The role of nanotechnology in enhancing dental implant performance

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This review discusses the basic building components of zirconia (zirconium dioxide) dental implants and discusses how to change them at the surface. It also discussed how to design processes for osseointegration procedures, surface treatment, and mechanical properties. Sandblasting, acid etching, and laser processing are a few of the treatments given to change the roughness of a surface to allow cells to bond and integrate well with bordering bone tissue. Removal torque tests (RTQs) show that zirconia and titanium implants coated on their surface are more stable than uncoated zirconia surfaces. One of these surface treatments that has proved to be effective in increasing bone-implant contact and transmission of mechanical load comparable to titanium implants is nanostructured surface engineering, bioactive molecule functionalization, and ceramic layer coating. Moreover, nanotechnology has been used to create antimicrobial nanocoatings using such materials as silver nanoparticles, antibiotics, and chitosan. The nanocoatings have been seen to be effective in treating the medical conditions commonly associated with implants, such as peri-implantitis and microbial biofilms. The enhanced antimicrobial action and osteogenic stimulation of the nanocoatings render the implants safe and effective. Nanotechnology thus presents an innovation in the bio-interaction modulation of dental implants and management of subsequent medical complications from common implant systems. Finally, nanotechnology significantly improves the toughness, biocompatibility, and clinical performance of zirconia dental implants.

Keywords: Zirconia, Titanium, Dental implants, Nanocoatings, Nanotechnology

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INTRODUCTION

Modified dental implants in the field of restoration dentistry provide strong, functional, and aesthetic replacements due to the lack of teeth. Unlike regular prosthetics and bridges, dental implants provide excellent biomechanical stability and a high degree of patient satisfaction [1]. The fundamental principle underlying dental implants is bone classification, a biological process in which bone cells adhere directly to the implant's surface and form a stable, long-term connection [2]. Titanium implants have been the material of choice for decades due to their excellent biocompatibility, mechanical properties, and corrosion resistance [3]. Despite these benefits, problems such as peri-implantitis, implant failure, and long periods of healing remain critical problems [4].

Tooth loss, due to injuries, diseases, and aging, can greatly affect the patient's quality of life and chewing, aesthetics, and speech [5]. Global epidemiological studies show that complete dental loss affects up to 9.19% of the population. Traditionally, dental prostheses have been used as standard treatment. However, the development of surgical methods and biomaterials has made dental implants a favorable choice for functional and aesthetic recovery [6]. Despite its benefits, dental implants have complications. One of the most common problems is the inflammation that affects tissues surrounding the implant [7]. If this inflammation is not treated, this can cause loss of bone and implant failure. The previous study assessed the prevalence of implant inflammation, ranging from 10% to 50% of implant patients. This condition is often associated with the formation of bacterial biofilms on the surface of the implant, suppressing the immune response and accelerating bone resorption [8,9]. Various strategies have been used to improve implant success metrics. These include optimizing implant geometry, surface changes, and postoperative assistance. Mechanical conversion, preservatives, and antibiotics are often used to treat peripheral inflammation, but their long-term efficiency remains limited [10]. Furthermore, the healing time after implantation can be extended from 3 to 6 months, depending on the bone classification process. Insufficient contact with bone grafts or systemic health problems can slow healing or lead to early or slow implants [11,12]. Recent studies have revealed patient-related risk factors, such as smoking, diabetes, osteoporosis, and disease disorders in participants' history that are important for inadequate implants [13] (Fig. 1). Results in the field of materials science have led to recognition outside of titanium systems. Zirconium implants (zirconium dioxide) have favorable interest due to their preferred aesthetics (same color of tooth), mechanical resistance, and biocompatibility [14]. Furthermore, they demonstrate promising results in soft tissue integration and bone preservation associated with titanium implants [15]. Despite these benefits, zirconium implants always face problems associated with bone classification and mechanical properties under dynamic loading.

To overcome these limitations, nanotechnology has become a transformative approach to implantology. Nanosized changes to the surface of the implant, such as coatings of bioactive molecules nanostructured by ceramics or antimicrobial agents, indicate increased bone regeneration and reduced microbial colony formation [16]. Silver nanoparticles with antibiotics, chitosan, and nanofiber are one of the most studied drugs in the creation of antibacterial surfaces [17]. These nanocoatings not only remove biofilm formation, they accelerate healing and contribute to osteogenic activity [18]. Additionally, intellectual coating systems have been developed to ensure controlled release of antimicrobial agents in response to environmental stimuli such as changes in pH and the presence of bacteria. These innovations provide timely and targeted therapies and reduce the risk of antibiotic resistance while increasing implant sustainability [19]. This review aimed to highlight the important role of nanotechnology in developing dental implants and preventing complications of dental implants [20].

