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Review Article

SURFACE MODIFICATION OF DENTAL IMPLANTS - A NARRATIVE REVIEW

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ABSTRACT

The dental implants have proven to be the most desired method of a replacement of the missing teeth, with the success rates of the dental implants reported to be between 90-99 per cent in the existing literature. Osseointegration, which is the close structural and functional bonding of viable bone tissue and the implant surface, is the key to the sustained performance of an implant. Surface modification has become the primary approach to improving the process of osseointegration, reducing the risk of peri-implant infections, and extending the total lifespan of implants. This narrative review will cover the history, classification, mechanism, and clinical outcomes of the surface modification methods of dental implants. Those methods covered in the review are subtractive techniques, like machining, sandblasting, and acid-etching, additive techniques, like hydroxyapatite (HA) coating and titanium plasma spraying (TPS), chemical techniques, including anodization, alkali treatment, and fluoride incorporation, and biochemical functionalization with growth factors, peptides, and drug-eluting systems. State-of-the-art technologies, such as nanoengineering, laser surface texturing, zirconia and PEEK modifications along with antimicrobial approaches are also discussed. Existing literature invariably advocates moderately rough surfaces (Ra = 102µm) as the most preferable in bone-implant contact, and the multifunctional coating of osteogenic and antibacterial properties as the future of the science of implant surfaces.

Keywords: Dental Implants, Surface Modification, Osseointegration, Hydroxyapatite, Titanium, Zirconia.

INTRODUCTION

Dental implants are considered to be one of the greatest advances in modern restorative dentistry which provide the patients with prosthetic tooth replacement that is closest to the form and functionality of natural teeth. Ever since the term osseointegration was coined by Per-Ingvar Brånemark in the 1960s, the field has expanded at an extremely quick rate, stimulated by innovation in biomaterials, surgical technique, and implant design (Branemark *et al.,* 1977). The dental implant market is also expected to increase in the worldwide market by a compound annual growth rate (CAGR) of 9.8% between 2024 and 2030 to USD 9.62 billion, which is already indicative of the growing clinical demand and patient acceptance (Kunrath *et al.,* 2022). An elaborate combination of factors unique to the patient, the condition during surgery, the design of the prosthesis, and, most importantly, the aspect of the implant surface, defines the implant success. The surface is the biological interface, where the process of osseointegration occurs: it regulates the adsorption of proteins, osteoprogenitor cell adhesion, and finally osteoneogenesis (Shayeb *et al*., 2024)· Smooth machined surfaces that defined the first-generation implants delivered satisfactory outcomes though steadily growing evidence indicated that moderately rough surfaces demonstrated significantly better bone-to-implant contact (BIC), enhanced biomechanical stability and accelerated healing (Coelho *et al*., 2015).

Surface modification refers to any deliberate change of the chemical composition, topography, surface energy or biological activity of an implant surface. All these interventions can be generalized into physical, chemical or biochemical methods and can be implemented either in subtractive (removal of material) or additive (deposition of material) process. (Qin *et al*., 2023). The aim is to create a

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state of affairs that promotes fast and sustainable osseointegration and at the same time prevents the development of bacteria, which is the main cause of peri-implantitis and late implant failure (Bakitian, 2024). The paper is a synthesis of in vitro, in vivo, and clinical studies, which were released in the last 40 years, and provides a comprehensive and well-structured description of dental implant surface modification (Figure 1). Special attention is given to the biological explanations of each of the methods, their comparative clinical results and future research directions.

