This paper is part of the Special Issue on Design and Manufacturing in Biomedical Engineering
Guest Editor: Dr. Jashanpreet Singh, University Center for Research and Development, Chandigarh University, Punjab, India.
Prof. Dr. Chander Prakash, University Center for Research and Development, Chandigarh University, Punjab, India.

Received August 14, 2025, accepted October 22, 2025, publication date for online-first December 21, 2025.

Review

Next-Generation Smart Biomaterials in Dental Implantology: Titanium and Emerging Alternatives

Aastha Palta[1], Prachi Palta[2] and Virinder Kumar[1,*]

[1] University Centre for Research and Development, Chandigarh University, Mohali - 140413, Punjab, India.
[2] Department of Physics, Chandigarh University, Mohali - 140413, Punjab, India.

[*]Corresponding author: virinderkumars@gmail.com; virinder.e18785@cumail.in

---

ABSTRACT

Background: Tooth loss affects approximately 3.74 billion people globally, with 7% of the population aged 20 years or older experiencing complete edentulism. Traditional prosthetic solutions present significant limitations, including poor retention and accelerated bone loss. Contemporary dental implantology has undergone substantial evolution since 2020, incorporating advanced biomaterials, multifunctional surface modifications, and digital AI-driven workflows to address these clinical challenges **Objective:** This review synthesises recent advances in dental implant materials, surface technologies, design methodologies, and clinical protocols published between 2020 and 2025, with an emphasis on emerging biomaterials and intelligent digital approaches that enhance osseointegration, survival rates, and personalised patient outcomes. **Material and Methods:** A comprehensive literature review was conducted examining established implant materials (commercially pure titanium, β-type titanium alloys, yttria-stabilised tetragonal zirconia polycrystal), emerging bioactive and bioresorbable systems (magnesium alloys, polylactic acid/β-tricalcium phosphate composites), surface modification strategies, digital technologies, artificial intelligence applications, mechanical complications, biological complications management, and clinical loading protocols. **Results:** Contemporary titanium implants with sandblasted, large-grit acid-etched surfaces achieve 96–99% five-year survival rates, while metal-free zirconia systems demonstrate survival rates of 94–97%. Emerging β-type alloys and bioresorbable systems show promising preclinical and early clinical results. Immediate and early functional loading protocols deliver comparable outcomes to conventional delayed loading when primary stability criteria are met. AI-assisted diagnostics achieve greater than 98% accuracy in anatomical segmentation and over 90% predictive accuracy for implant failure. Peri-implantitis remains a predominant challenge with 44% recurrence rates despite surgical intervention. **Conclusion:** Next-generation dental implantology represents a paradigm shift toward predictable, personalised care through synergistic integration of biomaterial innovation, digital workflows, and artificial intelligence. While established materials demonstrate reliable long-term success, bioresorbable and bioactive systems offer regenerative potential requiring optimisation of degradation kinetics and mechanical durability. Addressing peri-implantitis recurrence and standardising clinical endpoints for emerging technologies remain critical priorities for achieving consistent long-term clinical success.

Keywords—*Additive manufacturing, Artificial intelligence in dentistry, Bioactive implants, Bioresorbable implants, Dental implantology, Titanium implants.*

1. INTRODUCTION

Tooth loss represents one of the most significant global health challenges, affecting approximately 3.74 billion people worldwide, who suffer from various oral disorders. The World Health Organization estimates that complete tooth loss affects approximately 7% of people aged 20 years or older globally. Meanwhile, periodontal diseases are a leading cause of tooth loss, affecting around 1.07 billion individuals, with prevalence rates reaching up to 12,498 per 100,000 population in certain regions.[1–3] This substantial burden varies significantly across socioeconomic levels, with low- and low-middle-income regions experiencing disproportionately higher rates of edentulism and periodontal disease (Figure 1).[4–6]

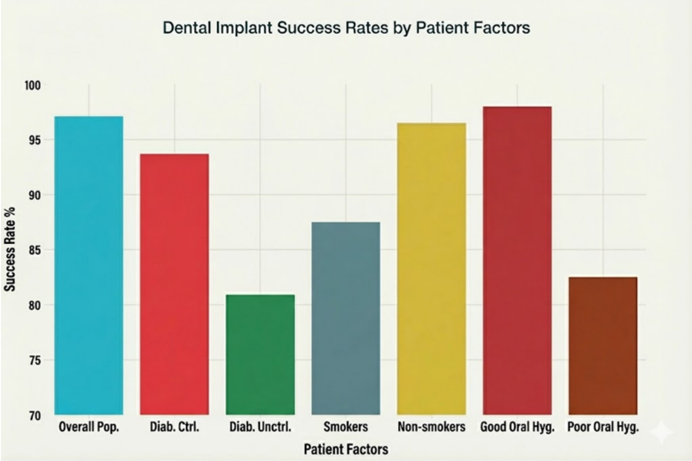

FIGURE 1. Bar chart showing dental implant success rates across patient factors and risk categories (the data were taken from Beschnidt et al.).[7] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

The clinical and psychosocial consequences of tooth loss are profound, encompassing impaired masticatory function, compromised speech, rapid alveolar bone resorption, and diminished quality of life. Traditional prosthetic solutions, including removable partial and complete dentures, often present limitations such as poor retention, discomfort, accelerated bone loss, and reduced chewing efficiency. These shortcomings have driven the global dental implants market to unprecedented growth, with market valuations projected to reach \$12.6–18.79 billion by 2030–2032, reflecting a compound annual growth rate of 6.9–8.4%.[8–12] Since 2020, dental implantology has transformed, driven by the convergence of emerging biomaterials, multipurpose surface modifications, and digital, AI-driven workflows. Metal-free, esthetic solutions now include high-performance ceramics, such as yttria-stabilized tetragonal zirconia polycrystal (Y-TZP), which has a low bacterial affinity and 94–97% five-year survival rates. Additionally, β-type titanium alloys (e.g., Ti-35Nb-7Zr-5Ta) achieve bone-like elastic moduli (65 GPa), thereby reducing stress shielding and maximizing load transfer.[13–16] Bioresorbable systems using magnesium alloys and polylactic acid/β-tricalcium phosphate composites provide gradual load transfer to regenerating bone, potentially eliminating the need for secondary retrieval surgery in select cases (Figure 2).[17–21]

Concurrent advances in surface functionalization, such as micro-roughening through sandblasted large-grit acid-etching (SLA) up to nano topographic coatings (e.g., nanostructured hydroxyapatite [HA]) and carbon-based films (e.g., graphene, diamond-like carbon, carbon nanotubes) similarly boost the bone-to-implant contact value from 50–60% at the 3 months mark, to a height of 75% within 8 weeks, while simultaneously conferring antibacterial capabilities. Growth factors, such as BMP-2 and leukocyte-platelet-rich fibrin (L-PRF), are utilised in bioactive coatings to promote osteogenesis, providing an additional method for stimulating bone growth. Still, ironically, their clinical translation is hindered by regulatory requirements.[22–26] At the same time, digital technologies have also allowed unprecedented precision, with cone-beam computed tomography (CBCT) and intraoral scanning being used to input the computer-aided design (CAD)-based planning, resulting in additive manufacture of patient-specific implants, usually made of metal or polymer–ceramic composites, with reasonable success rates even in severe defects.[27–32] The emerging technology of artificial intelligence (AI) has simplified diagnosis, automated the segmentation of nerves and evaluation of bone quality, and forecast the success of implants with an accuracy of > 0.90, favouring individualised, risk-adapted approaches.[33–35] These synergistic advances are supported by a more sophisticated knowledge of osseointegration as an immune-modulated and foreign-body equilibrium: once implanted, the adsorption of proteins on the oxide surface guides macrophage polarization to the regenerative M2 phenotype, whereas mesenchymal stem cells and endothelial progenitors facilitate vascularization and bone deposition of the matrix, while the directed micromotion has led to osteogenic pathways such as Wnt/β-catenin. Adding all of them, the developments are helping in taking implant dentistry to a more predictable and biologically harmonious, and personalised future.[36,37]

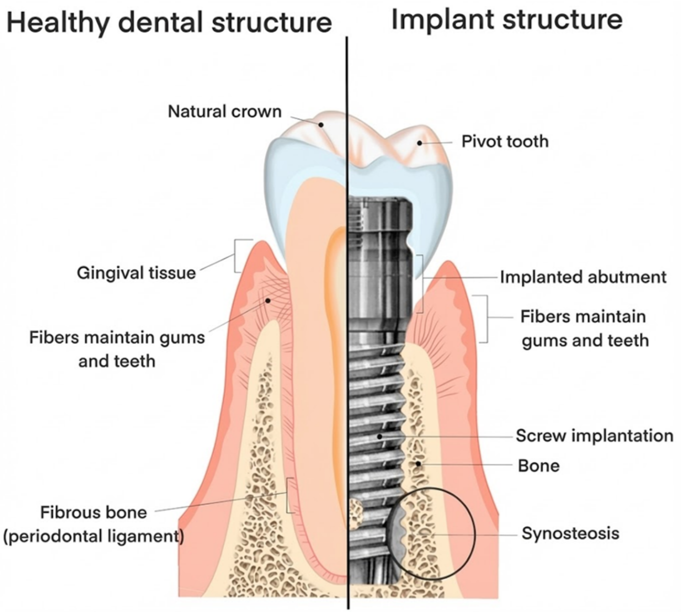

FIGURE 2. Comparative anatomy of natural tooth and dental implant attachment mechanisms demonstrating fundamental biomechanical differences.[38] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

2. MATERIALS AND SURFACE TECHNOLOGIES IN DENTAL IMPLANTS

Over the past five years, advancements in biomaterials and surface engineering strategies used in dental implants have led to improvements in their integration, longevity, and patient outcomes. Such developments include classical metals and ceramics, as well as newer bioactive and bioresorbable systems, and complex surface modification methods.[39–41]

2.1. Established Metals and Ceramics

Titanium (Ti) is considered the gold standard because it has been proven to be biocompatible, mechanically strong, and corrosion-resistant. Commercially pure titanium (cp-Ti) has an elastic modulus of approximately 110 GPa and exhibits long-term survival rates of 95–98% at 5 years. Surface finishing or SLA protocols also enhance the directness of the breast surface, increasing bone-to-implant contact (BIC) by 50% to 60% within 3 months. Titanium–SLA implants exhibit survival rates as high as 96–99%, and some immediate loading regimes have achieved rates of up to 99.5%. Titanium alloys of β-type (e.g., Ti-35Nb-7Zr-5Ta) with a lower elastic modulus and closer to that of natural bone (about 65 GPA) would mitigate the stress shielding effect and distribute occlusal loading more efficiently, perhaps allowing maintenance of bone health in treated sites otherwise compromised. Such alloys are biomechanically interesting, but their properties are mainly based on in vitro and finite element studies.[42,43] Y-TZP represents an alternative, metal-free solution with better esthetics and a bacterial-resistant survival rate of 94–97% at 5 years.[44–46] Moreover, the gingival tissues surrounding zirconia implants exhibit more organized collagen fibers and shallower sulcus depths than those surrounding titanium implants, which may enhance soft tissue attachment (Figure 3) and improve aesthetic outcomes. However, the inherent brittleness of the material remains a limitation that must be carefully considered when designing prosthetics. Polymers such as polyetheretherketone (PEEK) and ultra-high molecular weight polyethene (UHMWPE) have low elastic moduli (34 GPa), radiolucency, and retrievability, which make them useful in specific clinical situations, notably for patients with metal allergies.[47–51] They have non-compatible bioinert surfaces that necessitate functionalizing these surfaces using plasma treatments or bioactive coatings to confer osseointegration. Abutment reinforcement enhances the mechanical properties with the addition of carbon fibres. Table 1 presents the comparative properties and performance of implant materials. Table 2 summarizes practical indications, trade-offs, and selection cues, clarifying when each system is preferred based on esthetics, biomechanics, hypersensitivity, and loading strategy.

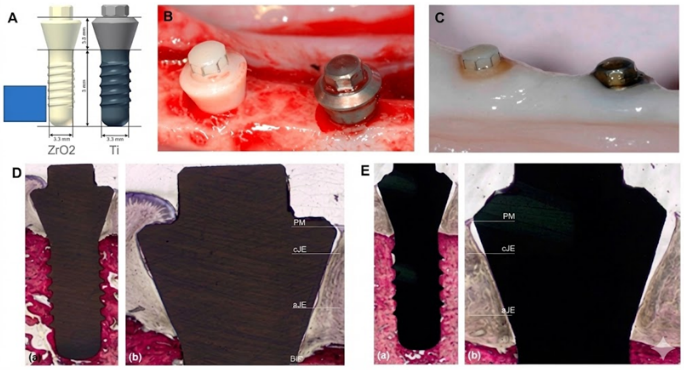

FIGURE 3. Zirconia and titanium implant systems differ in component architecture and material behaviour, directly influencing prosthetic flexibility, mechanics, and esthetics.[52] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

TABLE 1. Comprehensive material properties and clinical performance of dental implant systems.

Material	5-Year Survival	Highlights	Clinical Outcome
Commercial pure titanium	95–98%	Advanced connector designs for stress control	Proven biocompatibility, surface roughness
Titanium-SLA	96–99%	99.5% Success with immediate loading	Micro-roughness, immediate loading protocols
β-Ti35Nb7Zr5Ta	*in vitro*/early	Favourable cortical stress distribution	Reduced modulus, biomechanical stress sharing
Y-TZP zirconia	94–97%	Superior BIC after acid etching	Metal-free aesthetics, low bacterial affinity
PEEK & UHMWPE	Limited data	Carbon fiber reinforcement; bioactivation research ongoing	Osteoconduction, controlled degradation

TABLE 2. Summary of clinical selection cues for titanium versus zirconia implant systems.