Types of Dental Implants
Titanium dental implant

Titanium and titanium alloy materials are widely used in orthopedic and dental implants because of their outstanding biocompatibility, adaptable machinability, and excellent stability. Advanced dental implants made from titanium exhibit high success rates and are infrequently linked to complications or failures [21]. Implants consist of a metal structure that is indirectly connected to the bone. Alloys made from titanium are used to produce dental implants because of their favorable mechanical characteristics, low density 4.5 g/cm^3, and excellent biocompatibility with bone. The primary alloy employed is known as commercially pure titanium (cpTi) [22]. This metal comes in four grades, numbered 1 through 4, based on its purity and the amount of processing oxygen present [23]. Alloying elements with titanium can be alpha-stabilizers, like aluminum, or beta-stabilizers such as vanadium, iron, nickel, and cobalt. Oxygen is a stabilizer. A few metallic elements, including zirconium, also do not affect the stability of both phases [24]. In the production of implants, titanium alloys that are either fully or predominantly used are favored due to their exceptional corrosion resistance. The processing conditions can be chosen to enhance the micro-structure, influencing mechanical properties such as strength, ductility, fatigue resistance, and fracture toughness [25].

Role of nanotechnology to improve titanium dental implants

Surface Chemistry: For both primary alloys utilized in creating implantable devices, specifically cpTi, and Ti-6Al-4V, the surfaces predominantly consist of the oxide TiO_2 [26]. The oxide layers are 4–6 nm thick and also include hydroxyl groups alongside the oxide, the specific composition of the surface is crucial for enhancing the adhesion of osteoblasts, and the oxide layer typically exhibits beneficial biological characteristics [27] (Fig. 2). Nonetheless, the body continues to identify it as an alien substance, which means that in certain situations, it can lead to the formation of fibrosis around the implant [28].

Biocompatibility of Titanium for Dental Implants: The interface between the titanium alloy implant and living bone is essential for the process of osseointegration. This area, measuring 20–50 nm, is where growth factors are secreted by bone cells, triggering the processes that lead to bone formation [30]. The first step involves the deposition of proteins from blood plasma onto the surface oxide layer. Subsequently, a fibrin matrix is created, serving as a framework for osteoblasts (the cells responsible for bone formation) [31]. In this manner, the osteoblasts deposit bone that extends to occupy the interfacial area, allowing it to develop directly against the implant surface, leading to the implant becoming Osseointegrated [32]. A significant impact of adequate osseointegration is that the implant is securely held, in contrast to situations where a fibrous capsule develops, thus offering a stable support for the prosthetic appliance in dentistry. The oxide layer on the surface significantly contributes to the effectiveness of osseointegration [33]. Denser and coarser oxide layers promote osseointegration to happen consistently and swiftly, particularly in the short term [34]. The oxide layer additionally serves to passivate the metal, thereby reducing corrosion and limiting the release of titanium ions. Different types of cells engage with titanium surfaces [35].

Binary Alloys of Titanium: Numerous metals have been combined with titanium, generally as the secondary element, to create alloys for potential application as dental implants. These encompass niobium, silver, gold, manganese, and zirconium [36]. Certain alloying elements, like silver or chromium, are likely decreased the biocompatibility of the alloy [37]. This is due to the likelihood of them releasing silver or chromium, both of which are recognized for their negative biological impacts [38].

Conversely, many of the elements utilized, like niobium and zirconium, exhibit minimal biological effects, making the resulting alloys more favorable for implantation as materials [39]. Significant research has been conducted on titanium binary alloys with zirconium; these have shown considerable variation in composition, ranging from 10% by mass zirconium to as much as 50% by mass zirconium [40]. In one research, 70% by mass zirconium, zirconium offers several benefits as a metal for alloying in this application and easily creates alloys with titanium and exhibits strong corrosion resistance; nonetheless, Ti-Zr alloys demonstrate poorer osseointegration with viable bone [41].