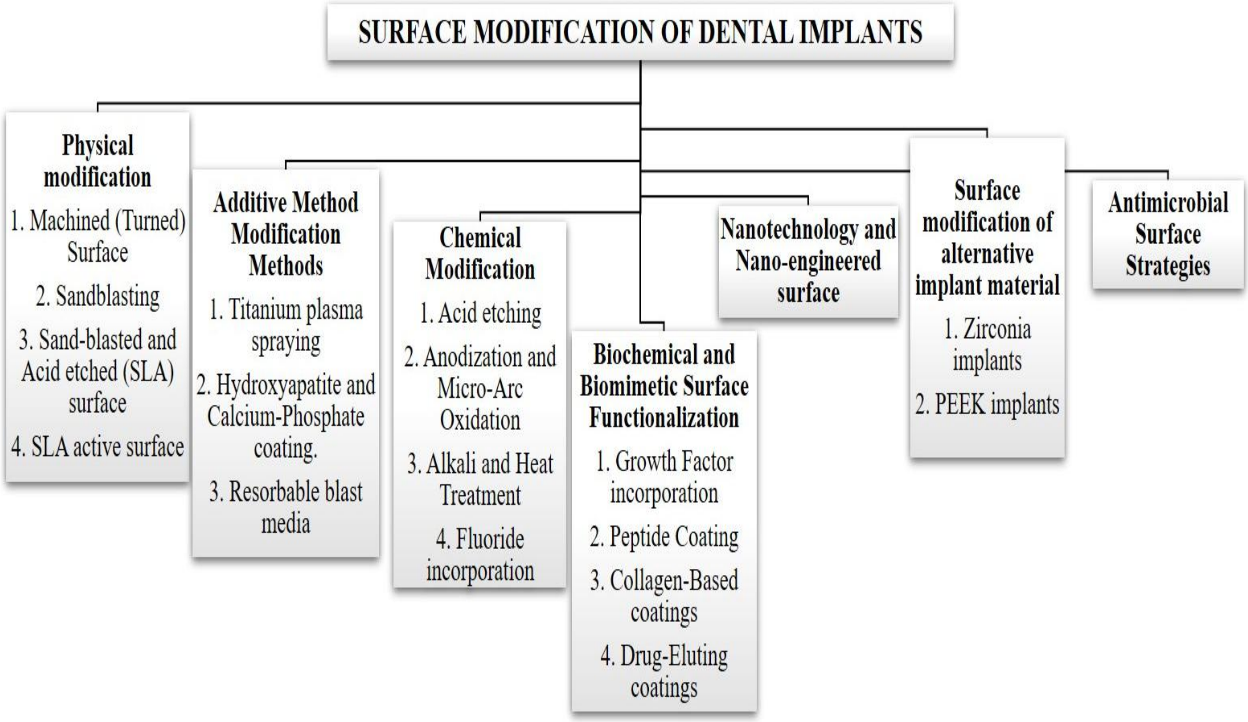

Figure 1. Surface modification of dental implants.

Biological Basis of Osseointegration and the Role of the Surface

Osseointegration is described as direct structural and functional connection between bone and the surface of a load-bearing implant at the light-microscopic level (Branemark *et al.,* 1977). It follows several overlapping steps, including an initial hemostatic and inflammatory reaction during the first hours of the implant placement, angiogenesis and mesenchymal stem cell (MSC) migration and finally woven bone deposition. These phases are greatly affected by the surface of the implant. After insertion, a film of plasma proteins (fibronectin, vitronectin, fibrinogen and albumin) adsorbs to the surface in milliseconds to form a biological interface that determines osteoblast adhesion, proliferation and differentiation (Shayeb *et al.,* 2024). The traditional way of quantifying surface roughness is with the average roughness parameter Ra (Roughness average) or (Sa on three-dimensional surfaces). Mediator Surface roughness (Ra = 1-2μm) has consistently been found to be optimal to support the process of osseointegration: too smooth surfaces do not mechanically interlock well, whereas too rough surfaces prevent the spreading of cells and harbor bacteria, thus slowing down the initial phases of osseointegration.

PHYSICAL SURFACE MODIFICATION METHODS

Machined (Turned) Surfaces

First commercially obtained implants had machined titanium surfaces created by traditional turning. The surfaces are smooth (Ra < 0.5 μm) and provide low surface area for cell adherence. Even though clinical trials had reported acceptable long-term survival rates, machined implants were found to have much lower BIC values and longer healing periods compared to subsequently roughened surfaces.

Sandblasting

Sandblasting (grit-blasting) is a technique of directing high velocity abrasive particles, most commonly aluminum oxide (Al_2O_3), silicon carbide (SiC), titanium dioxide (TiO_2), or hydroxyapatite, on the implant surface. This process provides a three-dimensional microroughness characterized by sharp peaks and valleys that increase the surface area of biological contact (Jambhulkar *et al.,* 2023). The size, composition, blasting pressure, and the impact angle of the particle all affect the resulting surface properties. Leftover abrasive particles on the titanium surface after the sandblasting can be potential cause of concern, as the particles can disrupt the osseointegration process and cause inflammatory reactions on exposure to the peri-implant tissues (Bakitian *et al.,* 2024).

