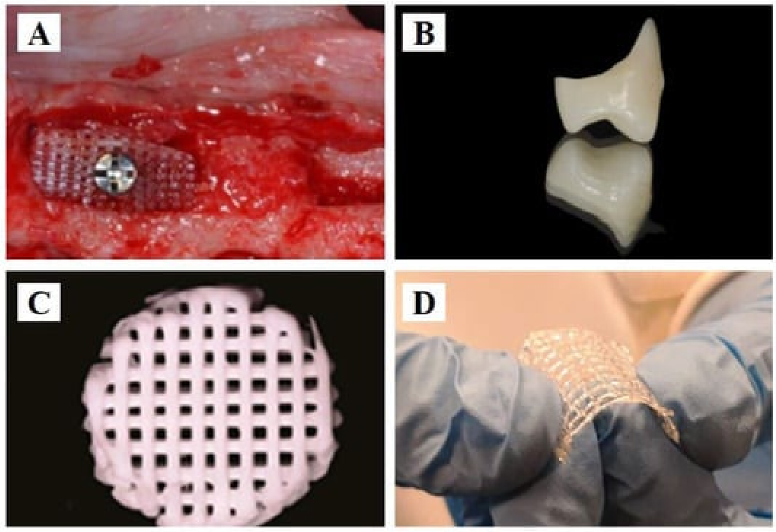

Fig. 2. Polymer applications in 3D printing dentistry [69].

3.2. Innovations and current utilization of 3D printing in dental implant fabrication and materials

Before 3D printing, dental implants were crafted using methods like the lost-wax casting technique, milling, and hand-crafting [70, 71]. These traditional techniques were effective but time-consuming and lacked the customization that 3D printing offers today, which allows for more precise and efficient implant fabrication [72].

3D and 4D printing technologies have significantly superior the sector of dentistry, permitting the rapid and unique production of dental merchandise. Dental specialists make use of these technologies to custom layout and manufacture a big selection of objects, which include surgical drill publications, crowns, bridges, orthodontic home equipment, implants, and mouthguards for medication transport [73].

The programs of 3D printing are enormous, covering dental implants, craniofacial and maxillofacial surgical procedures, orthognathic and periodontal treatments, as well as endodontic procedures. The generation additionally supports the creation of implant copings, frameworks, and dental restorations, with techniques like stereolithography and selective laser printing being specifically popular [63].

Polymer 3D printing is gaining traction inside the scientific enterprise for its price-effectiveness and capability to provide elements with diverse houses. This has led to its use in developing biocompatible and mechanically sturdy polymers for medication delivery systems, dental implants, and protecting gear [74].

Fabric jetting, binder jetting, stereolithography, and laser sintering are not unusual 3D printing techniques within the dental industry. To make 3D printing greater least expensive, it's miles critical to recognize the restrictions of every method, the substances that might be applied, and the operator talent level that is wanted. However, continuous advancements in the accuracy of these printing techniques and materials allow dental clinics to use a more widespread and effective digital workflow [75]. Additionally, 3D printing is used to create haptic simulators for patient education [60].

3D printing, or additive manufacturing (AM), has revolutionized medical therapies by enabling the creation of intricate geometric patterns and personalized medical devices. This technology, which includes liquid-based, solid-based, and powder-based techniques, allows for the production of customized organs and dosage forms, facilitating the advancement of personalized medicine [76, 77]. The growth of 3D printing has been significant, with the technology evolving from rapid prototyping to the production of functional parts in larger volumes. The adaptation of materials for design accuracy and the required physical and mechanical properties is key to this evolution [78, 79].

Diagnosed as a driving pressure inside the "next business revolution," 3-d printing is transforming healthcare shipping, especially in dentistry, in which it's far used to create drill publications, fashions, implants, and restorations. The technology's relevance is anticipated to boom with further advancements in 3-D modeling and imaging technology [79, 80].

3D printing is poised to transform the producing industry, with increasing hobby from the surgical zone. Its application in dentistry is in particular good sized, supported via improvements in three-D modeling and imaging technology like intraoral scanning and cone beam computed tomography. The generation, which has a strong basis in CAD/CAM utilization, is applied for an expansion of dental packages, such as the introduction of drill publications, models, implants, and restorations, making it a quintessential part of present-day dental practice [81].