Multi-Component Alloys of Titanium: Elements like tin, iron, and palladium have been utilized in only a limited number of studies, while others, including zirconium, niobium, and tantalum, have been examined by multiple research teams, leading to numerous publications featuring their findings. Niobium and tantalum both enhance the stabilization of titanium's phase [42]. This allows them to serve as substitutes for vanadium in Ti-6Al-4V, and in either case, this substitution leads to a better biological compatibility of the resultant alloy. Alloys made from niobium and/or tantalum include both the alpha and beta phases [43]. The existence of the phase is especially favorable in biomedical quality titanium as it provides a low elastic modulus and enhanced corrosion resistance, leading to improved performance [44]. A widely researched multi-component titanium alloy containing niobium for bone-contact applications is Ti-6Al-7Nb. Specifically, it has been used more frequently to produce dental implants [45]. It is an alloy and was originally created for orthopedics, which possesses better mechanical qualities compared with cpTi, also has properties of resistance to corrosion, and when corrosion takes place, its biological properties are favorable, mainly due to the absence of vanadium [46].

Surface Modification of Titanium Alloys: Another method that has been widely researched for improving implant surfaces is anodic oxidation. This is an enhancement of the electrochemical process that leads to the creation of a substantial oxide layer on the metal surface [47]. The modification of such a thick oxide coating on titanium implants may enhance corrosion resistance, as well as improve the bonding of bone cells to the surface [48]. The most obvious material for implant coating is hydroxyapatite (HA), which has been used effectively in orthopedics to create so-called cementless prostheses [49]. Titanium alloy surfaces exhibit significant bioactivity and consistently support osseointegration. As a result, any enhancement provided by HA coatings must be substantial to be clinically meaningful. However, current HA coatings have not yet demonstrated improvements of sufficient magnitude [50]. Another substance that has been utilized to coat dental implants, at least for experimental study, is diamond-like carbon (DLC) [51]. It has been applied for dental implants to enhance the rate of osseointegration. This is an amorphous substance that has high inherent biocompatibility with bone and has been deposited using chemical vapour deposition onto heated cpTi abutment screws [52]. The methods of application can be adjusted to some extent, including the use of electrodeposition. Ideally, the deposition of an intermediate layer, like amorphous silicon, should be included to promote adhesion of DLC to the substrate, and the objective has been to create surfaces with better corrosion resistance and increased biocompatibility [53].

Zirconium dioxide dental implant

Zirconium dioxide appears to be an ideal material for dental implants due to its tooth-like color, its mechanical properties, and consequently its biocompatibility. Zirconium dioxide implants prevent the loss of apical bone and gingival recession that normally occurs in metal implants and also meet the request of many patients to be “metal-free” [54].

Role of nanotechnology to improve zirconium dioxide dental implants

Surface analyses: Machined zirconia, sandblasted zirconia, and SLA (Sandblasted with Large-grit particles and then Acid-etched) zirconia surfaces were assessed, and the airborne particle abrasion, and additionally by acid-etching, increased the roughness of zirconia [55]. Cell proliferation showed significantly higher values at 3 days for surface-treated zirconia as compared with machined zirconia; however, no differences were noted between the zirconia groups and SLA titanium at 6 and 12 days [56]. Surface analyses indicated that the greatest surface roughness was measured for the SLA titanium implant, followed by the sandblasted zirconia implant and the machined zirconia implant [57]. The CO2 laser created noticeable surface changes in zirconia [58].

RTQ (removal torque testing): The zirconia implants with coatings and the titanium implants showed greater RTQ than the machined zirconia implants, and the RTQ values were assessed for machined zirconia implants, sandblasted zirconia implants, and SLA titanium implants [59]. The machined zirconia implants exhibited statistically significantly lower RTQ values compared to the other 2 implant types after 8 and 12 weeks, while the SLA titanium implant demonstrated significantly higher RTQ values than the sandblasted zirconia surface at 8 weeks [60]. The mean RTQ for machined zirconia implants was 25.9 N/cm, the mean RTQ for zirconia rough implants was 40.5 N/cm, and the mean RTQ for SLA titanium implants was 105.2 N/cm [61].

Strength: The compressive strength of zirconia dental implants with a tunnel-like configuration drilled by the laser method and created that samples with tunnels create lower compressive strength 237 kg/mm2 than samples without tunnels 371.5 kg/mm2, and they concluded that zirconia blades demonstrated sufficient strength [62].