Sandblasted and Acid-Etched (SLA) Surfaces

Large-grit sandblasting with subsequent acid etching, i.e. SLA (Sandblasted, Large-grit, Acid-etched) technique, is currently one of the most commonly used procedures of surface modification worldwide. This two-step procedure produces a hierarchical surface topography composed of both micro-scale roughness through sandblasting and nano-scale roughness through etching, which also result in a surface roughness average of about 2.93 -1 of SLA surfaces in a vast number of studies (Velasco-Ortega *et al.,* 2025). A prospective 12-year clinical trial comparing SLA implants in 114 patients measured a cumulative survival of 96.1 per cent and a mean marginal bone loss of merely 1.18 mm, confirming the long-term reliability of this surface (Velasco-Ortega *et al.,* 2025). This surface SLA accelerates adhesion and directional proliferation of osteoblastic lineage cells, controls pseudopodial architecture (Velasco-Ortega *et al.,* 2021).

SLActive (Chemically Modified SLA) Surfaces

The SLActive surface (Institute Straumann AG, Basel, Switzerland) is based on the SLA technology: the sandblasting and acid etching are performed; after that the implant is immersed in the isotonic Sodium chloride (NaCl) solution under the nitrogen atmosphere, avoiding the air-exposure and keeping the surface hydroxyl groups intact. This makes the surface super-hydrophilic and the water contact angle is about zero degree. (as opposed to 138140 in conventional SLA) (Sayin Ozel *et al.,* 2021). Clinical and preclinical trials have revealed that SLActive enhances earlier bone apposition, reduces the time taken to achieve the process of osseointegration, and increases the implant stability quotient (ISQ) values within the first few weeks of placement (Sayin Ozel *et al.,* 2021; Scarano *et al.,* 2017). Laser treatment is a developing subtractive and thermochemical surface alteration method. Ablation and remelt of the titanium surface can be done using pulsed laser irradiation creating localized micro- and nano-scale structures that have geometry. Recent advances comprise laser-modified surfaces that enhance the benefits of increased surface area, altered oxide chemistry, and improved wettability to increase the osseointegration and biomechanical anchorage of animal models, and most importantly, ultrafast laser techniques, or laser-induced periodic surface structures (LIPSS), are self-organizing nanostructures that guide osteoblast alignment and differentiation without generating thermal heat in the surrounding material.

ADDITIVE SURFACE MODIFICATION METHODS

Titanium Plasma Spraying (TPS)

The technique involves titanium plasma spraying, which consists of applying a high-energy plasma jet to the surface of the implant, to form a porous layer (titanium molten particles) of thickness (Ra ≈ 7 µm) and large surface area. TPS was one of the oldest additive surface treatment techniques to show better osseointegration as compared to machined surfaces. TPS has however, been to a large extent replaced by SLA and calcium phosphate coatings because of the possibility of particle detachment at the interface of the coating and substrate, non-uniform coating architecture, and the lack of ease in standardization of pore morphology(Wennerberg & Albrektsson 2009) (Inchingolo *et al*., 2023).Values of TPS surface in terms of biocompatibility (around 30-40 percent) are significantly lower than the values obtained with SLA surfaces (50-60 percent) at a similar healing time(Wennerberg & Albrektsson 2009).