4. Advances in 3D printing techniques for dental implants

4.1. Novel printing methods

With the appearance of cutting-edge techniques like direct metallic laser sintering (DMLS) and selective laser melting (SLM), the sphere of 3D printing for dental implants is growing speedy. Those strategies provide awesome precision and the potential to design intricate structures that are precise to the wishes of every patient [82].

DMLS and SLM inside the subject of three-D printing for dental implants are growing fast. These techniques offer extremely good precision and the capacity to design intricate structures that might be precise to the wishes of every affected person [83]. DMLS is a kind of additive production technology that makes use of a high-powered laser to sinter powdered cloth, generally metallic, to create a stable shape. This technique permits the advent of dental implants with complex geometries that carefully mimic the natural contours of the patient's oral anatomy, improving the shape and luxury of the implant [84]. DMLS uses a high-powered laser to sinter powdered material, usually metallic, to create a solid shape. This method allows for the creation of dental implants with complicated geometries that closely mimic the natural contours of the affected person's oral anatomy, improving the match and comfort of the implant [85]. SLM just like DMLS utilizes a laser to soften and fuse metal powders right into a stable structure. The important thing advantage of SLM is its ability to produce additives with excessive density and advanced mechanical homes, making it an excellent desire for developing durable and long-lasting dental implants [86].

Both DMLS and SLM share common advantages over traditional methods, such as customization of them allowing for the creation of patient-specific implants that precisely match the anatomy of the individual, enhancing fit and comfort. Reduced waste additive manufacturing processes like DMLS and SLM produce less waste compared to subtractive methods, as they only use the material necessary to build the part layer by layer [87]. The speed of these methods can potentially shorten the production time from design to the finished implant, as they eliminate the need for tooling and can directly produce the final part from digital designs. Improved osseointegration ability to create implants with specific surface textures and porosities can lead to better bone attachment and growth, improving the success rate of dental implants [88].

High precision of DMLS allows for the creation of highly accurate and detailed parts due to the tightly focused laser, which is essential for the intricate structures of dental implants [89]. Material Flexibility of this technology can accept a wider range of materials, providing the opportunity to use alloys tailored for specific properties required in dental applications [90].

Full melting of SLM involves the complete melting of metal powder, resulting in parts with high density and superior mechanical properties, which are crucial for the durability of dental implants [91].

Complex geometries of high-powered laser of SLM enable the production of complex geometries that are difficult or impossible to achieve with traditional manufacturing methods [92].

These advantages make DMLS and SLM highly suitable for the fabrication of dental implants, offering improvements in customization, efficiency, and implant performance compared to traditional manufacturing techniques [83].

One case study detailed the design and fabrication of a custom-made DMLS mandibular implant, showcasing the full digital workflow from imaging to implant production [93].

Another case defined the a success application of SLM for a full mouth rehabilitation with an implant-supported fixed dental prosthesis, demonstrating the method's precision and customization capabilities [94].

Furthermore, because of its mechanical traits and biocompatibility, polyetheretherketone (PEEK) has shown promise in three-D printing and will be used as a cloth for dental implants [95]. Moreover, the adaptability of three-D printing tactics makes it viable to use an expansion of substances and create complicated styles that have been previously difficult to do [96]. The direct anatomical and practical bond between the surface of a load-bearing synthetic implant and the residing bone is known as osseointegration, and it's far a crucial factor in the achievement of dental implants. Osteointegration is vital to the durability and long-term viability of dental implants published in the use of 3D printing generation [97]. Dental implantology is superior thanks to 3D printing technology, which enables the manufacturing of implants with intricate floor textures and geometries that can improve osseointegration. For instance, certain floor roughness or porosity may be engineered into 3D-revealed implants to promote bone attachment and boom, strengthening the hyperlink between the implant and the jawbone [98].

4.2. Material innovations and surface texture optimization in 3D printed dental implants

The utilization of novel substances, particularly titanium, and its alloys, is revolutionizing the sphere of 3D-revealed dental implants because of their brilliant mechanical homes and biocompatibility [99].