Advanced Methods of Nanotechnology for the Improvement of Dental Implants

Nanocoating Development

Choosing antimicrobial agents for nanocoating development is a favorable step that aims to guarantee both effectiveness and biocompatibility, and different antimicrobial substances like silver nanoparticles, chitosan, and antibiotics were considered [63]. Silver nanoparticles were selected because of their well-documented, wide-ranging antimicrobial characteristics and minimal toxicity at suitable concentrations [64]. Chitosan, a biopolymer known for its natural antimicrobial properties, was chosen due to its potential to improve cell adhesion and facilitate wound healing, and the antibiotics, like gentamicin, were incorporated due to their efficacy against a broad spectrum of oral pathogens [65]. The use of these agents is intended to create a versatile strategy for inhibiting bacterial colonization and biofilm development on titanium surfaces, and the use of nanocoating encompasses several critical stages [66]. The titanium surfaces were first polished and then cleaned with ultrasonic baths in acetone, ethanol, and deionized water to eliminate any organic impurities, and the titanium substrates that were cleaned underwent a surface activation process through plasma treatment to improve the adhesion of the nanocoating [67]. A chemical reduction technique was utilized for the synthesis of coatings made from silver nanoparticles, and Sodium borohydride was utilized to reduce silver nitrate in the presence of a stabilizing compound such as polyvinyl alcohol (PVA)[68]. The produced silver nanoparticles were analyzed via UV-Vis spectroscopy to verify their size and distribution, and Chitosan films were applied through a dip-coating method [69]. The titanium substrates were dipped in a chitosan solution made by dissolving chitosan powder in acetic acid, and the coated substrates were subsequently dried and crosslinked with glutaraldehyde to improve the coating's stability [70]. Nanocoating infused with antibiotics were created by embedding gentamicin within a biodegradable polymer matrix like poly (lactic-co-glycolic acid) (PLGA) [71]. The PLGA-gentamicin blend was dissolved in an appropriate solvent and deposited on the titanium surfaces through an electrospinning method, creating a nanofibrous layer with regulated antibiotic release characteristics [72].

Antimicrobial Efficacy

The nanocoating's antimicrobial effectiveness was assessed against prevalent oral pathogens, including Staphylococcus aureus and Porphyromonas gingivalis, and bacterial adhesion tests showed a notable decrease in bacterial colonization on the coated surfaces when compared to the uncoated titanium [73]. The silver nanoparticle coatings diminished S. aureus adhesion by more than 80%, but chitosan and gentamicin-loaded coatings showed comparable reductions for P. gingivalis [74]. Tests for biofilm formation further validated these results, revealing little biofilm growth on the coated surfaces, and the crystal violet assay measured biomass, showing a decrease in biofilm formation by as much as 90% relative to uncoated surfaces [75]. The comparison with uncoated titanium surfaces highlights the enhanced antimicrobial characteristics of the nanocoating, but Uncoated surfaces exhibited significant bacterial growth and biofilm development, resulting in increased colony-forming units (CFUs) [76]. In comparison, the surfaces with nanocoating greatly suppressed bacterial proliferation and biofilm formation, and this comparison highlights the efficacy of nanocoating in avoiding microbial-related problems like peri-implantitis, potentially prolonging the durability of dental implants [77].

Osseointegration Enhancement

In vitro experiments regarding cell adhesion and bone formation showed improved results for the titanium surfaces with nanocoating; human osteoblast-like cells (MG-63) showed markedly greater adhesion on the nanocoated surfaces than on regular titanium [78]. Fluorescence microscopy following DAPI staining validated heightened cell density and consistent distribution [79]. The MTT assay showed increased cell proliferation, with the nanocoated surfaces exhibiting a 40% high in cell viability compared to uncoated surfaces, and the comparative study with standard titanium implants indicated that the nanocoating significantly enhanced the osteogenic capabilities of the implants [80]. Osteogenic differentiation assays demonstrated elevated alkaline phosphatase (ALP) activity and enhanced expression of osteogenic markers like osteocalcin and collagen type I [81]. Alizarin Red S staining validated significant mineral deposition, signifying the formation of bone matrix, and these findings were confirmed by quantitative PCR, which showed a notable increase in the expression of osteogenic genes [82].