Hydroxyapatite (HA) and Calcium Phosphate Coatings

Hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] constitutes the principal inorganic component of bone and dentine. The use of HA or other calcium phosphate (CaP) phases to coat titanium implants to develop a bioactive surface result in a chemical bond between the bone tissue and the implant (contact osteogenesis) and a faster healing process of the BIC (early BIC) (Shayeb *et al*., 2024). Plasma spray is the most commonly used method of coating HA, although also biomimetic precipitation of simulated body fluid, sol-gel, electrochemical deposition, magnetron sputtering and the recently developed technique of laser-induced single-step coating (LISSC) can be used (Lee *et al*., 2025). Comparative in vivo of machined, SLA, resorbable blast media (RBM) and HA-coated implants revealed that implant stability quotient (ISQ) increased progressively in the healing period with HA implants over SLA controls and that bone volume (BV%) was high at 12 weeks (Lee *et al*., 2025). Systematic review and meta-analysis of bioactive surface modification such as HA coatings showed statistically significant increases in BIC with an overall mean difference of 7.29 (95% CI: 2.9411.65) and a significant increase in the longevity of the implants with an overall mean difference of 7.52 (95% CI: 3.1811.85) (Shayeb *et al*., 2024; Coelho *et al*., 2015). The risks of delamination and dissolution during the longevity of use of plasma-sprayed HA coating despite their osteogenic advantages, and the clinical results of these coating are critically dependent on the thickness of coating, crystallinity, and composition of phases (Inchingolo., *et al*., 2023). Advanced methods of forming thin, nanostructured HA coating are linked with the increased mechanical stability and more reliable long-term performance.

Resorbable Blast Media (RBM)

Resorbable blast media (RBM) employs the resorbable and biocompatible particles as the blasting media, which is usually calcium phosphate or hydroxyapatite. In contrast to aluminum oxide sandblasting, the remaining RBM particles dissolve slowly following implantation, and they give off calcium and phosphate ions that can promote localized osteogenesis. The wettability of the RBM surface is higher than the SLA surfaces and has shown good values of BIC during comparative studies (Lee *et al*., 2025).

CHEMICAL SURFACE MODIFICATION

Acid Etching

A chemical subtractive method, acid etching involves the exposure of an implant to strong acids, usually hydrofluoric (HF), nitric (HNO_3), sulphuric (H_2SO_4), or hydrochloric (HCl) acid(s). The acids dissolve surface oxides to form a homogenous topography at micro- and nano-scale consisting of pits and channels (Lee *et al*., 2025). The acid-etched surfaces have been found to be more hydrophilic compared to machined surfaces with research showing that there is more alkaline phosphatase (ALP) activity and hydroxyapatite deposition when immersed in simulated body fluid (SBF) than in control surfaces (Kligman *et al*., 2021). DAE method is an acid-etching method that utilizes sequential acid exposures to a biphasic micro-rough surface that has been implicated to result in increased reverse torque resistance and BIC in animal models (Wennerberg *et al*., 2009).

Anodization and Micro-Arc Oxidation (MAO)

The electrochemical deposition of the controlled titanium dioxide (TiO_2) on the surface of the implant is done through electrochemical anodization in the presence of an electrolyte bath in which anodic current is passed through the electrolyte bath to form the controlled titanium dioxide layer. Based on the voltage used and the electrolyte, the oxide layer may be made porous or tubular, especially by electrochemical anodization, producing ordered TiO_2 nanotube arrays (Alamoudi 2024). These nanotubes have significant enhancement of surface area, osteoblast adhesion and differentiation, and can serve as a drug or growth factor reservoir. A higher-voltage micro-arc oxidation (MAO) forms a smoother, coarser layer of oxide that includes electrolyte-derived ions (calcium, phosphorus, magnesium) which also increase bioactivity (Bakitian, 2024).

Alkali and Heat Treatment

The concentrated sodium hydroxide (NaOH) solution (alkali treatment) of titanium surfaces produces a sodium titanate hydrogel layer that is then converted into a bioactive sodium titanate or anatase phase by heat treatment at 400-800°C. This alteration forms an amorphous surface nanolayer which forms hydroxyapatite when in contact with physiological fluids and improves the ability to bond with bones (Alamoudi 2024). It has been shown that nanoscale texture created after alkali etching orientates osteoblast adhesion, directional growth, differentiation and enables efficient osseointegration of 3D-printed and conventional machined implant surfaces (Qin *et al*., 2023).

Fluoride Incorporation

Making sandblasted and acid-etched implants immersed in hydrofluoric acid (HF) solutions can make them integrate fluoride ions into the TiO_2 surface layer. Surface-modified with fluoride exhibits improved protein binding and osteoblast differentiation in mono culture, and bone apposition in animal models. The pathophysiology of this process is the development of a Titanium fluoride (TiF_4) surface compound and altered surface energy that favors early platelet activation and secretion of growth factors during the healing cascade (Bakitian, 2024).