Titanium's renowned electricity-to-weight ratio and resistance to corrosion make it an ideal preference for implants, in particular, while mixed with elements like aluminum and vanadium to in addition decorate its mechanical qualities [100, 101]. These alloys show remarkable sturdiness, vital for withstanding the continuous strain of mastication and ensuring the long-term achievement of dental implants [101, 102]. Moreover, the flexibility of titanium in 3D printing permits the creation of implants with tricky geometries, selling higher osseointegration and patient comfort [103].

Varma et al. [104], highlighted the significance of ceramic materials in tissue engineering and their potential applications, particularly in the biomedical field. It emphasizes the role of 3D printing techniques in enhancing ceramic scaffolds, making them suitable for hard tissue engineering, including dental, middle ear, spinal, and otolaryngology surgeries. They also underscored the mechanical strength, wear resistance, and low electrical conductivity of 3D printed ceramic scaffolds, positioning them as promising candidates for drug delivery applications.

In addition, the creation of biocompatible materials like titanium alloys, cobalt chromium, and stainless steel is helping to produce dental implants that are both more aesthetically pleasing and long-lasting [105, 106].

Surface modification approaches, including sandblasting, acid etching, and alkali etching, play a vital role in enhancing the biological activity and osseointegration of 3D printed dental implants [107].

Sandblasting increases surface roughness, improving bone attachment and reducing the failure rate of implants [108]. Acid etching creates micro-porosities, enhancing wettability and surface area for improved osseointegration [109]. Also, Alkali etching generates a bioactive surface layer, promoting bone-like appetite formation and enhancing osseointegration [110]. These strategies, along with ongoing studies on bioinspired coatings and porosity management, contribute to enhancing medical results for sufferers receiving dental implants [111].

In addition to the materials previously referred to, clever polymers are rising as novel candidates in the discipline of dental implants. While the quest outcomes did now not provide a direct comparison with titanium and smart polymers, within the context of 3D printing for dental packages, polymers love it is used for their biocompatibility and mechanical properties. PEEK and other polymers can be engineered to have specific traits beneficial for dental implants, including promoting bone attachment and increase [112].

Both materials have their precise advantages and are selected based totally on the precise necessities of the dental implant. Titanium is desired for its sturdiness and power, at the same time as clever polymers provide versatility and the ability for customization in response to organic conditions [113].

5. Integration and clinical application of smart polymers in dental implants

5.1. Surface modification techniques

Smart polymer surface modification of dental implants can greatly improve biocompatibility and osseointegration. The implant surface is modified using methods such as chemical vapor deposition, electrophoretic deposition, and anodic oxidation to enhance interactions with surrounding tissues [113]. Bioactive molecule coatings can also encourage the formation of new bone tissue and increase the implants' long-term durability [114]. The anodic Oxidation method increases the oxide layer on the titanium implants' surface by an electrochemical process that may result in better surface properties. The surface modification can promote bone cell adhesion and development more effectively [115].

The electrophoretic deposition technique deposits charged particles on the implant surface using an electric field. It is beneficial for evenly applying bioactive compounds, such as hydroxyapatite (mainly used as an implant for hard tissues) and bredigite, [116] coatings that might improve bone integration [117].

While chemical vapor deposition (CVD) is a widely used technique for forming solid coatings on implant surfaces, it is important to note that the resulting mechanical properties and adhesion can vary. To address these variations, we have expanded our discussion to include physical vapor deposition (PVD) and plasma-enhanced chemical vapor deposition (PECVD) techniques [118].

PVD has been utilized for coating specific commercial additives to beautify their mechanical surface residences. PVD coatings are acknowledged for their first-rate adhesion and uniformity, which have been significantly improved via process and device optimization [119].

PECVD is another technique that has shown promise in improving the mechanical residences of biomedical implants. For instance, PECVD has been used to adjust the surface of flax fibers, resulting in advanced adhesion between the changed fibers and the matrix, which is crucial for composite materials used in biomedical applications [120].