Dimension	Titanium Implants	Zirconia Implants
Primary indication	Broad indications, including posterior zones, limited bone volume, and complex prosthetics	High-aesthetic anterior zones, thin/translucent mucosa, patients prioritizing metal-free options
Evidence-based and ecosystem	Extensive long-term data; broad component ecosystem; versatile connection options	Growing evidence base, fewer component variants, improving but more constrained prosthetic options
Mechanical behaviour	High fracture toughness and fatigue resistance; reliable for narrow-diameter and angulated abutments	Lower fracture toughness; avoid high cantilevers and excessive torque; favour straightforward load paths
Loading protocols	Well-suited for immediate/early loading under high functional demand when stability thresholds are met	Prefer delayed or carefully selected immediate loading in low-risk, straightforward cases
Aesthetics and soft tissue	Possible grey shine-through in thin biotype; can be mitigated with zirconia abutments and soft-tissue management	Excellent mucosal colouration and low plaque affinity; favourable soft-tissue aesthetics in thin biotypes
Hypersensitivity/ allergy	Rare metal hypersensitivity; consider alternatives in sensitized individuals	Metal-free pathway suitable for hypersensitivity concerns if prosthetic demands allow
Connection and torque	Robust connections with higher torque ceilings; broad restorative flexibility	Torque limits generally lower; connection design selection critical; cautious with complex restorations
Peri-implant hygiene	Mature strategies; surface options to reduce biofilm; maintenance protocols well established	Lower plaque accumulation tendencies are reported, requiring rigorous maintenance and monitoring
When preferred	Heavy occlusal load, parafunction risk, narrow/angulated needs, immediate placement/ provisionalization	High aesthetic priority, thin biotype, metal sensitivity, simple prosthetic designs with minimal cantilever
Practical cue	Choose when mechanical reliability and prosthetic flexibility are paramount	Choose when mucosal aesthetics and metal-free solutions are primary goals and biomechanics are favourable

2.2. Emerging Bioactive and Bioresorbable Systems

The latest developments in dental implantology have focused on enhancing bioactive and bioresorbable materials to address the shortcomings of conventional long-term implants, including stress shielding and the potential for a durable foreign body, as well as the need for a second surgery to remove the implant. The systems aim to interact with the local biological environment. They are envisioned to be biologically active, encouraging tissue regrowth with eventual biodegradation over the same time frame, as the increasing load is transferred to the newly growing bone (Figure 4). Mg alloys are among the most promising groups of biodegradable metals used in dentistry in the form of implants and screws.[53,54] With elastic moduli that approach that of the cortical bone (about 45 GPa), these alloys offer more physiologically relevant conduction of loads and reduce stress shielding. Mg is bioresorbable as it undergoes corrosion in physiological fluids. However, they are vulnerable to rapid corrosion rates, which can cause premature failure and undesirable local reactions unless properly controlled. In response to this, hybrid coatings of HA and PLA have been designed to balance degradation rates with osteoconductivity.[55,56] These coated Mg implants promote early bone formation and already form the basis of preclinical and early clinical studies with applications as fixation screws and small load-carrying implants. Polymers like PLA, combined with 5-tricalcium phosphate (5-TCP), have gained momentum as a bioresorbable scaffold for alveolar ridge augmentation and the healing of craniofacial defects. Such composites may be manufactured accurately using 3D printing technologies at the point of care to provide patient-specific anatomically conforming meshes or plates. PLA–β-TCP constructs provide osteoconduction, supporting the attachment of cells and intracellular bone formation, in addition to biodegrading into lactic acid, which is naturally metabolised.[57,58] Owing to their bioactivity and mechanical support, these materials are adequately positioned to be used as a bone defect filling material without poor integration, especially in the case of complex anatomical areas. Functional surface coatings of commercially available implant materials have included bioactive glasses (BG) to augment bone bonding and protection against peri-implantitis.[59–61] BGs provide calcium (Ca^{2+}) and phosphate (PO_4^{3-}) ions in situ, creating a HA-like layer on the implant surface. This mineralised layer enhances osseointegration and simultaneously increases the local pH, forming an antimicrobial environment that prevents bacterial colonisation—an essential factor in avoiding peri-implant infections. Preliminary clinical and *in vivo* observations demonstrate the potential of BG coatings to mitigate the phenomenon of biological complications without compromising mechanical stability. There have been attempts to utilise nanostructured bioactive films and growth factors, such as bone morphogenetic protein-2 (BMP-2) and platelet-rich fibrin derivatives, to achieve faster early osseointegration and vascularisation. However, regulatory, stability, and cost issues restrain their broad adoption.

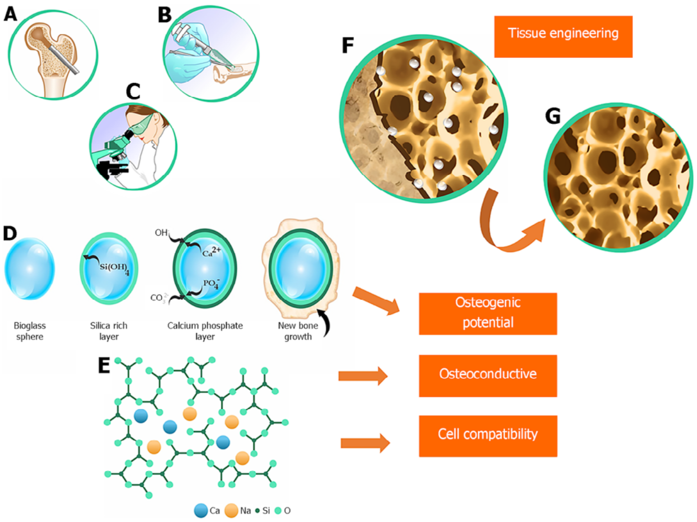

FIGURE 4. Illustration of bioactive glass coating facilitating bone regeneration and tissue engineering in dental implants.[62] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

Collectively, these new bioactive, bioresorbable systems signal a trend toward a more dynamic, structurally biologically integrated dental implant that can enhance regeneration and reduce the long-term presence of a foreign body. They have great potential for patients with poor bone quality and multifaceted defect geometries, as well as those requiring minimally invasive treatment. Moreover, Mg and polymer–ceramic systems (e.g., Mg alloys, PLA–β-TCP scaffolds) still face limited early-phase load-bearing capacity and sensitivity to corrosion/hydrolysis, which can precipitate rapid strength loss, gas formation, or dimensional changes before sufficient osseointegration takes place. Their elastic and fatigue performance under cyclic occlusal loads remains inferior to titanium in most posterior or parafunctional contexts, with tighter constraints on implant diameter, connection torque, and cantilever length. Clinically, this necessitates careful case selection (low load, temporary support, or adjunctive scaffolding), meticulous control of degradation kinetics through coatings, and avoidance of high immediate loading requirements until durable, standardized mechanical and *in vivo* longevity data are established. Among the ideas for future research priorities, one may mention optimising degradation kinetics to coincide with healing timelines, enhancing mechanical durability during the critical initial period, and testing long-term clinical effectiveness in cohorts with large numbers of patients.

2.3. Surface Modification Toolbox

Surface engineering has played a significant role in reducing the incidence of failure and enhancing integration by enabling the design and manipulation of implant surfaces' topography and surface chemistry, thereby facilitating the bonding of implants to bone and minimising biological adverse events. Table 3 outlines the key strategies for surface modification.

TABLE 3. Strategies of surface modification.

Technique	Surface Roughness (Ra, µm)	Bone Implant Contact (%)	Time to Load	Benefits	Limitations	Evidence Level
Dual-acid etch	0.4–3.5	45–60	3 Months	Hydrophilic micro-pits	Variable acid protocols	High
SLA (sandblast + acid)	2.5–3.0	50–60	3 Months	Clinical gold standard	Possible grit residue	High
Plasma-sprayed HA	2.1–9.4	55–70	2 Months	Osteoinductive	Brittleness, delamination	High
Nanostructured HA	1.2–3.5	60–75	2 Months	Biomimetic Nano topography	Manufacturing complexity	Moderate
Carbon coatings (diamond-like carbon [DLC], carbon nanotubes [CNT], and graphene)	Variable	44–63	≤2 Months	Antibacterial, improved mechanics	Limited long-term data	Emerging
Fullerene C60 film	—	+40% Cell proliferation	N/A	Thin uniform film	Early stage	Experimental
Growth factors (BMP-2, L-PRF)	—	Increased BIC	6 Weeks	Accelerated healing	Regulatory hurdles	Low-mode rate

Strategies based on the synergistic use of micro- and nano-scale surface modifications can potentially maximise the biological response at the implant interface. The most widely used titanium implants in clinical practice are currently micro-roughened SLA, with reported survival rates of up to 99%. Nano-topographical characteristics, such as nano TiO_2 nanotubes, further enhance cellular reactions, resulting in accelerated osteointegration, as demonstrated by laboratory studies. Hydroxyapatite-based bioactive coatings directly enhance attachment to bones, and antibacterial measures, involving silver nanoparticles, hinder the formation of biofilms and reduce the risk of peri-implantitis. Finally, carbon-based films, such as diamond-like carbon (DLC) films, exhibit mechanical durability and biocompatibility, resulting in a low volume of wear debris and avoiding chronic inflammatory reactions. This range of surface modifications demonstrates the tendency of multifunctional implants to be used at the optimal level of bone integration, as well as those that are stable in a longitudinal perspective.

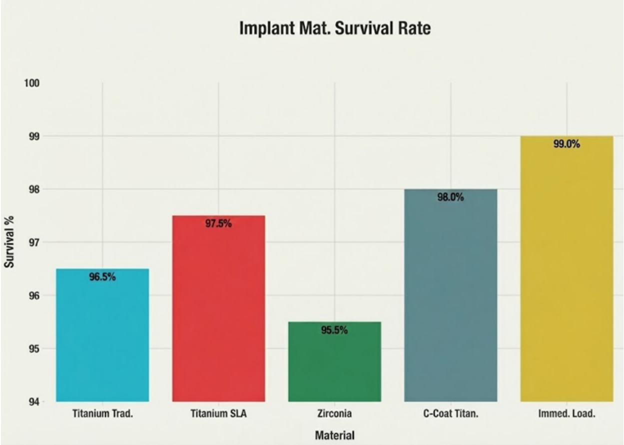

FIGURE 5. Five-year survival rates of contemporary dental implant materials and loading protocols, based on recent literature (data taken from a previous study).[63] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

2.4. Survival Outcomes

According to recent clinical studies and meta-analyses, there are better survival rates for established implant generations (96–99% for modified titanium and 94–97% for zirconia), and promising results have been obtained for emerging materials based on these findings. However, these results are yet to be confirmed (Figure 5). Essentially, immediate and early loading regimens yielded similar success to conventional delayed loading, with reviews indicating that appropriate primary stability is established by insertion torque and implant stability quotient (ISQ).

The cp-Ti implants have consistently recorded reliably high survival rates of 95–98%, which have been maintained for at least 5 years. We increased osseointegration by introducing micro-roughened surfaces, including SLA etched treatments, extending survival rates to 96–99%.[64,65] Good evidence of the maturity and reliability of such materials and surface technologies is evident in titanium implants with SLA surfaces, evidenced by impressive cumulative success rates of as high as 99.5% when loaded immediately, as opposed to the few years prior when loaders could not approach such winning percentages of titanium implants with SLA (Sandblasted, Large-grit, Acid-etched) surfaces. Although β-type titanium alloys, such as Ti-35Nb-7Zr-5Ta, remain primarily in the research and early clinical stages, they are promising due to their bone-matched elastic properties. Despite substantial evidence, large-scale survival is delayed; finite-element simulations and *in vitro* studies suggest positive biomechanical implications that can be applied to enhance longevity in challenging clinical settings. Y-TZP ceramic implants offer a competitive option on a case-by-case, metal-free basis, with a reported 5-year survival rate of 94–97%.[66–68] Acid etching, laser texturing, and other surface treatments facilitate an increased BIC of surface-treated implants, with some showing greater early osseointegration parameters than titanium implants. Another factor contributing to the significant clinical success of zirconia is that this oxide is biologically inert, thereby reducing the risk of bacterial attachment. Mg alloy, polymer–ceramic (e.g., PLA/β-TCP), and bioactive glass coatings are in the early stages of adoption with positive preclinical and pilot clinical outcomes.[69,70] The combination of osteoconductivity with their degradability offers a new paradigm in the success of implants, particularly in complex defects and sites that require the gradual transfer of load to the growing bone.

Table 1 illustrates the clinical outcomes and success factors of dental implant materials and techniques. Treatments that increase surface roughness, bioactivity, and hydrophilicity are directly related to bone integration rates, resulting in faster and stronger integration, thereby overcoming material-specific survival rates. The immediate and early loading protocols, previously deemed riskier, now show survival results comparable to those of conventional delayed loading, with primary stability measures including insertion torque values of 40 N cm and a reported ISQ of 70. Short implants (≤ 8 mm) under immediate loading have also demonstrated a cumulative success rate of over 98%, making sinus augmentation and additional surgeries unnecessary. Short implants (≤ 8 mm) can achieve high success when primary stability and occlusal control are optimized, offering a minimally invasive alternative to augmentation; however, their reduced crown-to-implant ratio elevates bending moments, making connection design, splinting strategy, and occlusal scheme critical. Narrow implants (≤ 3.5 mm) expand indications in thin ridges but face higher risks of mechanical complications (screw loosening and fracture) under parafunction or cantilevered loads; high-toughness titanium and internal conical connections mitigate these risks better than brittle ceramics. With zirconia, one-piece narrow designs require cautious case selection due to their lower fracture toughness; two-piece zirconia narrows torque ceilings and enhances prosthetic flexibility. For bioresorbable or hybrid systems, diameter/length constraints amplify early-phase strength limitations and degradation-related variability, reinforcing a preference for low-load, anterior, or interim indications until long-term datasets mature. Practical guidance has been added on stability targets, splinting, cantilever avoidance, and material–connection matching to support evidence-based use. These survival data provide compelling evidence that contemporary implant materials, advanced surface modifications, and optimized clinical protocols consistently deliver high long-term success rates, particularly when combined with rigorous patient selection and stability criteria. Current studies are being conducted to refine these emerging bioresorbable systems and increase the clinical application of new alloys and intelligent coatings.

3. DESIGN AND FABRICATION TECHNIQUES IN DENTAL IMPLANTS

The innovations in designing and fabrication utilised in dental implantology over the last half-decade have helped to enhance the precision of surgical practice, improve implant success, and yield better patient outcomes. This can mainly be attributed to digital workflow, new additive manufacturing processes, biomechanical optimisation, and emerging personalised and competent implant philosophies.