BIOCHEMICAL AND BIOMIMETIC SURFACE FUNCTIONALIZATION

Growth Factor Incorporation

The introduction of the osteogenic growth factors onto implant surfaces is a logical solution to hasten and enhance the process of osseointegration. The bone morphogenetic proteins (BMPs) especially the BMP-2 and BMP-7 represent some of the strongest osteoinductive molecules that have been investigated as surface coats widely. A literature review established that BMP-2 combinations were particularly good in stimulating osseointegration, although dose optimization is important since excessive dosing at supraphysiological levels is linked to undesirable effects such as osteolysis and formation of ectopic bone (Shayeb *et al*., 2024). Platelet-derived growth factor (PDGF), vascular endothelial growth factor (VEGF), fibroblast growth factor (FGF) and insulin-like growth factor (IGF) are other growth factors under investigation as implant surface functionalization. VEGF is especially of interest in facilitating angiogenesis at the implant interface; it has been found to be expressed in apatite-coated surface and is related to favorable early bone development and stability of implants (Shirazi *et al*., 2022).

Peptide Coatings

It is an Oligomeric peptide-based surface functionalization system. Short bioactive sequences of peptides constituting extracellular matrix (ECM) proteins offer a diverse and chemically defined functionalization route to the surface. The most widely researched is the Arginylglycylaspartic acid (RGD) peptide, an integrin-binding domain of fibronectin, which, when coated on titanium surfaces, increases the adhesion, spreading and differentiation of osteoblasts (Bakitian 2024). Other collagen, bone sialoprotein and statherin sequence targeting peptides have shown a superior mineralization and BIC of preclinical models. Peptide coatings have excellent chemical specificity and scalability and low immunogenicity relative to protein-based counterparts.

Collagen-Based Coatings

The main organic bone mass element is collagen, which is a natural scaffold of osteoblast differentiation. Coatings of implants made of collagen have always demonstrated promise in encouraging early bone integration evidence in systematic reviews due to their ability to attract osteoprogenitor cells and give a biologically familiar microenvironment mineralization (Shayeb *et al.*, 2024). Collagen can be incorporated with HA or CaP particles to form composite biomimetic coatings which can replicate the organic-inorganic composite architecture of native bone.

Drug-Eluting Coatings

The surfaces of implants can be designed to deliver therapeutic agents in localized and sustained and controlled release. Bisphosphonates impregnated on HA-coated or polymer-coated implant surfaces have been investigated to increase bone density around the implants especially in osteoporotic patients. Statin-eluting surfaces are based on the pleiotropic osteogenic activities of statins (HMG-CoA reductase inhibitors) to promote bone formation in the implant interface. Antibiotic releasing surfaces provide localized antimicrobial prophylaxis throughout the critical first healing period, which avoids the systemic undesirable effects of parenteral antibiotics (Bakitian 2024).

NANOTECHNOLOGY AND NANOENGINEERED SURFACES

Nanotechnology has radically transformed the modification of the surfaces of implants by allowing the exact engineering of surface features at the nanometer dimension, or the same dimension in which proteins, growth factors, and cell receptors operate (Alamoudi 2024). Some of the methods used to produce nanoengineered surfaces are acid etching using solutions containing nanoparticles, anodization, sol-gel deposition, magnetron sputtering, and electrospinning. Anodized nanotube arrays of TiO_2 have received much interest: these provide a large surface area / volume ratio, allow selective adsorption of fibronectin and other adhesion proteins and were shown to promote osteoblast focal adhesion formation and increase differentiation when compared to smooth controls (Alamoudi 2024). The diameter of nanotubes has been shown to have a critical impact on cellular behavior; nanotube diameters of 15-30 nm favors osteoblast adhesion and differentiation and larger diameters (>70 nm) can induce apoptosis. Notably, TiO_2 nanotubes can be impregnated with osteoinductive/antimicrobial agents and be engineered to be released in a slow manner.