Another crucial development is using coatings with bioactive molecules. Boom elements, peptides, and different substances that actively stimulate bone tissue boom and beautify the implant's long-time period durability and integration can be included in those coatings. The implant surface becomes extra receptive to bone integration and healing whilst these bioactive chemicals are released in a controlled way. This could shorten the recuperation length and increase the achievement rate of dental implants [121].

Zhang [122] pronounced that three-D printing is good for biomedical applications because of its capability to create complex structures speedy. But, due to restricted materials, the biofunctionality of 3D-published additives is regularly disregarded. Post-3D printing change can bridge this gap, focusing on architectural reconfiguration and floor functionalization. Strategies which include structural reconfiguration and surface functionalization can be employed to obtain favored biofunctionality, bridging the distance between 3D printing generation and biomedical utility requirements. The use of clever polymers together with those surface amendment strategies marks a prime development in dental implant technology. Higher affected person consequences can result from the improvement of extra biocompatible and efficient implants that greater intently resemble the herbal traits of bone.

5.2. Corporation of bioactive agents

One promising tactic to inspire osseointegration and prevent infections in dental implants is the incorporation of bioactive compounds into clever polymers. Making use of biocompatible substances along with hyaluronic acid and chitosan for encapsulation and biomimetic coprecipitation are ways to integrate bioactive compounds which can enhance implant integration and recovery [123]. Moreover, the usage of nanotechnology and biomaterials in drug delivery systems has validated promise in improving dental implant remedy consequences [124]. The biomimetic coprecipitation method uses inorganic materials and bioactive chemicals co-deposited to form coverings that resemble actual bone. Through this technique, substances consisting of increased factors or antibiotics may be directly integrated into the hydrogel matrix after which released in a regulated way to encourage the bone formation and stave off contamination [125].

Encapsulation using biocompatible substances, like bioactive tablets are encapsulated with the aid of biocompatible polymers like hyaluronic acid and chitosan. The natural polymer chitosan, which is made from chitin, is well renowned for being non-toxic and biodegradable. Drugs can be administered locally at the implant site to improve osseointegration without harming effect on the body as a whole [126]. Another naturally occurring polymer that is known to play a part in wound healing and tissue regeneration is hyaluronic acid. It can create a hydrophilic environment that promotes cell migration and growth [127].

Nano and Biomaterials in Medication Delivery Systems are a number of benefits to using biomaterials and nanosized carriers in medication delivery systems for dental implants. High surface area drug loading can be facilitated by nanostructured carriers, allowing for sustained release profiles that sustain therapeutic concentrations for prolonged periods of time. This may be especially helpful in reducing the risk of surgical site infections and encouraging the implant's integration with the surrounding bone tissue [128].

These cutting-edge techniques improve dental implants' usefulness and growth in their capability to facilitate integration and healing, which ultimately improves affected person consequences. A considerable development in dental implantology is the usage of smart polymers and cutting-edge drug shipping structures that are meant to lower risks and enhance the nice of existence for sufferers getting dental implants.

5.3. Customization for patient specificity

To meet the wonderful structure of each patient's jaw and face tissues, dental implants need to be custom-designed. Improvements in CAD/CAM generation have made it viable to create implants that are greater precisely and readily custom-designed for each affected person. With this technique, implants are custom-designed to meet each affected person's demands, improving medical effects and patient pleasure [129].

Dental implant customization for patient specificity is a game-changing approach that uses the accuracy of CAD/CAM technology to make implants, in particular, proper to each patient's character anatomical desires. Cone-beam computed tomography (CBCT) is frequently used in this method to provide unique measurements and lines of the patient's jaw and surrounding structures [130].

CAD software program is then used to combine the information from those images to produce a digital version of the implant that is exactly fashioned to suit the affected person's anatomy. This version can be excellent-tuned till it satisfies all the requirements for the fine viable fit and capability [131].

CAM technology is utilized after the design is complete. The implant is manufactured with extreme precision using the design parameters, frequently using sophisticated manufacturing processes like 3D printing or milling. Implants with intricate geometries that would be challenging or impossible to produce using conventional manufacturing techniques can now be produced thanks to these procedures [132].

As a result, a patient-specific implant is created that has several advantages over generic, off-the-shelf implants, including better fit because custom implants are made to fit the patient's anatomy exactly, fewer intraoperative alterations may be necessary, which might make the installation process simpler and less intrusive [133].