3.1. Digital Technologies and AI Integration in Implantology

Over the past five years alone, disruptive shifts toward digitally enhanced workflows in dental implantology have incorporated the latest imaging technology, AI, and the power of additive manufacturing to deliver new levels of precision, efficiency, and individualised patient outcomes. Such workflows encompass the entire treatment sequence, from diagnosis and surgery planning to guided surgery and restoration with prosthetics. At the centre of these innovations are digital imaging and scanning, primarily using CBCT and intraoral scanners. CBCT provides a 3D high-resolution image of the patient's maxillofacial anatomy, outlining essential structures such as nerves and sinus cavities, as well as bone density levels necessary for implant placement.[71–73] Fast and comfortable, requiring no discomfort of taking emergency impressions, intraoral snappers generate veritable digital casts of the dentition and soft tissues within a few seconds, and the patient experience is significantly improved. The volumetric imaging data input is analysed using sophisticated AI algorithms, which automate anatomy segmentation, detect nerves, and identify bone structure in seconds. This enables precise virtual planning of the implants' positions, angulation, and depth, thereby minimising the risk of nerve damage and ensuring optimal load distribution.[74–78] Surgical guides for running surgical procedures are printed in 3D using an additive manufacturing technique using resins (Figure 6). These face-to-face guides fit the teeth or gum comfortably and guide implant osteotomies exactly as planned, minimizing surgical errors and operation time.

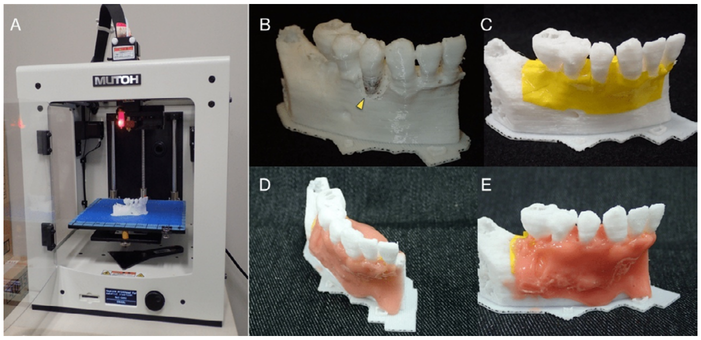

FIGURE 6. A 3D printer fabricates a customised dental implant model, demonstrating advanced personalised implant manufacturing technology.[79] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

In restorative stages, CAD/computer-aided design (CAD) and CAM technologies plan and manufacture exactly fitting crowns and bridges digitally, machining or printing them. Optimisation algorithms based on AI improve prosthesis fit, occlusion, and aesthetics, and prompt a 40% decrease in laboratory turnaround time. Additive manufacturing has also enabled the manufacturing of patient-specific implants (PSIs). Porous lattice titanium alloy (Ti-6Al-4V) implants manufactured via powder bed fusion offer advantages, including porous lattice structures, that encourage osseointegration and provide custom mechanical properties.[80–82] Complex bone defects require reconstruction using resolvable scaffolds produced by extrusion 3D printing over ceramic–polymer–based implants, such as PLA/β-TCP. Clinical reports have shown a success rate of approximately 87% for such intricate maxillofacial applications employing these individual implants. Tables 4 and 5 outline the key phases, technologies, and clinical benefits of digital workflows and 3D printing in contemporary dentistry, with a specific focus on dental implants.

TABLE 4. Digital workflow stages and technologies in dental implantology.

Stage	Technology Used	Description	Benefits
Digital imaging and scanning	Cone-beam computed tomography (CBCT), intraoral scanners	High-resolution 3D anatomy and digital mouth models	Precise bone assessment, comfort
Virtual treatment planning	CAD software, AI algorithms	Implant simulations with nerve and bone quality mapping	Optimized placement, risk reduction
3D-printed surgical guides	Resin-based 3D printing	Custom guides for precise drill direction	Surgical accuracy, reduced time
CAD/CAM for prosthetics	Digital milling and printing	Crowns and bridges are designed and fabricated digitally	Improved aesthetics, faster restoration

TABLE 5. 3D Printing Techniques, Materials, and Clinical Outcomes in Implant Dentistry.

3D Printing Technique	Material Used	Application	Advantages	Clinical Success/ Outcome
Powder bed fusion (selective laser melting)	Titanium alloy (Ti-6Al-4V)	Patient-specific metal implants	Porous structure, mechanical strength, biocompatibility	87% Success in maxillofacial reconstructions
Extrusion printing (Arburg plastic free forming)	Polymer-ceramic (PLA/β-TCP)	Resorbable scaffolds and alveolar augmentation	Patient-specific, osteoconductive, degradable	Promising integration in pilot studies
Resin-based 3D printing	Surgical guide resins	Custom surgical guides	Precision fit reduces surgery time	Widely adopted, it enhances placement accuracy

Artificial intelligence in dental implants has also transformed the workflow, enabling automation, precision, and prediction across diagnosis, planning, surgical guidance, and prosthesis planning, as shown in Table 6. Generative design algorithms combine AI and subsequent optimisation of implant macro- and micro-geometries, relying on patient-specific finite element models. Such designs promote a balance between mechanical strength, stress utilisation, and osseointegration topographical details, downplaying the planning bias and enhancing great functional results. These customised implants also precisely fit irregular or damaged bone structures when used in conjunction with additive manufacturing, providing enhanced load transfer and reducing micromotion. Robots equipped with AI-based navigation software strengthen the accuracy of surgery, as demonstrated by pilot studies, which show accuracy in implant placement within 0.5 mm. The reason is that these systems reduce variability caused by hand, lessen trauma, and allow partial invasive procedures. Allowing AI to provide feedback on-the-fly to correct the drilling trajectory and depth can maximise primary stability and prevent the encounter of anatomical hazards. In addition to surgery, AI perfects the architecture and adaptation of prosthesis parts, including abutments and caps. Algorithms can maximise occlusal contacts, marginal fit, and esthetic outcomes, minimising the need for adjustments and remakes. This saves as much as 40% of chair time and minimises patient dissatisfaction by improving function and cosmesis.

TABLE 6. AI Applications in Dental Implantology: Functions, Benefits, and Performance Outcomes.

AI application	Description	Benefits	Accuracy/ outcome
Anatomical segmentation	Automated nerve and bone structure detection in CBCT scans	Enhances accuracy, reduces risk	> 98% Accuracy in nerve identification
Bone quality assessment	Prediction of bone density and morphology	Personalizes implant choice	High predictive accuracy (AUC > 0.90)
Failure risk prediction	Forecasts the likelihood of implant complications	Supports personalized risk management	Predictive models with AUC > 0.90
Surgical navigation	Real-time AI-guided implant placement during surgery	Improves precision, reduces surgical trauma	Placement accuracy within 0.5 mm (pilot)
Prosthetic design optimization	AI fine-tunes abutment and crown morphology	Better fit, reduced chair time	40% reduction in lab turnaround time

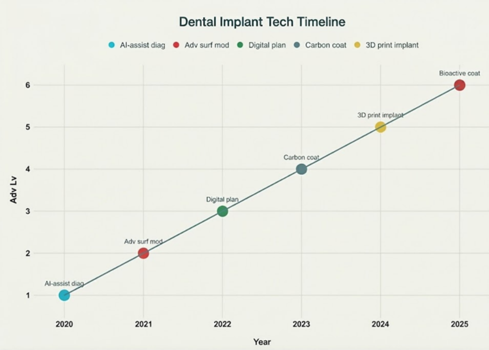

FIGURE 7. Timeline of transformative technological developments in dental implantology, highlighting the convergence of digital workflows and advanced biomaterials (the data were taken from a previous study).[83] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

These technological developments in digital imaging, AI, 3D printing, and CAD/CAM technologies have brought dental implantology to an era of customised, efficient, and highly predictable treatment (Figure 7). They decrease operative complications, streamline implant placement, reduce treatment duration, and enhance aesthetic and functional outcomes. Advances in the future are expected to be presented by augmented and virtual reality in serving as intraoperative guidance, generative AI in designing implants, and additional incorporation of bioactive materials in the context of digital fabrication.

3.2. Mechanical Failure and Wear in Dental Implants

The long-term success of dental implants is still a factor of mechanical failure and wear. Although the future holds promise for improvements in biomaterials, implant design, and surgical procedures, complications such as screw loosening, ceramic chipping, implant fracture, and wear-induced corrosion still occur at varying rates, which can ultimately undermine the integrity of osseointegration and prosthetic stability. This is one of the most frequent mechanical complications in 6–12% of implants within 5 years. It is generally caused by micromovements between the implant and the abutment interface, commonly resulting from prosthetic misfit or inadequate load torque generated during installation. The loosening of screws may cause microleakage of bacteria, peri-implant inflammation, and prosthetic failures.[84–89] Mitigation measures involve optimising screw preloading through torque control, internal hex, or tri-channel connectors to enhance mechanical interlocking and minimise micro-movement, as well as fine digital processes for aligning the fit of parts. Ceramic chipping is a typical complication in zirconia-based restoration. It is encountered in most cases (4–8%), often in conjunction with parafunctional habits (e.g., bruxism), occlusal loading, or less-than-ideal prosthetic framework design. There has been a significant reduction in the use of monolithic zirconia crowns that do not require bonding layers of ceramics. Moreover, the personalisation of occlusal forces distribution with the help of occlusal analysis and occlusal adjustment guided by AI ensures the prevention of risks associated with chipping and posterior restoration.

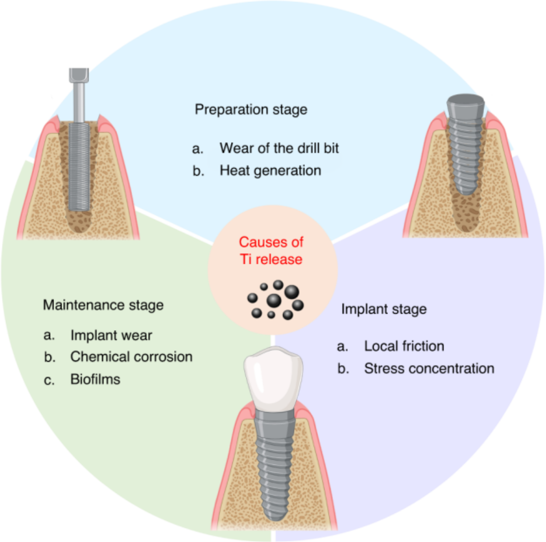

FIGURE 8. Causes of titanium release during dental implant preparation, implant, and maintenance stages.[90] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

Although relatively uncommon (< 1%), implant fractures may be initiated by overload, particularly in implants with narrow diameters or poor bone quality. β-type titanium alloys produce more elastic moduli, unlike other types of alloys; the closer they are to those in the bone, the less the stress concentrations and hence the possibility of fracture (Figure 8).[91–95] Another effective preventive measure is prosthetic splinting, which decompresses occlusal forces and spreads them to several implants. Table 7 presents common failure modes in dental implants, including prevalence, causes, and mitigation strategies. The release of titanium particulates due to wear or corrosion has been suspected of inducing peri-implant inflammation and peri-implantitis. The sources of wear debris could be micromotion between the implant and abutment or abrasion. To minimise the release of particles and biological impact, wear and chemical degradation resistance are improved by surface coatings, such as zirconia or carbon-based films (DLC and graphene). They are also antibacterial in nature and help fight the presence of biofilms.

TABLE 7. Common Failure Modes in Dental Implants: Prevalence, Causes, and Mitigation Strategies.

Failure Mode	5-Year Prevalence	Primary Causes	Mitigation Strategies
Screw loosening	6–12%	Micromotion, component misfit	Preload optimization, internal-hex/tri-channel connectors
Ceramic chipping	4–8%	Bruxism, framework design	Monolithic zirconia crowns, AI-balanced occlusal design
Implant fracture	< 1%	Overload, narrow diameter	β-type alloys, prosthetic splinting
Wear debris/ corrosion	-	Titanium particle release	Zirconia/carbon coatings for wear resistance

Finite-element analyses have played a significant role in identifying stress concentration zones and making design adjustments to distribute loading more evenly. Implant–abutment connections, such as Morse-taper, improve the dispersal of forces to the cortical bone.[96] Still, they can increase stress within components of the abutment, requiring the patient to choose with caution. Problems in mechanical failure often occur due to biological and prosthetic factors, indicating that more integrated treatment solutions should incorporate biomechanics, materials science, and treatment strategies to address these issues. The current standard of care involves prevention through optimised implant design, accurate surgical placement facilitated by digital workflow, and prosthetic planning that is also accurate based on AI analysis.

3.3. Bioactive and Bioresorbable Implants in Dental Implantology

Recent trends in the development of dental implants over the last 5 years have led to the conception of bioactive and bioresorbable materials as a crucial technology, focusing on accelerating the speed of biological adhesion and reducing the long-term foreign body burden. These advances signify a paradigm change toward nonactive, fixed objects to activate interactive systems that enable bone growth and support bone remodelling at the same rate of healing. Mg alloys have been a preferred choice of biodegradable dental implants because their elastic modulus (about 45 GPa) is similar to that of the cortical bones, effectively avoiding stress shielding effects. Mg alloys can biodegrade through an orderly corrosion process, thereby liberating Mg ions that are known to induce bone tissue development and angiogenesis.[97–101] Nonetheless, rapid corrosion presents issues such as local gas formation and early mechanical failure. To address this, synthesised methods for complex hybrid coatings that consist of HA and PLA have emerged (Figure 9). Such coatings slow the biodegradation rate and promote osteogenesis, stabilizing implant function during the critical early osseointegration phase. Early animal and pilot human studies have demonstrated positive findings regarding implant fixation and bone regeneration, particularly for small load-bearing and screw-like implants.

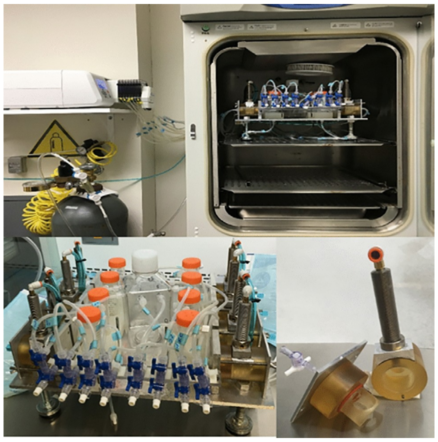

FIGURE 9. Laboratory setup for testing orthopaedic implants with fluid systems to evaluate bone formation on implant surfaces.[102] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

A combination of PLA and β-TCP has gained popularity in producing bioresorbable scaffolds using advanced 3D printing technology.[103–106] The composites serve as osteoconductive scaffolding for alveolar ridge distension and craniofacial remodelling. Patient-specific geometries can be printed in 3D to enable an accurate anatomic fit, thereby accelerating the integration of functions. These materials resorb over time into natural metabolites (e.g., lactic acid) and gradually transfer the loads to the regenerating bone while acting as temporary mechanical support. Components of surface coatings, such as BG, facilitate bone bonding by dissolving and releasing calcium and phosphate ions, thereby encouraging the growth of an HA-like mineral layer.[107–110] This mineralised layer can promote osseointegration and raise the local pH, creating an antimicrobial environment that prevents bacterial colonisation and peri-implantitis (Figure 10). Preliminary clinical and animal studies suggest that BG coatings could be used to minimise biological complications due to their minimal impact on mechanical performance.