Antimicrobial surface additives Nanoparticles of silver (AgNPs) have been widely examined as antimicrobial agents. Silver nanoparticles used as AgNPs in HA, TiO_2, or zirconia-silver composite coatings release silver ions that interfere with bacterial cell membrane and cellular pathways, showing a broad-spectrum effect on peri-implantitis-related bacteria such as *Porphyromonas gingivalis* and *Staphylococcus aureus* (Zhai *et al*., 2023). Dose-dependent cytotoxicity, however, should be controlled, and the best concentrations of Ag are 0.2-2.5 mmol/L to strike the balance between antimicrobial activity and biocompatibility of osteoblasts (Zhai *et al*., 2023). The alternative antibacterial agents with increasing interest include copper (Cu) and zinc oxide (ZnO) nanoparticles. Cu ions interact with bacterial biomolecules in a manner that removes structural integrity by chelating both phosphorus and Sulphur, whereas ZnO is broad-spectrum in activity, and can be used on titanium and zirconia surfaces (Zhai *et al*., 2023) (Hosseini Hooshiar *et al*., 2024). Novel formulations such as copper-doped hollow mesoporous organosilica nanoparticle systems have been developed to scavenge reactive oxygen species (ROS) generated by Cu^{2+}, preventing collateral tissue damage while preserving antimicrobial potency (Yang *et al*., 2026).

SURFACE MODIFICATION OF ALTERNATIVE IMPLANT MATERIALS

Zirconia (ZrO_2) Implants

Zirconia (yttria-stabilized tetragonal zirconia polycrystal, Y-TZP) has also become a prospective clinically viable implant material with a high biocompatibility, excellent aesthetic qualities due to its natural white color, high mechanical strength (comparable to titanium), and reduced tendency to bacterial adhesion (because of its hydrophobic nature and its surface charge properties) (Chen *et al*., 2021). In vitro studies have demonstrated statistically significant reductions in plaque mass and thickness on both zirconia and titanium samples following 72 hours of anaerobic incubation (Chen *et al*., 2021). Regardless of these benefits, the low surface energy of zirconia inhibits cell attachment as compared to titanium that has been roughened. Surface modification of zirconia implants is a developing area of research, therefore. Methods such as sandblasting, acid etching, laser treatment and nanoparticle coating have been used. The use of silver-coated high-translucency zirconia abutments with aluminosilicate porous structures as nanoparticle carriers have been shown to be effective broad-spectrum antibacterial agents against peri-implant pathogens with preservation of osteoblast viability (Peng *et al*., 2023). ZnO layers on zirconia surfaces also exhibit dose-effective bacteria-killing properties without interfering with biocompatibility (Zhai *et al*., 2023).

Polyether-Ether-Ketone (PEEK) Implants

PEEK is a high-performance polymer with biomechanical properties more akin to cortical bone than titanium (elastic modulus 3.6 GPa versus 110 GPa in Ti), which can potentially relieve stress-shielding and peri-implant bone loss. PEEK is radiolucent, chemically resistant, and can be used with MRI and CT imaging. But it lacks biological activity and is hydrophobic, which limits its ability to integrate with bone, which severely limits its clinical use as an endosseous implant on its own (Gnanasekar *et al*., 2025). Surface modification methods of PEEK involve plasma treatment to increase the surface energy, sulfonation to add reactive functional groups and coating with HA, bioactive glass or titanium layers by the use of physical vapor deposition and magnetron sputtering. PEEK coated with Titanium Carbide (Ti_3C_2T x MXene) modified with carbon fibers has also been shown to possess better mechanical properties as well as photothermal antibacterial properties in the presence of near infrared radiation (Gnanasekar *et al*., 2025). The developments are pointing towards the possibility of having a future where composite polymer-ceramic systems that have customized surface modification are able to provide biomechanical and biological advantages that are better than titanium or ceramics.

ANTIMICROBIAL SURFACE STRATEGIES AND PERI-IMPLANTITIS PREVENTION

Peri-implantitis is a destructive bacterial infection that destroys the soft and hard tissues around a dental implant is estimated to occur in 10-47% of implants, and is the most serious biological complication in contemporary implantology (Zhang *et al*., 2025). Peri-implantitis is characterized by progressive alveolar bone resorption and inflammation of the soft tissue, which is mainly provoked by the development of biofilm on the implant surface by such pathogens as *Porphyromonas gingivalis*, *Tannerella forsythia, Treponema denticola* (the Socransky red complex), *Fusobacterium nucleatum* and *Aggregatibacter* (Teulé-Trull, *et al*., 2025).