Improved osseointegration precise fit may also encourage improved osseointegration, which is essential to the stability and durability of the implant. Enhanced comfort and aesthetics, can provide a more comfortable fit and a more natural appearance because they are made to match the patient's jaw and teeth's natural curves [97, 134].

Increased comfort and aesthetics, because the implants are designed to align with the natural contours of the patient's jaw and teeth, they can offer a more comfortable fit and a more natural appearance [135]. Reduced surgical time, precisely fitted implant can shorten the duration of surgery, which could hasten the patient's recuperation and ease their discomfort [136].

A major advancement in personalized medicine has been made with the incorporation of CAD/CAM technology into dental implantology, which provides tailored treatments that may improve results and increase patient satisfaction [137].

Patient-specific implants, which provide individualized solutions to match each patient's particular demands, are probably going to become the standard of care in dental implantology as this technology develops. Table 2 summarizes types of polymers synthesized via 3D printing methods.

5.4. Enhancing dental implant performance

Utilizing nanocomposites and smart polymers to increase mechanical characteristics, biocompatibility, and corrosion and wear resistance can improve the performance of dental implants. Adapting the characteristics of nanoparticles and encouraging osseointegration via clever material design are two tactics [148]. The benefits of using smart nanoparticles in dentistry, particularly in restorative and preventive dentistry, have also been investigated [149].

Customizing nanoparticle properties makes it possible to create nanoparticles to have particular qualities that suit them for use in dental implants. Through manipulation of nanoparticle size, shape, and composition, scientists may fabricate materials with desired mechanical strengths, improve osseointegration, and withstand corrosion and wear. For example, large surface area-to-volume ratio nanoparticles can offer superior bone cell attachment sites, promoting implant integration with the jawbone [150].

Encouraging osseointegration with intelligent material design adapts to changes in their surroundings, including variations in pH or temperature. These materials can be engineered to encourage osseointegration and bone formation in the setting of dental implants [151].

For instance, smart polymers that react to pH variations or body temperature to release growth factors might hasten the healing process and guarantee that the implant is firmly embedded in the mandible [152].

Use of smart nanoparticles in dental applications beyond implant performance, smart nanoparticles has been investigated for their potential in a range of dental applications. They can be applied in preventative dentistry to make coatings that lower the incidence of peri-implantitis by preventing bacterial colonization. To increase the strength and longevity of fillings and crowns in restorative dentistry, nanoparticles can be added. Furthermore, focused therapy can be provided by smart nanoparticles in drug delivery systems, improving oral health in general [153].

Although the topic of using smart polymers using the 3D printing method in dental implants is a new approach, very little study has been done in this field and more research is needed in this field for progress.

Pandey et al. [154] explored the shape memory effect (SME) of 3D printed scaffolds made from chitosan (CS) reinforced poly-lactic acid (PLA). Composite filaments with varying CS content were created and used to print scaffolds, which demonstrated an 18.8% shape recovery after heat treatment. The scaffolds also exhibited good wettability and cell proliferation, indicating their potential as biocompatible, self-healing implants for bone deficiencies.

Table 2. Summary of benefit of 3D printing techniques with smart polymers.

Material	3D printing technique	Application	Main result	References
Smart polymers	Stereolithography (SLA)	Customized dental implants	Enhanced osseointegration	[8, 138, 139]
Shape memory polymers	Fused deposition modeling (FDM)	Peri-implantits management	Reduce inflammation	[140–142]
Self-healing polymers	Selective laser sintering (SLS)	Implant longevity	Improved durability	[141, 143, 144]
Conductive polymers	Digital light processing (DLP)	Bioactive agent delivery	Targeted therapy	[145–147]

Singh et al. [155] developed novel 3D printed scaffolds using hydroxyapatite-reinforced polylactic acid (PLA) that respond to thermal stimuli. The research analyzed how varying HA proportions, infill densities, and temperatures affected the scaffolds' mechanical strengths through optimization techniques. The scaffolds exhibited a high shape memory effect of 95.77% and showed promising mechanical properties, biocompatibility, and hydrophilicity, making them suitable for creating customized biomedical devices with shape recovery capabilities [155].