To further accelerate early bone growth and vascularisation of implants, an experimental coating has been developed that incorporates osteoinductive factors, such as BMP-2 and L-PRF (Figure 11).[112–119] They are promising, but regulatory hurdles, manufacturing costs, and difficulty achieving stable formulations with predictable controlled release kinetics constrain their clinical translation. Table 8 presents the emerging biodegradable and bioactive systems for dental implantology.

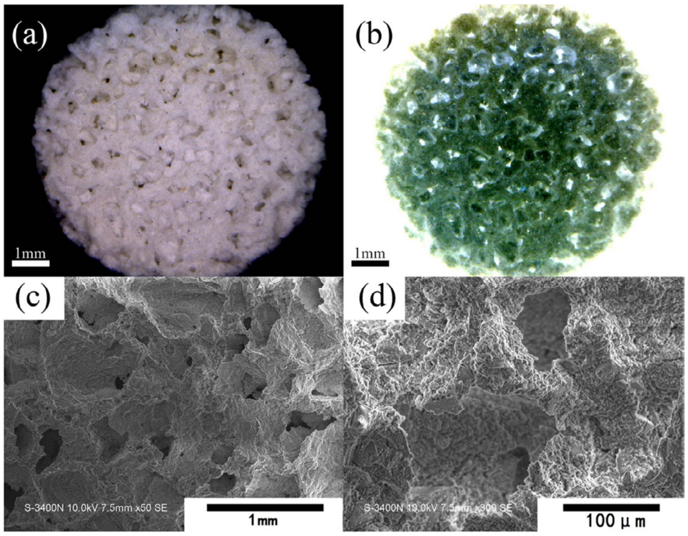

FIGURE 10. Optical and scanning electron microscope (SEM) images of mesoporous bioactive glass scaffolds showing porous microstructure relevant to bioresorbable bone implants.[111] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

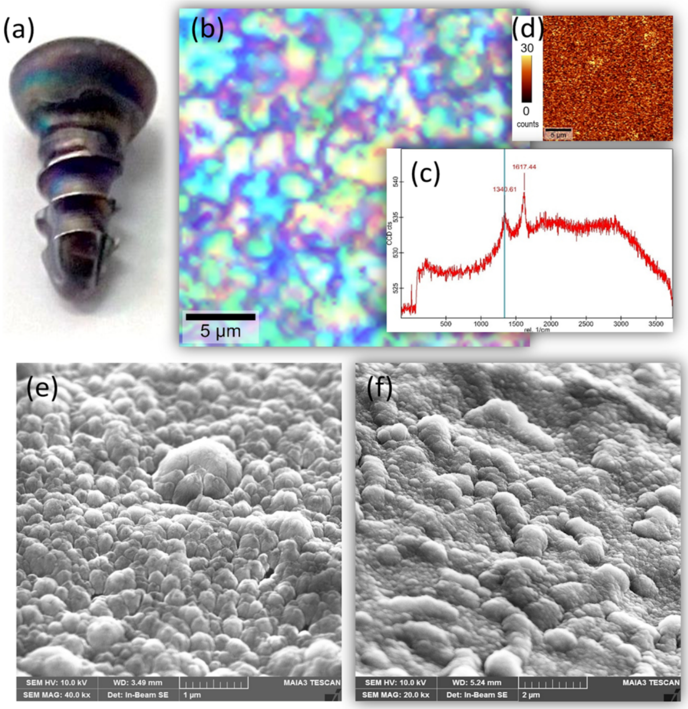

FIGURE 11. Microscopic and spectroscopic characterization of nanocrystalline coatings on Ti-6Al-4V implant screw, showing surface morphology and chemical fingerprinting relevant to bioactive implant coatings.[120] (Permission under the Creative Commons International Attribution CC BY-NC-ND 4.0 license)

TABLE 8. Emerging biodegradable and bioactive systems for dental implantology.

Material/ System	Key Properties	Advantages	Current Status/ Evidence
Magnesium alloys	Elastic modulus about 45 GPa; biodegradable	Bone-matched stiffness; osteogenic ion release	Preclinical & pilot clinical; coatings moderate corrosion
PLA/β-TCP composites	Osteoconductive polymer-ceramic blend	Patient-specific 3D-printable scaffolds; resorbable	Early clinical use in alveolar grafting
Bioactive glass coatings	Ion release (Ca^{2+}, PO_4^{3-}); antimicrobial	Enhances osseointegration; resists infection	Clinical trials ongoing
Growth factor films (BMP-2, L-PRF)	Osteoinductive biological coatings	Accelerates healing; stimulates vascularization	Experimental; regulatory challenges

Using bioactive and bioresorbable implants helps eliminate the disadvantages of permanent dental implants, including chronic foreign body reactions and the need for removal interventions. They are most appropriate to use when it involves patients with impaired bones or defective combinations, and then a gradual transfer of the load and increased regeneration is essential. Nonetheless, issues persist in altering degradation by modifying degradation rates to correlate with bone healing chronologies and providing adequate mechanical support at the initial stage of implantation. Acquiring further long-term safety and efficacy would require larger clinical trials. Key hurdles include regulatory complexity for combination products (device plus drug/biologicals) requiring robust and standardized evidence of long-term safety, controlled release profiles, and manufacturing consistency; scalability and quality control for surface functionalization (batch-to-batch reproducibility, sterilization compatibility, and shelf-life); clinical validation gaps, that is, paucity of large, prospective, multi-center trials with harmonized endpoints and cost-effectiveness data; integration challenges with the existing digital workflows and component ecosystems; and reimbursement, procurement, and training constraints that slow adoption. These factors necessitate the coordinated generation of clinical evidence, clear regulatory pathways, and robust manufacturing/QA frameworks to enable the routine use of these technologies.

3.4. Personalized Implants and AI-Driven Design in Dental Implantology

A combination of AI and individualised design strategies has significantly transformed dental implantology, enabling the provision of personalised approaches to treatment that consider each patient's anatomy, biology, and risk factors. Over the five years between 2020 and 2025, AI-enhanced technologies have progressed from the research phase into a clinical application phase, enhancing diagnostic accuracy, implantation, treatment planning, and outcome prediction. Patient-specific implants are now utilising advanced manufacturing methodologies to optimise fit and functionality. The latest AI protocols can now achieve stunning accuracies (> 98%) in robotic tooth counting, defining implant types, and detecting anatomical landmarks (Figure 12). The built-in capabilities enable chair-side real-time diagnostics, which minimize human error and streamline the workflow. For example, neural networks identify nerves and anatomical structures on fixed-scan CBCT with an almost perfect accuracy essential for avoiding surgical complications. AI models incorporate a variety of patient variables, such as bone quality, systemic conditions, and loading regimes, to

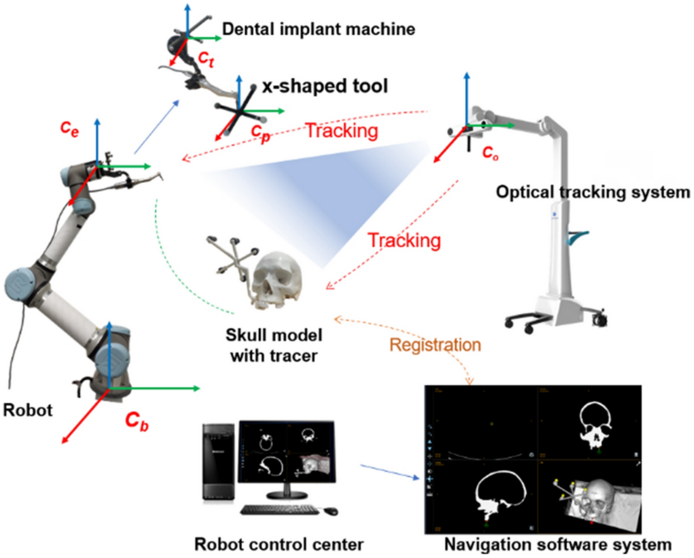

FIGURE 12. An optics-guided robotic system integrates robotic arms, optical tracking, and navigation software to enhance precision in dental implant surgery.[128] (Permission under the

predict implant success rates and the risks of biological complications.[121–127] The AUC values of machine learning classifiers are larger than 0.90 in terms of discriminatory power to predict peri-implantitis, implant failure, or mechanical complications. This prognostic ability allows data-driven individual treatment planning, informed consent, and optimisation of clinical decision-making.

Table 9 summarizes the primary AI technologies currently applied in dental implantology, outlining their clinical applications, associated benefits, and documented performance metrics. The result of blending AI and personalised implant design is the creation of highly customised treatment plans that can enhance surgical safety, improve the success of prosthetic implants, and increase the postoperative durability of implants. The AI workflows are helpful because they help reduce operator variability, thereby speeding up clinical processes and supporting informed decision-making about complex issues. Individual-tailored implants using additive manufacturing processes can better match patient anatomy, enhancing primary stability and biomechanical performance, primarily when used in compromised or unusual bone models.

TABLE 9. AI technologies in dental implantology: applications, clinical benefits, and performance.

Application Area	AI Technology/ Method	Clinical Benefits	Outcome/ Accuracy
Anatomical segmentation	Deep learning neural networks	Precise nerve and bone mapping	> 98% accuracy in nerve segmentation
Implant classification	Machine learning classifiers	Automated implant type recognition	> 98% classification accuracy
Predictive risk modelling	Multivariate AI models	Risk stratification for peri-implantitis/failure	AUC > 0.90 in predictive performance
Generative implant design	AI-driven finite-element optimization	Personalized, optimized implant geometries	Improved biomechanical load distribution
Robotic-assisted Navigation	AI-guided real-time surgical control	Sub-0.5 mm placement accuracy	Pilot clinical use success
Prosthetic design optimization	AI-based occlusal and fit adjustment	Reduced adjustment time; improved aesthetics	Up to 40% reduced lab turnaround time

Expanded opportunities in the future include continuous learning of AI algorithms that improve over time and with the accumulation of clinical data, as well as utilising augmented reality (AR) to create intraoperative visualisation. These smart, closed-loop implants can monitor and adapt in real-time. Regulatory frameworks and broad clinical validation are the most essential aspects that need improvement and development. Specifically, AI solutions often entail non-trivial upfront and recurring costs (such as software licenses, hardware, and integration with imaging/records), which can be prohibitive for small or resource-limited practices. Effective use requires staff training in data acquisition quality (CBCT/intraoral scans), workflow integration, and interpretation of model outputs, along with ongoing calibration and updates. Accessibility is uneven due to variable Internet infrastructure, interoperability with existing systems, and data privacy and consent requirements; reimbursement pathways are still evolving. To promote equitable deployment, the text highlights phased implementation (pilot modules with measurable ROI), vendor support/education, and preference for interoperable, standards-compliant tools that integrate with the current imaging and CAD–CAM pipelines. Over the past five years alone, disruptive shifts toward digitally enhanced workflows in dental implantology have incorporated the latest imaging technology, AI, and the power of additive manufacturing to deliver new levels of precision, efficiency, and individualised patient outcomes. Such workflows span the entire treatment sequence, from diagnosis and surgery planning to guided surgery and restoration with prosthetics.

4. CLINICAL LOADING CONCEPTS IN DENTAL IMPLANTOLOGY

The implant loading protocol, including the timing and method of placing the prosthetic crown or denture into a functional occlusion, has undergone considerable changes. The clinical intervention ensures the most advantageous osseointegration, reduces complications, and promotes patient satisfaction, which in turn depends on a shorter treatment period. Various loading protocols have been broadly categorised into three: immediate loading (prosthetic restoration is placed within 1 week of implant positioning); early loading (loading that occurs after 1 week to 2 months after implantation); and conventional (or delayed) loading, in which restoration is not placed up to 2 months to allow extended healing before functional loading.[129–132] It is now known with reasonable certainty that survival with immediate and early loading can be equivalent to conventional loading as long as specific stability criteria have been fulfilled according to recent systematic reviews and consensus guidelines. These are an insertion torque of at least 40 N·cm, or typically around this value, to achieve mechanical fixation, and an ISQ of at least 70, as tested by resonance frequency analysis, which indicates that the implant is stable. The 3D and 6D gain measures, which minimise micromotion that may interfere with osseointegration, make these thresholds essential, thus allowing for safe and functional early loading. They significantly reduce the time patients live without teeth, thereby enhancing their overall quality of life, enabling them to eat comfortably, speak clearly, and restore their smile and social confidence more quickly. This restoration, carried out promptly, improves psychological well-being and comfort. Furthermore, since secondary surgeries are usually minimized with immediate or early loading protocols, the treatment does not become cumbersome, with a drastic decrease in patients' overall morbidity. Special attention should be paid to short implants (≤ 8 mm), the immediate loading of which under appropriate stability conditions is associated with cumulative success rates exceeding 98%. Such implants often eliminate the need for sinus augmentation or excessive bone grafting, especially when treating atrophic maxillae, making treatment significantly easier.[133–136] Table 10 presents the definitions, typical survival rates, and key inclusion criteria for the three primary loading protocols in implant dentistry. Notably, the loading scheme is to be made considering the quality of the bone, general patient factors, and anatomy. AI-driven risk assessment and modern digital imaging modalities are commonly incorporated into clinical practice to individualise loading strategies and maximise outcomes at the individual level. These developments have elevated implant loading practices from a conservative, long-term process to an objective, evidence-based methodology that balances the biological wound-healing process and patient-based efficiency and comfort.

TABLE 10. Dental Implant Loading Protocols: Definitions, Survival Rates, and Key Inclusion Criteria.