Some Problems and Solutions by Nanotechnology

Peri-implantitis

Inflammatory disorder resulting from bacterial colonization and biofilm development on implant surfaces, causing tissue inflammation and loss of bone [83]. The optimal solution is antimicrobial nanocoating, which offers advanced coatings that ensure a continuous release of antimicrobial agents to inhibit bacterial growth and biofilm development [84] (Figure 3).

Resistance to Conventional Treatments

Mechanical debridement, antiseptic washouts, and antibiotics frequently do not fully eliminate bacterial biofilms or stop recolonization [86]. The optimal solution is Silver Nanoparticles, which gradually release silver ions, creating an environment that remains unfavorable for bacterial growth for long durations [87].

Biofilm Resilience

Biofilms consist of organized bacterial populations that are extremely resistant to standard treatments, making them challenging to eliminate once formed [88]. The optimal solution is chitosan coatings, which utilize a natural biopolymer with inherent antimicrobial features that inhibit bacterial adhesion and enhance wound healing and tissue regeneration [89].

Incomplete Bacterial Removal, Recolonization, and the Development of Antibiotic Resistance

Current therapies often fail to sufficiently inhibit the reformation of biofilms, threatening the long-term success of implants [90]. Overuse of antibiotics in such treatments further contributes to the development of resistance, ultimately reducing the effectiveness of these drugs over time [91].

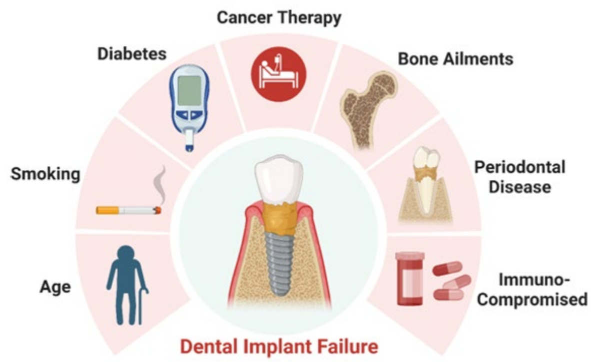

Figure 1. Patient-related risk factors, representation of ongoing conditions that can cause dental implant complications and failure, adapted from Gulati et al. [14].

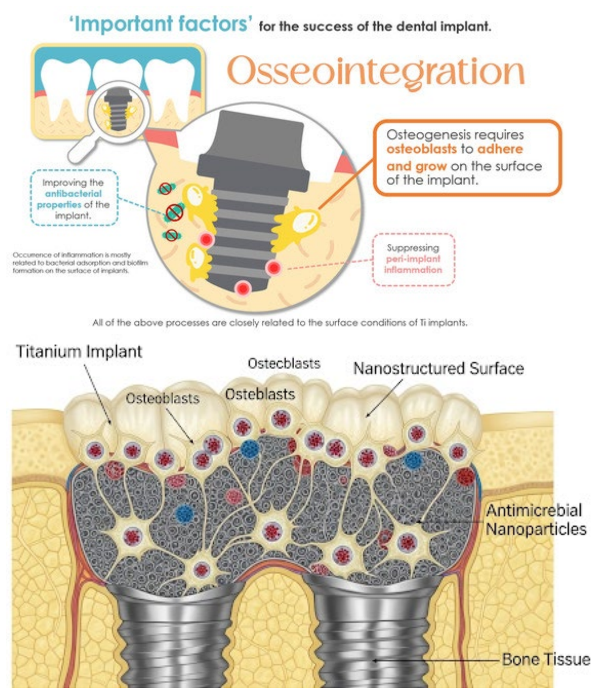

Figure 2. Titanium implant with a specially engineered nanostructured surface adapted from Tuikampee et al. [29].

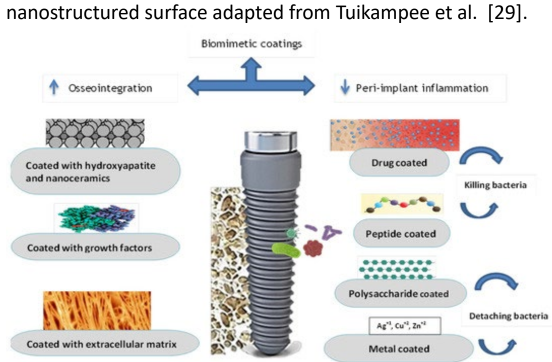

Figure 3. Surface coatings to enhance osseointegration and reduce peri-implantitis, adapted from Abdulghafor et al. [85].