Traditional methods of treatment (mechanical debridement, local and systemic antibiotics) are not consistent and may cause antibiotic resistance. A systematic review of the 2010-2023 publications revealed that there are three major types of antimicrobial implant surfaces: antimicrobial peptides (AMPs), synthetic antimicrobial molecules (polymers, antibiotics), and metallic nanoparticles (mostly, silver). The best and most permanent solution became the AMP coatings which are broad-spectrum, biocompatible, and not prone to induce resistance (Teulé-Trull, *et al*., 2025). Passive anti-biofilm properties may be provided by micro- and nano-scale surface topography itself, which decreases the amount of contact surface available to bacteria to adhesively bind to the surface. Non-contact bactericidal surfaces being investigated include nanostructured surfaces that are cicada wing topography imitators.

Titanium dioxide Photocatalyzed or MXene-based Photothermal Therapy (PTT) Photodynamic antimicrobial therapy (PACT) activated by light is the most recent strategy with promising preclinical results (Gnanasekar *et al*., 2025). Another newly developing area is epigenetic systems, such as microRNA-based surface functionalization, which have the ability to bind particular microRNAs to stimulate the further differentiation of bone marrow stromal cells and improve the implant surface environment, representing the point of convergence between the science of gene regulation and the science of implant surfaces (Kunrath *et al*., 2022). An optimal antimicrobial implant surface must also facilitate oral environment osseointegration, inhibit early and late microbial colonization, be devoid of cytotoxicity, mechanical integrity over decades, and ideally, have self-generative or stimuli-responsive antimicrobial capacity. The key issue in the field is to establish this multifunctionality in one coating system (Zhang *et al*., 2024).

EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

The interface of implant surface science is traversed by a number of fast-moving directions. Artificial intelligence (AI) and machine learning are also used to design and optimize surface modification protocols in order to allow on-demand drug release or antimicrobial activation in response to an infection or particular healing stage, through characterization of the surface. The selective laser melting (SLM) process of three-dimensional (3D) printing produces implants with porosity customized to specific requirements and complex internal architecture that aids primary stability and facilitates vascularization. Nanoscale texture and biological activity is enhanced by post printing surface modification by sandblasting and alkali etching, and 3D-printed implants have compressive strength exceeding 6,000 N, or many times higher than physiological occlusal forces, and better osseointegration than non-porous controls (Qin *et al*., 2023).

Omics technologies (proteomics, transcriptomics, metabolomics) of the implant-host interface are giving new levels of insight into the molecular detail of how different surface modifications control the host immune response, osteoprogenitor recruitment, and microbial ecology at the peri-implant interface (Jadhav *et al*., 2026). It is possible that, using epigenetic methods that utilize the delivery of microRNA on surfaces and chromatin remodeling, the cell fate within the implant interface can be targeted with unprecedented precision (Kunrath *et al*., 2022). These developments together with the ongoing developments in nanotechnology and bio-mimetic coating design have put the field on the edge of a paradigm shift to personalized, biologically intelligent surfaces of implants with regards to anatomy of the patient, systemic health and bone quality.

CONCLUSION

Surfacing of dental implants is a dynamic and clinically critical area that has essentially transformed the implant dentistry within the last 40 years. The development of smooth machined surface to hierarchically structured biochemically active and antimicrobial multifunctional surfaces has driven the success rates of implants to 97-99% in modern practice. The reviewed evidence consistently attests that moderately rough surfaces (Ra = 1-2 μm), especially those obtained using SLA and its chemically modified counterpart SLActive, currently represent the clinical standard of osseointegration. Calcium phosphate and HA coatings have been shown to have an osteogenic benefit in defective bone states, and nanoengineering provides new opportunities to balance protein adsorption, cell signaling, and drug delivery at the nanoscale. The increased incidence of peri-implantitis has provoked an active search of antimicrobial surface solutions, and AMP coating, metallic nanoparticles, and stimuli-responsive systems show specific promise. Other materials like zirconia and PEEK when properly surface-modified provide interesting options to patients exhibiting metal sensitivities or have definite aesthetic requirements. The most important agenda in future research should be intensive, longitudinal, randomized controlled clinical trials to ensure that the large body of preclinical evidence is converted into clinical guidelines. It is likely that the best implant surface of the future will combine topographic, chemical, and biological modification in a synergistic and patient-specific way, an ambition that places surface modification squarely at the interface of materials science, cell biology, and precision medicine.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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