Loading Protocol	Definition	Typical Survival Rate (%)	Key Inclusion Criteria
Immediate loading	Prosthesis in occlusion ≤ 1 week	98–100	Insertion torque ≥ 40 N cm; ISQ ≥ 70
Early Loading	Restoration between 1 week and 2 months	97–99	Adequate primary stability
Conventional loading	Restoration after >2 months	96–98	No specific stability requirement

Clinicians must pay close attention to the primary stability by measuring torque, ISQ, and patient-specific factors (bone quality, systemic health, and smoking). Protocols applicable to immediate and early loading are implemented successfully and without jeopardising the longevity of implants when the criteria are followed. Improved technology includes AI-based predictive models, CAD–CAM fabricated prostheses, and robotic devices that assist in planning treatment and facilitating a smooth transition from implant positioning to its ultimate restoration, which further positively influences accelerated loading. The current research aims to optimise biomaterials and surface treatments to allow further acceleration and stability of osseointegration, which in turn could expand indications toward immediate loading. Using biosensors on implants to measure loading forces and track healing in real-time promises to play a role in the near-term use of dynamic, patient-specific loading programs. Table 11 summarizes the loading thresholds, timing definitions, and clinical recommendations for implant-supported restorations.

TABLE 11. Loading thresholds and clinical recommendations for different implant loading protocols.

Protocol	Timing Definition	Primary Stability Thresholds	When to Recommend	Typical Notes
Immediate loading	Prosthesis in occlusion within 1 week of implant placement	Insertion torque ≥ 40 N·cm; ISQ ≥ 70	Single units or splinted cases with excellent bone quality, intact socket walls, controlled occlusion, and an experienced operator	Prefer nonfunctional occlusion if borderline; ensure a protective occlusal scheme and patient compliance
Immediate restoration (non-occlusal)	Provisional placed within 1 week, kept out of occlusion	Insertion torque ≥ 30–35 N·cm; ISQ ≥ 65–70	Aesthetic zones where soft tissue support is desired, but functional loading risk is high	Strict soft diet; frequent follow-up and RFA monitoring
Early loading	Restoration in occlusion at 1 week–2 months	Insertion torque ≥ 35–40 N·cm; ISQ ≥ 70 at loading visit	Good bone density and primary stability; sites without graft immaturity	Verify the rising ISQ trend before loading
Conventional (delayed) loading	Restoration after > 2 months	No fixed torque/ISQ, prioritize complete uneventful healing	Compromised bone quality, extensive augmentation, systemic risk factors, or low initial stability	Consider staged increases in function and progressive occlusion
Short implants (≤ 8 mm) under immediate/early loading	As above	Insertion torque ≥ 40 N·cm; ISQ ≥ 70	Atrophic ridges where grafting is to be avoided and stability is confirmed	Favour splinting and carefully controlled occlusion

5. MANAGEMENT OF BIOLOGICAL COMPLICATIONS IN DENTAL IMPLANTS

Although advances in materials and surgery indicate that dental implantology is becoming more efficient, clinical and biological complications, especially peri-implant diseases, including peri-implant mucositis and peri-implantitis, remain a significant issue in the field of dental implantology. Peri-implant mucositis is an inflammatory process that affects the non-sensitised (soft) tissues surrounding an implant, causing the latter to bleed on probing, but with no bone loss, and is reversible when properly addressed and maintained. On the contrary, peri-implantitis is a condition characterised by both inflammation and progressive bone loss around the implant. Peri-implantitis encompasses 10–20% of both patients and implants within a 5–10-year period.[137–140] Prevention and early detection are the first steps for proper management. Proactive measures can be taken to reduce the number of diseased cases by educating patients about oral maintenance, controlling risk factors such as smoking and systemic diseases, and providing professional patient care tailored to the risk profile, which significantly minimises disease incidents. Peri-implant mucositis and early peri-implantitis are typically treated using nonsurgical management as the first line of therapy, aiming for mechanical debridement with plastic or titanium curettes, ultrasonic equipment, and glycine powder air-polishing to safely eliminate biofilm without harming the implant surface. Photodynamic therapy, although potentially helpful in a limited way, is a potential adjunctive therapy that, when combined with an antibiotic regimen and antiseptics, such as chlorhexidine irrigation, can reduce microbial count. Although persistent nonsurgical treatment usually resolves mucositis, surgery is typically required for peri-implantitis in most instances. Surgical management may be performed through surgery of the access flap, allowing for the visualisation and cleaning of the implant surface with mechanical assistance and other adjunctive means, such as lasers and chemical cleaning agents.[141–145] The intention is to replace lost bone during bone regenerative surgery, which involves the use of grafts and membranes. However, roughened or contaminated implant surfaces are altered in the corresponding surgeries, such as implantoplasty.

Nevertheless, even after surgical intervention, one-year recurrence rates of peri-implantitis vary considerably, ranging from approximately 3% in carefully selected cases with complete decontamination and augmentation to 44% in patients with multiple risk factors such as poor oral hygiene, smoking, and severe baseline bone loss. This substantial variation highlights the multifactorial nature of recurrence and underscores the importance of individualised risk assessment and maintenance protocols. Recurrence in the long term is a predominant clinical dilemma, depending on the features of the implant surface, implant duration, the presence of basic suppuration, and the severity of bone loss at the initial diagnosis. Titanium implant debris and reservoir of microbial organisms might also blur the healing process, which leads to the ongoing inflammation [146–150]

New adjunctive treatments in research include novel bioactive coatings, such as bioactive glass and antimicrobial carbon-based films (e.g., graphene and DLC), to reduce bacterial colonisation and promote re-osseointegration. Innovative solutions, such as locally controlled-release antimicrobials and host modulation therapies, as well as other novel laser treatment options, are currently under clinical trial and are yet to be completed. Peri-implant diseases should be treated using a stepwise management protocol. This involves proper diagnosis and categorisation of the level of illness, educating the patient and reinforcing oral healthcare, providing nonsurgical mechanical debridement as the first line of treatment, repeating these lessons after evaluation, and surgical intervention in cases of need. Longer, individualised peri-implant care is essential to prevent recurrences and maintain the implant's health.[151–154] Table 12 outlines the main management approaches, their indications, key techniques or interventions, and the associated clinical outcomes and limitations. It is a multi-modal approach that is still necessary to adequately address biological issues in dental implants, produce durable implants, and achieve good, long-term clinical outcomes.

TABLE 12. Management Strategies for Peri-Implant Diseases: Indications, Techniques, and Outcomes.

Management Approach	Indications	Key Techniques/ Interventions	Outcomes and Limitations
Nonsurgical therapy	Peri-implant mucositis, early peri-implantitis	Mechanical debridement, air-polishing, and photodynamic therapy	Effective for mucositis; limited for advanced peri-implantitis
Surgical therapy	Advanced peri-implantitis	Access flap, decontamination, regenerative, or respective surgery	Improves clinical parameters; recurrence rates up to 44%
Adjunctive therapies	Supporting nonsurgical/ surgical treatment	Laser therapy, antiseptics, and antimicrobial coatings	Promising but evidence variable; under study
Maintenance and prevention	All implant patients	Regular professional cleaning, risk factor control	Reduces disease incidence; critical for long-term success

The treatment of biological complications surrounding dental implants is increasingly shifting toward evidence-based and integrated pathways, where precise diagnosis, individualised treatments, and long-term maintenance are strictly adhered to. Although the number of treatment methods is now diverse, the frequency of reappearance and development of peri-implant diseases, including mucositis and peri-implantitis, is represented by high clinical rates, which dictate the need to improve on several levels.[155–157] Among the main priorities are innovations in early detection and risk evaluation based on AI methods and salivary markers or crevicular biomarkers, which enable the provision that allow providing timely and customized interventions before the damage is irreparable. Similar works aim to create more effective bioactive and antimicrobial surfaces for implants (coatings containing BG, bioactive peptides, and carbon-based nanofilms) that would enable them to resist bacterial colonisation and achieve re-osseointegration even at damaged sites. There is a focus on new regenerative treatments to replace lost peri-implant bone and enhance long-term strength, including the use of growth factors, stem cell therapy, and biomimetic scaffolds. Improved patient education can be equally vital for achieving better oral hygiene and compliance with the maintenance program, as patient compliance is a key factor in preventing recurrence.[158–161] Therefore, a multimodal, holistic approach, encompassing prosthodontic, surgical, periodontal, microbiological expertise, and digital diagnostic and reasoning skills, involving adherence to contemporary international clinical guidelines, is the most promising way to manage these complicated sequelae and maintain peri-implant health and implant longevity.

Antimicrobial strategies for next-generation implants encompass several innovative approaches aimed at preventing infection and promoting tissue integration. Peptide coatings, such as GL13K and engineered chimerics, inhibit early pathogenic adhesion and biofilm formation on titanium surfaces while maintaining compatibility with surrounding cells. These coatings often incorporate adhesion motifs to promote effective sealing of soft tissue around the implant. Another approach involves metallic ion-doped surfaces, including zinc-, fluorine-, and bismuth-modified calcium phosphates, as well as photoactivated titanium dioxide and titanium nitride variants. These surfaces offer bactericidal and antibiofilm properties against peri-implant pathogens, and in many cases, enhance bone growth; however, long-term durability still requires validation. Controlled-release interfaces, such as chlorhexidine reservoirs and antimicrobial peptide–graphene oxide hybrids, maintain antimicrobial activity around the abutment–implant and transmucosal regions while exhibiting low cytotoxicity in vitro. Complementing these methods, mesoporous bioactive glass and other ion-releasing coatings elevate the local pH and release calcium and phosphate ions, forming a hydroxyapatite-like layer that discourages bacterial colonization and promotes bone bonding. Incorporating fluoride or zinc into calcium phosphate or glass matrices further contributes to antibacterial effects without compromising osteoconductivity. Together, these multifaceted strategies provide a dual-action preventive approach against peri-implantitis by combining infection control with the promotion of bone integration.

6. FUTURE PERSPECTIVES IN DENTAL IMPLANTOLOGY

The last few years have taken dental implantology to the edge of the next era, whose future orientations will be determined by the convergence of disciplines in materials science, digital technologies, AI, and regenerative medicine. The idea behind next-generation dental implants is to address unresolved clinical problems, individualise their approach to therapy, and adopt biologically mediated processes to create a positive tissue reception environment. Studies are rapidly developing the so-called smart surfaces of implants that can release treatment agents in response to environmental stimuli. For example, coatings that sense local pH or bacterial metabolites can provide an antibiotic, growth factor, or anti-inflammatory agent in a time- and place-specific manner. As demonstrated by preclinical research, no such responsive coatings can prevent biofilm formation and regulate peri-implant bone remodelling better than static surfaces. It is predicted that applying antimicrobial peptides, silver nanoparticles, or growth factors (such as BMP-2) to the coating of implants will enhance infection control and accelerate osseointegration, thereby minimizing the need for systemic medications.

Future implant material development encompasses fully absorbable implants, particularly Mg screws, scaffolds, and combinations with 3D-printed PLA/β-TCP polymers. The purpose of these systems is to create initial stability and wear out over time as bone cells rebuild on their own, thereby eliminating the need for surgery to remove the implant. Clinical translation must optimise degradation rates and mechanical performance to achieve specific healing curves, which, thus far, have had to be speculative. A highly desirable clinical translation goal is currently being achieved through novel surface engineering and the design of composite materials. Clinical decision-making, risk profiling, and real-time intraoperative adjustments are now guided by predictive analytics and machine learning. Patient-specific anatomical and biomechanical information is used in an AI-based generative design loop to iteratively optimize the geometry, surface features, and surgical access of implants. These tools can generate thousands of combinations and select the one that provides optimum primary stability, the lowest stress concentration, and adjusts to local bone quality. This type of automation yields less operator-induced bias and provides more predictable data outcomes. In future, clinical practice will likely need the integration of on-site 3D printing of patient-specific implants with high-quality standards (ISO 13485). As digital imaging, CAD, and in-clinic prototyping advance, there is hope to provide fully personalised metallic, ceramic, or resorbable implants in a single sitting. The paradigm eliminates the backlog of off-site production and expands access to innovative treatments for complex or emergency cases.

Since peri-implantitis is one of the significant reasons for implant failure, it is one of the topics that are studied extensively as far as the prevention and treatment of the complication is concerned. Bioactive coatings on glasses, antibacterial nanofilms on carbon, and machine learning-based risk stratification are underway to reduce the likelihood of recurrence and re-osseointegration at affected sites. In the future, dental implants may include biosensors that provide real-time, physical feedback on mechanical load, temperature, or biochemical indicators of peri-implant health. These smart implants can trigger premonitory signs of biomechanical overload or infection and even initiate the release of therapeutic compounds, leading to real closed-loop care. Additionally, future convergence with tissue engineering through stem cell seeding and grafting, as well as the delivery of growth factors and immune modification, may lead to the on-demand reconstitution of whole dento-periodontal tissues. The given innovations necessitate revisions to regulatory frameworks and interdisciplinary collaboration among clinicians, materials scientists, engineers, and data scientists. Additional focus on using evidence to support adoption, safety, and long-term monitoring is crucial to realising the full clinical potential of these gains.

7. CONCLUSIONS

Contemporary implant dentistry is transitioning toward predictable personalized care enabled by synergistic advances in implant materials, multifunctional surface engineering, and digitally enhanced workflows. Established systems, such as micro-roughened titanium and high-performance ceramics, demonstrate high mid-term survival. In contrast, β-type titanium alloys, polymer-based frameworks, and bioresorbable constructs broaden indications with biomechanical tailoring and regenerative intent. Coupling CBCT and intraoral scanning with AI-assisted planning, CAD–CAM prosthetics, and additive manufacturing improves surgical precision, prosthetic fit, and the feasibility of stability-guided immediate or early loading in appropriately selected cases. These developments emphasize increased bone-to-implant contact, reduce biofilm susceptibility through surface functionality, and streamline clinical pathways. Key challenges remain and define the near-term agenda. First, peri-implantitis recurrence persists despite improved decontamination and maintenance protocols. This underscores the need for durable antibiofilm strategies, ion-releasing or peptide-based coatings, and robust soft tissue integration around transmucosal components. Second, for bioresorbable and hybrid systems (e.g., Mg alloys, PLA–β-TCP scaffolds), precise control of degradation kinetics and an early-phase mechanical reliability are essential to match healing timelines, mitigate particulate/corrosion by-products, and ensure long-term host compatibility. Priorities include standardized clinical endpoints and longer prospective cohorts for preventive surfaces, traceable metrology for *in vivo* degradation and wear, and integration of AI decision support with outcomes registries to translate design and materials innovation into consistently improved clinical performance.