Sharma et al. [156] examined the mechanical and surface properties of 3D printed electro-active polymer (EAP) matrix-based prototypes. Using a composite of polyvinyl diene fluoride (PVDF, 78 wt%), graphene (Gr, 2 wt%), and barium titanate (BT, 20 wt%), the study found that printing at an infill speed of 50 mm/s and an angle of 45 ° at 100% density resulted in the strongest mechanical properties, with a peak strength of 42.98 MPa and break strength of 40.70 MPa. The high-density parts showed minimum porosity and better mechanical performance, supported by surface hardness correlation, microphotographs, 3D images, and surface roughness profiles.

Schönhoff et al. [157] compared the mechanical properties of PPSU and PEEK materials used in the 3D printing of dental prostheses. 3D printed PPSU (PPSU1-3D and PPSU2-3D) exhibited lower flexural strength than extruded PPSU (PPSU1-EX) and PEEK (PEEK-CG). The highest wear was seen in PPSU1-3D, while PEEK-CG showed the highest hardness and indentation modulus. The study concludes that 3D printed PPSU needs optimized printing parameters to match the mechanical properties of extruded PPSU and PEEK, which are suitable for dental prostheses.

Chen et al. [158] focused on enhancing 3D printing materials for the industry by improving PMMA resin with 1% titanium dioxide (TiO_2) and 1% PEEK fillers. This combination was found to optimize mechanical and antibacterial properties, with the PMMA (TiO_2-1%-PEEK-1%) composite showing promising results for use as a functional, light-curing resin in dental restorations, due to its smooth surface and precise resolution.

Crenn et al. [159] compared the mechanical residences of PLA, a biopolymer received through 3D printing, with a conventional period in between resins for meantime prosthesis fabrication. Four agencies (n=10) were studied, such as PLA constructed via fused deposition modeling and conventional meantime resins (Unifast®, Integrity®, transient CB®). The PLA organization exhibited elastic modulus and flexural strength comparable to the Integrity organization, superior to the Unifast®-institution, and not so good as the temporary CB®-organization (P<0.05). PLA-institution microhardness turned into just like Unifast®-organization and decreased than Integrity® and transient CB® corporations (P<0.05). The porosity of PLA turned into calculated from the crystallinity degree and density, revealing a low porosity fee. Those findings propose that PLA, with mechanical properties akin to standard resins and coffee porosity, could serve as a feasible opportunity for constructing temporary prostheses [159].

Çelebi-Saltik et al. investigated the effects of coating polyurethane (PU) 3D printed scaffolds with boric acid (BA) on the proliferation and osteogenic differentiation ability of dental pulp stem cells (DPSCs). Fused deposition modeling was applied to fabricate three-D scaffolds from PU filament, which have been subsequently lined with BA with the usage of the thermionic vacuum arc method. Microstructure evaluation was performed to assess macro-pore dimensions, while FESEM-EDS and ATR-FTIR showed BA presence at the scaffolds before and after cellular lifestyle. Cell viability and proliferation were assessed on days three and 7, and osteogenic differentiation was evaluated on day 14 through calcium deposition evaluation, alizarin pink staining, and gene expression evaluation (Runx2, OCN, DSPP). The observation found that coating PU scaffolds with BA improved mobile viability on day three but caused decreased cellular proliferation on day 7 in comparison to uncoated scaffolds. However, BA-covered scaffolds exhibited accelerated calcium accumulation in cells on day 14, indicating stronger osteogenic differentiation ability. Gene expression analysis revealed upregulation of osteogenic markers (OCN, DSPP) in BA-coated scaffolds, suggesting their ability to induce differentiation of DPSCs towards an osteogenic lineage. Overall, the findings suggest that BA-coated 3D printed scaffolds hold promise for promoting osteogenic differentiation in DPSCs, highlighting their potential for use in tissue engineering applications [160].