AUTHOR CONTRIBUTIONS

Conceptualization, A.P., P.P. and V.K.; Methodology, A.P.; Validation, A.P., P.P. and V.K.; Formal Analysis, A.P., P.P. and V.K.; Investigation, A.P., P.P. and V.K.; Resources, A.P. and P.P.; Data Curation, A.P. and P.P.; Writing–Original Draft Preparation, A.P.; Writing–Review & Editing, V.K.; Visualization, P.P. and V. K.; Supervision, V.K.; Project Administration, V.K.

FUNDING

This research received no external funding.

DATA AVAILABILITY STATEMENT

All data that support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

REFERENCES

1. Alfaraj, T.A., Al-Madani, S., Alqahtani, N.S., et al. Optimizing osseointegration in dental implantology: a cross-disciplinary review of current and emerging strategies. *Cureus*. 2023;15(10):e47943. https://doi.org/10.7759/cureus.47943.
2. Kumar, V., Seth, J., Aeran, M., et al. From surface to success: how implant surfaces shape osseointegration. *IJPI*. 2024;9(2):58–63. https://doi.org/10.18231/j.ijpi.2024.013.
3. Joshi, N.P., Agwani, K.M., Mathur, R., et al. Rooted in bone: the role of osseointegration in dental implantology. *IJISRT*. 2025;10(4):2164–2169. https://doi.org/10.38124/ijisrt/25apr1088.
4. Pandey, C., Rokaya, D., Bhattarai, B.P. Contemporary concepts in osseointegration of dental implants: a review. *BioMed Res Int*. 2022:6170452. https://doi.org/10.1155/2022/6170452.
5. Cooper, L.F., and Shirazi, S. Osseointegration—the biological reality of successful dental implant therapy: a narrative review. *Front Oral Maxillofac Med*. 2022;4:39. https://doi.org/10.21037/fomm-21-77.
6. Sharma, P., Mishra, V., Murab, S. Unlocking osseointegration: surface engineering strategies for enhanced dental implant integration. *ACS Biomat Sci Eng*. 2025;11(1):67–94. https://doi.org/10.1021/acsbiomaterials.4c01178.
7. Beschnidt, S.M., Cacaci, C., Dedeoglu, K., et al. Implant success and survival rates in daily dental practice: 5-year results of a non-interventional study using CAMLOG SCREW-LINE implants with or without platform-switching abutments. *Int J Implant Dent*. 2018;4(1):33. https://doi.org/10.1186/s40729-018-0145-3.
8. Waghmare, G., Waghmare, K., Bagde, S., et al. Materials evolution in dental implantology: a comprehensive review. *J Adv Res Appl Mech*. 2024;123(1):75–100. https://doi.org/10.37934/aram.123.1.75100.
9. Manfredini, M., Poli, P.P., Giboli, L., et al.Clinical factors on dental implant fractures: a systematic review. *Dent J*. 2024;12(7):200. https://doi.org/10.3390/dj12070200.
10. Kupka, J.R., König, J., Al-Nawas, B., et al. How far can we go? A 20-year meta-analysis of dental implant survival rates. *Clin Oral Invest*. 2024;28(10):541. https://doi.org/10.1007/s00784-024-05929-3.
11. Liu, C., Liu, Y., Xie, R., et al. The evolution of robotics: research and application progress of dental implant robotic systems. *Int J Oral Sci*. 2024;16(1):28. https://doi.org/10.1038/s41368-024-00296-x.
12. Hakim, L.K., Yari, A., Nikparto, N., et al. The current applications of nano and biomaterials in drug delivery of dental implant. *BMC Oral Health*. 2024;24(1):126. https://doi.org/10.1186/s12903-024-03911-9.
13. Bahrami, R., Pourhajibagher, M., Nikparto, N., et al. Robot-assisted dental implant surgery procedure: a literature review. *J Dent Sci*. 2024;19(3):1359–1368. https://doi.org/10.1016/j.jds.2024.03.011.
14. Wu, X.Y., Shi, J.Y., Qiao, S.C., et al. Accuracy of robotic surgery for dental implant placement: a systematic review and meta-analysis. *Clin Oral Implants Res*. 2024;35(6):598–608. https://doi.org/10.1111/clr.14255.
15. Maher, N., Mahmood, A., Fareed, M.A., et al. An updated review and recent advancements in carbon-based bioactive coatings for dental implant applications. *J Adv Res*. 2025;72:265–286. https://doi.org/10.1016/j.jare.2024.07.016.
16. Accioni, F., Vázquez, J., Merinero, M., et al. Latest trends in surface modification for dental implantology: innovative developments and analytical applications. *Pharmaceutics*, 2022;14(2):455. https://doi.org/10.3390/pharmaceutics14020455.
17. Kochar, S.P., Reche, A., Paul, P. The etiology and management of dental implant failure: a review. *Cureus*. 2022;14(10):e30455. https://doi.org/10.7759/cureus.30455.
18. Sailer, I., Karasan, D., Todorovic, A., et al. Prosthetic failures in dental implant therapy. *Periodontol 2000*. 2022;88(1):130–144. https://doi.org/10.1111/prd.12416.
19. Papadakis, I., Spanou, A., Kalyvas, D. Success rate and safety of dental implantology in patients treated with antiresorptive medication: a systematic review. *J Oral Implantol*.

2021:47(2):169–180. https://doi.org/10.1563/aaid-joi-D-19-00088.

20. Ebenezer, S., Kumar, V.V., Thor, A. Basics of dental implantology for the oral surgeon. In *Oral and maxillofacial surgery for the clinician*. Bonanthaya, K., Panneerselvam, E., eds. Springer Nature: Singapore, 2021; pp. 385–405. https://doi.org/10.1007/978-981-15-1346-6_18.
21. Matos, G.R.M. Surface roughness of dental implant and osseointegration. *J Maxillofac Oral Surg*. 2021;20(1):1–4. https://doi.org/10.1007/s12663-020-01437-5.
22. Lokwani, B.V., Gupta, D., Agrawal, R.S., et al. The use of concentrated growth factor in dental implantology: a systematic review. *J Indian Prosthodont Soc*. 2020;20(1):3–10. https://doi.org/10.4103/jips.jips_375_19.
23. Zhang, Y., Gulati, K., Li, Z., et al. Dental implant nano-engineering: advances, limitations and future directions. *Nanomaterials*. 2021;11(10):2489. https://doi.org/10.3390/nano11102489.
24. Lang, N.P., Berglundh, T., Giannobile, W.V., et al. *Lindhe's clinical periodontology and implant dentistry*, 7th ed.; John Wiley: Hoboken, NJ, USA; 2021; pp. 3–49.
25. Dutta, S.R., Passi, D., Singh, P., et al. Risks and complications associated with dental implant failure: critical update. *Nat J Maxillofac Surg*. 2020;11(1):14–19. https://doi.org/10.4103/njms.NJMS_75_16.
26. Dutta, S.R., Passi, D., Singh, P., et al. Risks and complications associated with dental implant failure: Critical update. *Nat J Maxillofac Surg*. 2020;11(1):14–19. https://doi.org/10.4103/njms.NJMS_75_16.
27. Pellegrino, G., Bellini, P., Cavallini, P.F., et al. Dynamic navigation in dental implantology: the influence of surgical experience on implant placement accuracy and operating time. An in vitro study. *Int J Environ Res Public Health*. 2020;17(6):2153. https://doi.org/10.3390/ijerph17062153.
28. Nulty, A. A literature review on prosthetically designed guided implant placement and the factors influencing dental implant success. *Br Dent J*. 2024;236(3):169–180. https://doi.org/10.1038/s41415-024-7050-3.
29. Jia, S., Wang, G., Zhao, Y., et al. Accuracy of an autonomous dental implant robotic system versus static guide-assisted implant surgery: a retrospective clinical study. *J Pros Dent*. 2025;133(3):771–779. https://doi.org/10.1016/j.prosdent.2023.04.027.
30. Li, Z., Xie, R., Bai, S., et al. Implant placement with an autonomous dental implant robot: a clinical report. *J Prosth Dent*. 2025;133(2):340–345. https://doi.org/10.1016/j.prosdent.2023.02.014.
31. Panahi, O. Smart robotics for personalized dental implant solutions. *Dental*. 2025;7(1):21. https://doi.org/10.35702/dent.10021.
32. Kang, D.Y., Duong, H.P., Park, J.C. Application of deep learning in dentistry and implantology. *J Implant Appl Sci*. 2020;24(3):148–181. https://doi.org/10.32542/implantology.202015.
33. Do, T.A., Le, H.S., Shen, Y.W., et al. Risk factors related to late failure of dental implant—a systematic review of recent studies. *Int J Environ Res Public Health*. 2020;17(11):3931. https://doi.org/10.3390/ijerph17113931.
34. Mohammad-Rahimi, H., Motamedian, S.R., Pirayesh, Z., et al. Deep learning in periodontology and oral implantology: a scoping review. *J Periodont Res*. 2022;57(5):942–951. https://doi.org/10.1111/jre.13037.
35. Kligman, S., Ren, Z., Chung, C.H., et al. The impact of dental implant surface modifications on osseointegration and biofilm formation. *J Clin Med*. 2021;10(8):1641. https://doi.org/10.3390/jcm10081641.
36. Lee, J.H., Kim, Y.T., Lee, J.B., et al A performance comparison between automated deep learning and dental professionals in classification of dental implant systems from dental imaging: a multi-center study. *Diagnostics*. 2020;10(11):910. https://doi.org/10.3390/diagnostics10110910.
37. Kim, J.C., Lee, M., Yeo, I.S.L. Three interfaces of the dental implant system and their clinical effects on hard and soft tissues. *Mat Horiz*. 2022;9(5):1387–1411. https://doi.org/10.1039/D1MH01621K.
38. Gao, J., Pan, Y., Gao, Y., et al. Research progress on the preparation process and material structure of 3D-printed dental implants and their clinical applications. *Coatings*. 2024;14(7):781. https://doi.org/10.3390/coatings14070781.
39. Hossain, N., Mobarak, M.H., Islam, M.A., et al. Recent development of dental implant materials, synthesis process, and failure – a review. *Results Chem*. 2023;6:101136. https://doi.org/10.1016/j.rechem.2023.101136.
40. Jambhulkar, N., Jaju, S., Raut, A., et al. A review on surface modification of dental implants among various implant materials. *Mat Today Proc*. 2023;72:3209–3215. https://doi.org/10.1016/j.matpr.2022.12.022.
41. Alagatu, A., Dhapade, D., Gajbhiye, M., et al. Review of different material and surface modification techniques for dental implants. *Mat Today Proc*. 2022;60:2245–2249. https://doi.org/10.1016/j.matpr.2022.03.338.

42. Kurup, A., Dhatrak, P., Khasnis, N. Surface modification techniques of titanium and titanium alloys for biomedical dental applications: a review. *Mats Today Proc*. 2021;39:84–90. https://doi.org/10.1016/j.matpr.2020.06.163.
43. Sun, X.D., Liu, T.T., Wang, Q.Q., et al. Surface modification and functionalities for titanium dental implants. *ACS Biomat Sci Eng*. 2023;9(8):4442–4461. https://doi.org/10.1021/acsbiomaterials.3c00183.
44. Herráez-Galindo, C., Rizo-Gorrita, M., Maza-Solano, S., et al. A review on CAD/CAM yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) and polymethyl methacrylate (PMMA) and their biological behavior. *Polymers*. 2022;14(5):906. https://doi.org/10.3390/polym14050906.
45. Bai, Z., Wang, B., Bian, J., et al. Antibacterial and osteogenic activities of thiolated and aminated yttria-stabilized tetragonal zirconia polycrystal with tolerance to low temperature degradation. *Ceramics Int*. 2023;49(23):37817–37828. https://doi.org/10.1016/j.ceramint.2023.09.110.
46. Cho, Y.E., Lim, Y.J., Han, J.S., et al. Effect of yttria content on the translucency and masking ability of yttria-stabilized tetragonal zirconia polycrystal. *Materials*. 2020;13(21):4726. https://doi.org/10.3390/ma13214726.
47. Küçükekenci, A.S., Çakmak, G., Güven, M.E., et al. Implant-supported fixed complete denture frameworks in additively and subtractively manufactured high-performance polymers: fabrication and fit accuracy. *J Dent*. 2025;105838. https://doi.org/10.1016/j.jdent.2025.105838.
48. Alqutaibi, A.Y., Alghauli, M.A., Algabri, R.S., et al. Applications, modifications, and manufacturing of polyetheretherketone (PEEK) in dental implantology: a comprehensive critical review. *Int Mat Rev*. 2025;70(2):103–136. https://doi.org/10.1177/09506608251314251.
49. Zol, S.M., Alauddin, M.S., Said, Z., et al. Description of poly (aryl-ether-ketone) materials (PAEKs), polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) for application as a dental material: a materials science review. *Polymers*. 2023;15(9):2170. https://doi.org/10.3390/polym15092170.
50. McMullan, R., Golbang, A., Salma-Ancane, K., et al. Review of 3D printing of polyaryletherketone/apatite composites for lattice structures for orthopedic implants. *Applied Sci*. 2025;15(4):1804. https://doi.org/10.3390/app15041804.
51. Menini, M., Delucchi, F., Bagnasco, F., et al. Shock absorption capacity of high-performance polymers for dental implant-supported restorations: in vitro study. *Dent J*. 2024;12(4):111. https://doi.org/10.3390/dj12040111.
52. Dong, H., Liu, H., Zhou, N., et al. Surface-modified techniques and emerging functional coating of dental implants. *Coatings*. 2020;10(11):1012. https://doi.org/10.3390/coatings10111012.
53. Nasr Azadani, M., Zahedi, A., Bowoto, O.K., et al. A review of current challenges and prospects of magnesium and its alloy for bone implant applications. *Prog Biomat*. 2022;11(1):1–26. https://doi.org/10.1007/s40204-022-00182-x.
54. Herber, V., Okutan, B., Antonoglou, G., et al. Bioresorbable magnesium-based alloys as novel biomaterials in oral bone regeneration: general review and clinical perspectives. *J Clin Med*. 2021;10(9):1842. https://doi.org/10.3390/jcm10091842.
55. Omigbodun, F.T., Oladapo, B.I., Osa-uwagboe, N. Exploring the frontier of polylactic acid/hydroxyapatite composites in bone regeneration and their revolutionary biomedical applications – a review. *J Reinforced Plast Comp*. 2024;0(0). https://doi.org/10.1177/07316844241278045.
56. Topuz, M. Hydroxyapatite – Al2O3-reinforced poly(lactic acid) hybrid coatings on magnesium: characterization, mechanical and in vitro bioactivity properties. *Surf Interfaces*. 2023;37:102724. https://doi.org/10.1016/j.surfin.2023.102724.
57. Nilawar, S., Uddin, M., Chatterjee, K. Surface engineering of biodegradable implants: emerging trends in bioactive ceramic coatings and mechanical treatments. *Mat Adv*. 2021;2(24):7820–7841. https://doi.org/10.1039/D1MA00733E.
58. Eldokmak, M.M., Essawy, M.M., Abdelkader, S., et al. Bioinspired poly-dopamine/nano-hydroxyapatite: an upgrading biocompatible coat for 3D-printed polylactic acid scaffold for bone regeneration. *Odontology*. 2025;113(1):89–100. https://doi.org/10.1007/s10266-024-00945-x.
59. Zhao, F., Yang, Z., Liu, L., et al. Design and evaluation of a novel sub-scaffold dental implant system based on the osteoinduction of micro-nano bioactive glass. *Biomat Translat*. 2020;1(1):82. https://doi.org/10.3877/cma.j.issn.2096-112X.2020.01.008.
60. Cannillo, V., Salvatori, R., Bergamini, S., et al. Bioactive glasses in periodontal regeneration: existing strategies and future prospects—a literature review. *Materials*. 2022;15(6):2194. https://doi.org/10.3390/ma15062194.
61. Ali, N., Lone, N.F., Siddiquee, A.N., et al. A novel hybrid approach to develop bioresorbable material. *J Orthopaed*. 2022;34:61–66. https://doi.org/10.1016/j.jor.2022.08.012.

62. Nogueira, D.M.B., de Oliveira Rosso, M.P., Buchaim, D.V., et al. Update on the use of 45S5 bioactive glass in the treatment of bone defects in regenerative medicine. *World J Orthoped*. 2024;15(3):204–214. https://doi.org/10.5312/wjo.v15.i3.204.
63. Manesh, M.B., Vatankhah, N., Manesh, F.B. Comparison of microbiota in zirconia and titanium implants: a qualitative systematic review. *Int Dent J*. 2025;75(1):51–58. https://doi.org/10.1016/j.identj.2024.08.001.
64. Zhang, L.C., Chen, L.Y., Wang, L. Surface modification of titanium and titanium alloys: technologies, developments, and future interests. *Adv Eng Mat*. 2020;22(5):1901258. https://doi.org/10.1002/adem.201901258.
65. Losic, D. Advancing of titanium medical implants by surface engineering: recent progress and challenges. *Expert Opinion Drug Deliv*. 2021;18(10):1355–1378. https://doi.org/10.1080/17425247.2021.1928071.
66. Li, M., Cokic, S., Van Meerbeek, B., et al. Novel zirconia ceramics for dental implant materials. *J Mat Sci Technol*. 2025;210:97–108. https://doi.org/10.1016/j.jmst.2024.05.041.
67. Hong, G., Liao, M., Wu, T., et al. Improving osteogenic activity of Y-TZP (Yttria-stabilized tetragonal zirconia polycrystal) surfaces by grafting of silanes with different end groups. *App Surf Sci*. 2021;570:vp. https://doi.org/10.1016/j.apsusc.2021.151144.
68. Fiorin, L., Moris, I.C., Faria, A.C., et al. Effect of different grinding protocols on surface characteristics and fatigue behavior of yttria-stabilized zirconia polycrystalline: an in vitro study. *J Prosth Dent*. 2020;124(4):486.e1–486.e8. https://doi.org/10.1016/j.prosdent.2020.03.016.
69. Dobrzyńska-Mizera, M., Dodda, J.M., Liu, X., et al. Engineering of bioresorbable polymers for tissue engineering and drug delivery applications. *Adv Healthcare Mat*. 2024;13(30):e2401674. https://doi.org/10.1002/adhm.202401674.
70. Narayanan, S., Singh, M., Kandasubramanian, B. Innovative approaches in regenerative medicine for the development of sustainable and bioactive implants. *Biomed Mat Devices*. 2025;1–25. https://doi.org/10.1007/s44174-025-00397-z.
71. Chio, A., Mak, A. The digital workflow in implant dentistry. In *Prac Proc Implant Dent*. Ho, C.C.K. John Wiley: Hoboken, NJ, USA; 2021; pp. 335-349. https://doi.org/10.1002/9781119399186.ch34.
72. Pradies, G., Morón-Conejo, B., Martínez-Rus, F., et al. Current applications of 3D printing in dental implantology: a scoping review mapping the evidence. *Clin Oral Implants Res*. 2024;35(8):1011–1032. https://doi.org/10.1111/clr.14198.
73. Papaspyridakos, P., Chen, Y.W., Alshawaf, B., et al. Digital workflow: in vitro accuracy of 3D printed casts generated from complete-arch digital implant scans. *J Prosth Dent*. 2020;124(5):589–593. https://doi.org/10.1016/j.prosdent.2019.10.029.
74. Altalhi, A.M., Alharbi, F.S., Alhodaithy, M.A., et al. The impact of artificial intelligence on dental implantology: a narrative review. *Cureus*. 2023;15(10):e47941. https://doi.org/10.7759/cureus.47941.
75. Macrì, M., D'Albis, V., D'Albis, G., et al. The role and applications of artificial intelligence in dental implant planning: a systematic review. *Bioengineering*, 2024;11(8):778. https://doi.org/10.3390/bioengineering11080778.
76. Wu, Z., Yu, X., Wang, F., et al. Application of artificial intelligence in dental implant prognosis: a scoping review. *J Dent*. 2024;144:104924. https://doi.org/10.1016/j.jdent.2024.104924.
77. Revilla-León, M., Gómez-Polo, M., Vyas, S., et al. Artificial intelligence applications in implant dentistry: A systematic review. *J Prosth Dent*. 2023;129(2):293–300. https://doi.org/10.1016/j.prosdent.2021.05.008.
78. Alqutaibi, A.Y., Algabri, R.S., Elawady, D., et al. Advancements in artificial intelligence algorithms for dental implant identification: a systematic review with meta-analysis. *J Prosth Dent*. 2025;134(4):1089–1098. https://doi.org/10.1016/j.prosdent.2023.11.027.
79. Tomohisa O, Kamio T, Maeda Y, et al. Application of medical imaging and 3D printing technology in teaching the handling of novel medicine in periodontal surgery. *Cureus*. 2022;14(9):e29271. https://doi.org/10.7759/cureus.29271.
80. Zaheer, M.U., Razzaq, M.H., Aycan, M.F., et al. AI-assisted design and evaluation of SLM-Ti64 implants for enhanced bone regeneration. *Adv Healthcare Mat*. 2025;e03154. https://doi.org/10.1002/adhm.202503154.
81. Joshi, N., Patil, S., hatrak, P. March design and development of porous titanium alloy dental implant: a review. *AIP Conf Proc*. 2025;3227(1):020007. https://doi.org/10.1063/5.0241968.
82. Chen, Z., Liu, Y., Xie, X., et al. Influence of bone density on the accuracy of artificial intelligence-guided implant surgery: an in vitro study. *J Pros Dent*. 2024;131(2):254–261. https://doi.org/10.1016/j.prosdent.2021.07.019.

83. Zaww, K., Abbas, H., Sáenz, J.R.V., et al. AI-driven innovations for dental implant treatment planning: a systematic review. *J Pros Res*. 2025. https://doi.org/10.2186/jpr.JPR_D_24_00338.
84. Verma, A., Singh, S.V., Arya, D., et al. Mechanical failures of dental implants and supported prostheses: a systematic review. *J Oral Biol Craniofac Res*. 2023;13(2):306–314. https://doi.org/10.1016/j.jobcr.2023.02.009.
85. Romanos, G.E., Fischer, G.A., Delgado-Ruiz, R. Titanium wear of dental implants from placement, under loading and maintenance protocols. *Int J Mol Sci*. 2021;22(3):1067. https://doi.org/10.3390/ijms22031067.
86. Kashi, A., and Saha, S. Failure mechanisms of medical implants and their effects on outcomes. In: *Biointegration of medical implant materials*. Sharma, C.P. Woodhead Publishing: Cambridge, UK; 2020; pp. 407–432. https://doi.org/10.1016/B978-0-08-102680-9.00015-9.
87. Gherde, C., Dhatrak, P., Nimbalkar, S., et al. A comprehensive review of factors affecting fatigue life of dental implants. *Mat Today Proc*. 2021;43:1117–1123. https://doi.org/10.1016/j.matpr.2020.08.414.
88. Markarian, R.A., Galles, D.P., França, F.M. Dental implant-abutment fracture resistance and wear induced by single-unit screw-retained CAD components fabricated by four CAM methods after mechanical cycling. *J Pros Dent*. 2022;128(3):450–457. https://doi.org/10.1016/j.prosdent.2020.08.052.
89. Sailer, I., Karasan, D., Todorovic, A., et al. Prosthetic failures in dental implant therapy. *Periodontol 2000*. 2022;88(1):130–144. https://doi.org/10.1111/prd.12416.
90. Chen, L., Tong, Z., Luo, H., et al. Titanium particles in peri-implantitis: distribution, pathogenesis and prospects. *Int J Oral Sci*. 2023;15(1):49. https://doi.org/10.1038/s41368-023-00256-x.
91. Ossowska, A., and Zieliński, A. The mechanisms of degradation of titanium dental implants. *Coatings*. 2020;10(9):836. https://doi.org/10.3390/coatings10090836.
92. Saha, S., and Roy, S. Metallic dental implants wear mechanisms, materials, and manufacturing processes: a literature review. *Materials*. 2022;16(1):161. https://doi.org/10.3390/ma16010161.
93. Souza, J.C., Apaza-Bedoya, K., Benfatti, C.A., et al. A comprehensive review on the corrosion pathways of titanium dental implants and their biological adverse effects. *Metals*. 2020;10(9):1272. https://doi.org/10.3390/met10091272.
94. Rodríguez-Rojas, F., Kovylina, M., Pinilla-Cienfuegos, E., et al. Effect of a DLC film on the sliding-wear behaviour of Ti-6Al-4V: implications for dental implants. *Surf Coat Technol*. 2023;460:129409. https://doi.org/10.1016/j.surfcoat.2023.129409.
95. Gaur, S., Agnihotri, R., Albin, S. Bio-tribocorrosion of titanium dental implants and its toxicological implications: a scoping review. *Sci World J*. 2022:4498613. https://doi.org/10.1155/2022/4498613.
96. Levin, L. Nonsurgical and surgical management of biologic complications around dental implants: peri-implant mucositis and peri-implantitis. *Quintessence Int*. 2020;51(10):810–820. https://doi.org/10.3290/j.qi.a44813.
97. López-Valverde, N., Flores-Fraile, J., Ramírez, J.M., et al. Bioactive surfaces vs. conventional surfaces in titanium dental implants: a comparative systematic review. *J Clin Med*. 2020;9(7):2047. https://doi.org/10.3390/jcm9072047.
98. Eftekhar Ashtiani, R., Alam, M., Tavakolizadeh, S., et al. The role of biomaterials and biocompatible materials in implant-supported dental prosthesis. *Evid Based Comp Altern Med*. 2021:3349433. https://doi.org/10.1155/2021/3349433.
99. Ngo, H.X., Bai, Y., Sha, J., et al. A narrative review of u-HA/PLLA, a bioactive resorbable reconstruction material: applications in oral and maxillofacial surgery. *Materials*. 2021;15(1):150. https://doi.org/10.3390/ma15010150.
100. Sonaye, S.Y., Dal-Fabbro, R., Bottino, M.C., et al. Osseointegration of 3D-printable polyetheretherketone–magnesium phosphate bioactive composites for craniofacial and orthopedic implants. *ACS Biomat Sci Eng*. 2025;11(2):1060–1071. https://doi.org/10.1021/acsbiomaterials.4c01597.
101. Wychowański, P., Starzyńska, A., Adamska, P., et al. Methods of topical administration of drugs and biological active substances for dental implants—a narrative review. *Antibiotics*. 2021;10(8):919. https://doi.org/10.3390/antibiotics10080919.
102. Dua, R., Jones, H., Noble, P.C. Evaluation of bone formation on orthopedic implant surfaces using an ex vivo bone bioreactor system. *Sci Rep*. 2021;11(1):22509. https://doi.org/10.1038/s41598-021-02070-z.
103. Naig, P.J., Kuo, Z.Y., Chung, M.F., et al. Enhancing bone regeneration using blended poly (L-lactide-co-D, L-lactide) and β-tricalcium phosphate nanofibrous periodontal biodegradable membranes. *Polymers*. 2025;17(3):256. https://doi.org/10.3390/polym17030256.

104. Ni, X., Feng, J., Liang, M., et al. Enhancing bone repair with β-TCP-based composite scaffolds: a review of design strategies and biological mechanisms. *Orthoped Res Rev*. 2025;17:313–340. https://doi.org/10.2147/ORR.S525959.

105. Wang, W., Liu, P., Zhang, B., et al. Fused deposition modeling printed PLA/nano β-TCP composite bone tissue engineering scaffolds for promoting osteogenic induction function. *Int J Nanomed*. 2023;18:5815–5830. https://doi.org/10.2147/IJN.S416098.

106. Kucko, S.K., Raeman, S.M., Keenan, T.J. Current advances in hydroxyapatite- and β-tricalcium phosphate-based composites for biomedical applications: a review. *Biomed Mat Devices*. 2023;1(1):49–65. https://doi.org/10.1007/s44174-022-00037-w.

107. Abodunrin, O.D., El Mabrouk, K., Bricha, M. A review on borate bioactive glasses (BBG): effect of doping elements, degradation, and applications. *J Mat Chem B*. 2023;11(5):955–973. https://doi.org/10.1039/D2TB02505A.