Bell et al. [161] evaluated the accuracy of implants placed using two different guided implant surgery materials including thermoplastic versus 3D printed. The methodology involved converting CBCT scans to DICOM files and planning models for printing. Twenty 3D printed mandibular quadrant jaws and 10 thermoplastic surgical guides were produced. One implant was placed per guide and replica jaw model pair, following the guided surgical protocol. CBCT scans were taken for each test implant, and deviations were evaluated through superimposition. Statistical analysis was performed using the Mann-Whitney U test and descriptive statistics. Implants placed with thermoplastic surgical guides showed an average angular deviation of 3.40 degrees, compared to 2.36 degrees for implants placed with 3D printed surgical guides (P=0.143). The head of implants placed with thermoplastic guides had an average deviation of 1.33 mm, compared to 0.51 mm for implants placed with 3D printed guides (P<0.001). Moreover, the apex of implants placed with thermoplastic guides had an average deviation of 1.6 mm, compared to 0.76 mm for implants placed with 3D printed guides (P<0.001).

While angular deviations were not significantly different between thermoplastic and 3D printed surgical guides, the accuracy of implant head and apex locations was significantly higher with 3D printed guides [161]. Table 3 summarizes the types of smart polymers synthesized via 3D printing techniques for dental implants.

Based on the abovementioned discussion, the application of smart polymers and nanocomposites to improve dental implant performance is a major development in dental technology. Through the customization of nanoparticle characteristics and the development of intelligent materials that facilitate osseointegration, dentists can provide their patients with implants that exhibit enhanced dependability, robustness, and harmony with the body's native tissues. Research on the use of these cutting-edge materials in dental implants is exciting and has the potential to greatly enhance patient outcomes.

Table 3. Smart polymers and their applications in 3D printed dental implants.

Polymer type	Example polymers	Application in dental implants	Numeric details	3D printing technique	References
pH-responsive	PAA, PMAA, copolymers containing acidic groups	Drug delivery systems within dental implants	Drug release rate: pH dependence can be tailored	Vat-photo polymerization, material jetting	[112, 124]
Light-sensitive (photo responsive)	Azobenzene, spiropyran	Light-activated adhesives for dental repairs	Response time: seconds to minutes	DLP, SLM, SLA, and SLS	[112, 129]
Electroactive	Polyaniline (PANI), polypyrrole (PPy), polythiophene	Conductive frameworks for enhanced osseointegration	Conductivity: up to 100 S/cm	VAT-photo polymerization, material jetting	[129, 149]
Shape memory	TPU, crosslinked PE, polyurethane-based block copolymers	Customized dental braces, retainers	Recovery stress: up to 5 MPa	Stereo lithography (SLA), material jetting	[149, 162]
Temperature-responsive	Poly(N-isopropylacrylamide) (PNIPAM)	Scaffolds for tissue engineering	Transition temperature: around 32 °C	SLA, DLP material jetting, material extrusion (ME)	[163, 164]

6. Challenges, future perspectives, and conclusions

As smart polymer-primarily based dental implants preserve to adapt, regulatory frameworks and standardization efforts will play pivotal roles in ensuring their widespread recognition and safe implementation. Regulatory bodies must adapt to the particular demanding situations posed using those innovative substances, emphasizing the want for stringent production requirements and scientific protocols. Standardization efforts could be instrumental in streamlining manufacturing methods and ensuring steady first-class throughout smart polymer implants, in the long run benefiting patients and practitioners alike.

Searching beforehand, research efforts should be aware of addressing the lengthy-term sturdiness and stability of smart polymer implants. Whilst cutting-edge effects are encouraging, assessing their overall performance over prolonged periods is crucial. Elements consisting of put-on, fatigue, and degradation ought to be thoroughly evaluated to beautify the toughness and reliability of these implants. Moreover, integrating clever polymer materials with digital dentistry technologies, which includes design and patient-precise modeling, holds superb promise for advancing the sphere of dental implants. This collaborative technique between researchers, industry stakeholders, and clinicians will power further innovation, in the long run improving patient consequences and nice of existence.

CRediT authorship contribution statement

Aliasghar Abouchenari: Project administration, Writing – review & editing.
Neda Tajbakhsh: Supervision, Writing – review & editing.
Amirhosein Shahbaz: Writing – original draft.
Ghazal Alamdari-Mahd: Writing – original draft.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

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