108. Chand, P., Malik, M., Prasad, T. Bioactive glass for applications in implants: a review. *Chem Select*. 2024;9(29):e202304337. https://doi.org/10.1002/slct.202304337.

109. Huang, C., Yu, M., Li, H., et al. Research progress of bioactive glass and its application in orthopedics. *Adv Mat Interfaces*. 2021;8(22):2100606. https://doi.org/10.1002/admi.202100606.

110. Al-Harbi, N., Mohammed, H., Al-Hadeethi, Y., et al. Silica-based bioactive glasses and their applications in hard tissue regeneration: a review. *Pharmaceuticals*. 2021;14(2):75. https://doi.org/10.3390/ph14020075.

111. Zhang, X., Zeng, D., Li, N., et al. Functionalized mesoporous bioactive glass scaffolds for enhanced bone tissue regeneration. *Sci Rep*. 2016;6:19361. https://doi.org/10.1038/srep19361.

112. de Lima Barbosa, R., Stellet Lourenço, E., de Azevedo dos Santos, J.V., et al. The effects of platelet-rich fibrin in the behavior of mineralizing cells related to bone tissue regeneration—a scoping review of in vitro evidence. *J Funct Biomat*. 2023;14(10):503. https://doi.org/10.3390/jfb14100503.

113. Blanco, J., García, A., Hermida-Nogueira, L., et al. How to explain the beneficial effects of leukocyte-and platelet-rich fibrin. *Periodontol 2000*. 2025;97(1):74–94. https://doi.org/10.1111/prd.12570.

114. Farshidfar, N., Apaza Alccayhuaman, K.A., Estrin, N.E., et al. Advantages of horizontal centrifugation of platelet-rich fibrin in regenerative medicine and dentistry. *Periodontol 2000*. 2025. https://doi.org/10.1111/prd.12625. Epub ahead of print. PMID: 40130760.

115. Tarallo, F., Mancini, L., Pitzurra, L., et al. Use of platelet-rich fibrin in the treatment of grade 2 furcation defects: systematic review and meta-analysis. *J Clin Med*. 2020;9(7):2104. https://doi.org/10.3390/jcm9072104.

116. Hwan Jung, M., Hun Lee, J., Wadhwa, P., et al. Bone regeneration in peri-implant defect using autogenous tooth biomaterial enriched with platelet-rich fibrin in animal model. *App Sci*. 2020;10(6):1939. https://doi.org/10.3390/app10061939.

117. On, S.W., Park, S.Y., Yi, S.M., et al. Current status of recombinant human bone morphogenetic protein-2 (rh-BMP-2) in maxillofacial surgery: should it be continued? *Bioengineering*. 2023;10(9):1005. https://doi.org/10.3390/bioengineering10091005.

118. Aghaloo, T., Valentini, P., Yardley, R., et al. Application of biologics in maxillary sinus augmentation surgery: a narrative review. *Clin Implant Dent Related Res*. 2025;27(3):e70004. https://doi.org/10.1111/cid.70004.

119. Soares, C.S., Babo, P.S., Faria, S., et al. Standardized platelet-rich fibrin (PRF) from canine and feline origin: an analysis on its secretome pattern and architectural structure. *Cytokine*. 2021;148:155695. https://doi.org/10.1016/j.cyto.2021.155695.

120. Nemcakova, I., Litvinec, A., Mandys, V., et al. Coating Ti-6Al-4V implants with nanocrystalline diamond functionalized with BMP-7 promotes extracellular matrix mineralization in vitro and faster osseointegration in vivo. *Sci Rep*. 2022;12(1):5264. https://doi.org/10.1038/s41598-022-09183-z.

121. Afrashtehfar, K.I., Abuzayeda, M.A., Murray, C.A. Artificial intelligence in reconstructive implant dentistry—current perspectives. *Prosthesis*. 2024;6(4):767–769. https://doi.org/10.3390/prosthesis6040054.

122. Memon, A.R., Li, J., Egger, J., et al. A review on patient-specific facial and cranial implant design using artificial intelligence (AI) techniques. *Expert Rev Med Devices*. 2021;18(10):985–994. https://doi.org/10.1080/17434440.2021.1969914.

123. Hu, C., Li, F., Wang, S., et al. The role of artificial intelligence in enhancing personalized learning pathways and clinical training in dental education. *Cogent Edu*. 2025;12(1):2490425. https://doi.org/10.1080/2331186X.2025.2490425.

124. Pitchika, V., Büttner, M., Schwendicke, F. Artificial intelligence and personalized diagnostics in periodontology: a narrative review. *Periodontol 2000*. 2024;95(1):220–231. https://doi.org/10.1111/prd.12586.

125. Kumar, N.V., Chakradhar, D., Abhilash, P.M. Advancing bioimplant manufacturing through artificial intelligence. In: *Bioimplants manufacturing*. 1st ed.; M, P.A., Gajrani, K.K., eds. CRC Press: Boca Raton, USA; 2024; pp. 284–312. https://doi.org/10.1201/9781003509943-13.

126. Najeeb, M., and Islam, S. Artificial intelligence (AI) in restorative dentistry: current trends and future prospects. *BMC Oral Health*. 2025;25(1):592. https://doi.org/10.1186/s12903-025-05989-1.

127. Elgarba, B.M., Fontenele, R.C., Tarce, M., et al. Artificial intelligence serving pre-surgical digital implant planning: a scoping review. *J Dent*. 2024;143:104862. https://doi.org/10.1016/j.jdent.2024.104862.

128. Yan, B., Zhang, W., Cai, L., et al. Optics-guided robotic system for dental implant surgery. *Chin J Mech Eng*. 2022;35(1):55. https://doi.org/10.1186/s10033-022-00732-1.

129. Huang, Y.C., Huang, Y.C., Ding, S.J. Primary stability of implant placement and loading related to dental implant materials and designs: a literature review. *J Dent Sci*. 2023;18(4):1467–1476. https://doi.org/10.1016/j.jds.2023.06.010.

130. Aiquel, L.L., Pitta, J., Antonoglou, G.N., et al. Does the timing of implant placement and loading influence biological outcomes of implant-supported multiple-unit fixed dental prosthesis—a systematic review with meta-analyses. *Clin Oral Implants Res*. 2021;32(Suppl 21):5–27. https://doi.org/10.1111/clr.13860.

131. D'Amico, C., Bocchieri, S., Sambataro, S., et al. Occlusal load considerations in implant-supported fixed restorations. *Prosthesis*. 2020;2(4):252–265. https://doi.org/10.3390/prosthesis2040023.

132. Zhao, G., Zhou, Y., Shi, S., et al. Long-term clinical outcomes of immediate loading versus non-immediate loading in single-implant restorations: a systematic review and meta-analysis. *Int J Oral Maxillofac Surg*. 2022;51(10):1345–1354. https://doi.org/10.1016/j.ijom.2022.03.057.

133. Francisco, H., Marques, D., Pinto, C., et al. Is the timing of implant placement and loading influencing esthetic outcomes in single-tooth implants?—a systematic review. *Clin Oral Implant Res*. 2021;32(Suppl 21):28–55. https://doi.org/10.1111/clr.13811.

134. Pardo-Zamora, G., Ortiz-Ruíz, A.J., Camacho-Alonso, F., et al. Short dental implants (≤ 8.5 mm) versus standard dental implants (≥10 mm): a one-year post-loading prospective observational study. *Int J Environ Res Public Health*. 2021;18(11):5683. https://doi.org/10.3390/ijerph18115683.

135. Yang, Q., Guan, X., Wang, B., et al. Implant survival rate and marginal bone loss with the all-on-4 immediate-loading strategy: a clinical retrospective study with 1 to 4 years of follow-up. *J Prost Dent*. 2023;130(6):849–857. https://doi.org/10.1016/j.prosdent.2021.12.020.

136. Valera-Jiménez, J.F., Burgueño-Barris, G., Gómez-González, S., et al. Finite element analysis of narrow dental implants. *Dent Mat*. 2020;36(7):927–935. https://doi.org/10.1016/j.dental.2020.04.013.

137. Atieh, M.A., Almutairi, Z., Amir-Rad, F., et al. A retrospective analysis of biological complications of dental implants. *Int J Dent*. 2022;2022:1545748. https://doi.org/10.1155/2022/1545748.

138. Chochlidakis, K., Ercoli, C., Einarsdottir, E., et al. Implant survival and biologic complications of implant fixed complete dental prostheses: an up to 5-year retrospective study. *J Prost Dent*. 2022;128(3):375–381. https://doi.org/10.1016/j.prosdent.2020.12.011.

139. Monje, A., and Nart, J. Management and sequelae of dental implant removal. *Periodontol 2000*. 2022;88(1):182–200. https://doi.org/10.1111/prd.12418.

140. Thoma, D.S., Gil, A., Hämmerle, C.H., et al. Management and prevention of soft tissue complications in implant dentistry. *Periodontol 2000*. 2022;88(1):116–129. https://doi.org/10.1111/prd.12415.

141. Kotsakis, G.A., and Romanos, G.E. Biological mechanisms underlying complications related to implant site preparation. *Periodontol 2000*. 2022;88(1):52–63. https://doi.org/10.1111/prd.12410.

142. Adler, L., Buhlin, K., Jansson, L. Survival and complications: a 9-to 15-year retrospective follow-up of dental implant therapy. *J Oral Rehab*. 2020;47(1):67–77. https://doi.org/10.1111/joor.12866.

143. Tsigarida, A., Chochlidakis, K., Fraser, D., et al. Peri-implant diseases and biologic complications at implant-supported fixed dental prostheses in partially edentulous patients. *J Prosthodont*. 2020;29(5):429–435. https://doi.org/10.1111/jopr.13165.

144. Silva, R.C., Agrelli, A., Andrade, A.N., et al. Titanium dental implants: an overview of applied nanobiotechnology to improve biocompatibility and prevent infections. *Materials*. 2022;15(9):3150. https://doi.org/10.3390/ma15093150.

145. Wychowański, P., Starzyńska, A., Adamska, P., et al. Methods of topical administration of drugs and biological active substances for dental implants—a narrative review. *Antibiotics*. 2021;10(8):919. https://doi.org/10.3390/antibiotics10080919.

146. Karlsson, K., Derks, J., Wennström, J.L., et al. Occurrence and clustering of complications in implant dentistry. *Clin Oral Implants Res*. 2020;31(10):1002–1009. https://doi.org/10.1111/clr.13647.

147. Roccuzzo, A., Imber, J.C., Marruganti, C., et al. Clinical outcomes of dental implants in patients with and without history of periodontitis: a 20-year prospective study. *J Clin Periodontol*. 2022;49(12):1346–1356. https://doi.org/10.1111/jcpe.13716.

148. D'Ambrosio, F., Amato, A., Chiacchio, A., et al. Do systemic diseases and medications influence dental implant osseointegration and dental implant health? An umbrella review. *Dent J*. 2023;11(6):146. https://doi.org/10.3390/dj11060146.

149. Urban, I., Sanz-Sánchez, I., Monje, A., et al. Complications and treatment errors in peri-implant hard tissue management. *Periodontol 2000*. 2023;92(1):278–298. https://doi.org/10.1111/prd.12472.

150. Cortes-Breton Brinkmann, J., García-Gil, I., Pedregal, P., et al. Long-term clinical behavior and complications of intentionally tilted dental implants compared with straight implants supporting fixed restorations: a systematic review and meta-analysis. *Biology*. 2021;10(6):509. https://doi.org/10.3390/biology10060509.

151. Lampkin, A., Bensoussan, J., Curtis, D., et al. Effect of self-reported clinician experience level on perceptions of the relative rankings of risk factors for biological complications with dental implant therapy. *J Prosth Dent*. 2025;133(1):209–214. https://doi.org/10.1016/j.prosdent.2023.03.019.

152. Schwarz, F., and Ramanauskaite, A. It is all about peri-implant tissue health. *Periodontol 2000*. 2022;88(1):9–12. https://doi.org/10.1111/prd.12407.

153. Dioguardi, M., Spirito, F., Quarta, C., et al. Guided dental implant surgery: systematic review. *J Clin Med*. 2023;12(4):1490. https://doi.org/10.3390/jcm12041490.

154. Schierz, O., and Reissmann, D.R. Dental patient-reported outcomes—the promise of dental implants. *J Evid Dent Pract*. 2021;21(1):101541. https://doi.org/10.1016/j.jebdp.2021.101541.

155. Wang, I.C., Barootchi, S., Tavelli, L., et al. The peri-implant phenotype and implant esthetic complications. Contemporary overview. *J Esthet Restor Dent*. 2021;33(1):212–223. https://doi.org/10.1111/jerd.12709.

156. Cervino, G., Meto, A., Fiorillo, L., et al. Surface treatment of the dental implant with hyaluronic acid: an overview of recent data. *Int J Environ Res Public Health*. 2021;18(9):4670. https://doi.org/10.3390/ijerph18094670.

157. Comino-Garayoa, R., Cortés-Bretón Brinkmann, J., Peláez, J., et al. Allergies to titanium dental implants: what do we really know about them? A scoping review. *Biology*. 2020;9(11):404. https://doi.org/10.3390/biology9110404.

158. Cortellini, P., Stalpers, G., Mollo, A., et al. Periodontal regeneration versus extraction and dental implant or prosthetic replacement of teeth severely compromised by attachment loss to the apex: a randomized controlled clinical trial reporting 10-year outcomes, survival analysis and mean cumulative cost of recurrence. *J Clin Periodontol*. 2020;47(6):768–776. https://doi.org/10.1111/jcpe.13289.

159. Barrak, F.N., Li, S., Muntane, A.M., et al. Particle release from implantoplasty of dental implants and impact on cells. *Int J Implant Dent*. 2020;6(1):50. https://doi.org/10.1186/s40729-020-00247-1.

160. Agliardi, E.L., Panigatti, S., Romeo, D., et al. Clinical outcomes and biological and mechanical complications of immediate fixed prostheses supported by zygomatic implants: a retrospective analysis from a prospective clinical study with up to 11 years of follow-up. *Clin Implant Dent Related Res*. 2021;23(4):612–624. https://doi.org/10.1111/cid.13017.

161. Omori, Y., Lang, N.P., Botticelli, D., et al. Biological and mechanical complications of angulated abutments connected to fixed dental prostheses: a systematic review with meta-analysis. *J Oral Rehab*. 2020;47(1):101–111. https://doi.org/10.1111/joor.12877.