An optimal solution lies in the application of antibiotic-loaded nanocoating, which enable targeted delivery and controlled release of antibiotics. This approach ensures effective bacterial elimination at the implant site while minimizing systemic side effects and reducing the risk of antibiotic resistance.

Maintenance of Implant Surface Integrity

Continuous exposure to microbial colonization, mechanical stress, and biochemical interactions can compromise implant integrity. The best solution is Surface Property Enhancements; improve the biocompatibility and mechanical properties of titanium implants through advanced surface modifications to support better osseointegration and tissue health [92].

Challenges of Dental Implants

Peri-implantitis, an inflammatory disease, is one of the largest problems in dental implantology that affects the soft and hard tissues around dental implants [93]. Peri-implantitis leads to inflammation and loss of bone around of implant and leads to failure of the implant if left untreated [94]. Between 10% and 50% of patients who replaced missing teeth with dental implants have peri-implantitis, which is a significant clinical problem. Bacterial colonization and biofilm formation on the implant surface led to disturbance in the immune response and led to bone resorption [95]. Antibiotic medication and mechanical debridement are the current state of treatment to eliminate the infection and avoid its recurrence [96]. So, we need more research to increase the long-term viability of dental implants and to avoid peri-implantitis, so the healing period (osseointegration) of dental implants takes between three to six months [97].

The success of osseointegration following implantation is essential for the success of the dental implant [98]. Progressive marginal bone loss during osseointegration occurs due to Poor implant-bone contact. After healthy osseointegration, the contact between bone and implant is durable, resilient, and resistant to bone loss in a typical environment [99]. Systemic health, bacterial infection, or trauma is the most important reason for implant failure (both early and late), which leads to the final removal of the implant [100]. The dental implant failure is divided into early failure, which refers to the failure of osseointegration of dental implants, whereas late failure refers to failure of osseointegration or the loss of function of dental implants [101]. The most significant factors that lead to early implant failure are a lack of primary stability and perioperative contamination that occur due to surgical stress. The most important variables related to late implant failure are peri-implantitis and overloading [102]. Moreover, the distinctive characteristic of dental implants is the present transmucosal portion, which penetrates the soft tissue found between the bone and the prosthesis. Soft tissue integration (STI) is the most important factor for dental implants to function in the long term, and also proper osseointegration [103]. Different methods are used with surgical and non-surgical implants to eliminate biofilms from the implant surface, and the most common non-surgical methods for treating peri-implantitis are the use of antibiotics or antiseptics, mechanical debridement methods, and laser applications [104]. In comparison, surgical techniques involve more advanced procedures, including not only debridement but also enhancement or regeneration of the affected tissues. A systematic approach should be taken when executing a non-surgical or surgical peri-implant treatment, starting with the most basic procedure and working up to a detailed treatment [105].

The physician needs to be knowledgeable about the local and systemic risk factors that could impact dental implant success to perform a thorough review of patients. The future of the implant may be impacted by the patient's social and medical habits, including smoking, osteoporosis, and diabetes [106]. Another important risk factor for implant loss is the history of periodontitis. The Patients should be taught how to change or get rid of risk factors. Without medical consultation, it is impossible to determine a patient's overall health status while dealing with systemic diseases [107].

According to the cost of adding nanomaterials to dental implant reviews, it highlights that nano-material processes (coatings, nanopatterning) introduce extra manufacturing steps and use premium materials but may be more efficient at scale. While nanoscale approaches aim to offer "high efficiency, low cost, and high volume," widespread clinical adoption (and cost-effectiveness) is still under evaluation. Based on extra materials and tech steps, expect an added cost of 10–20% per implant on top of premium standard implants $3,000–$5,000 per tooth. For full-arch systems, e.g., All-on-4/6, clinics already using advanced technologies may charge more, especially for nano-hybrid or nano-ceramic finishes, e.g., $18k–$20k/arch compared to acrylic at ~$12k [108].

Future Perspectives

There remain vast opportunities for further exploration in surface functionalization and nano-engineering to enhance implant integration, improve surface maintenance, and extend the functional lifetime of dental implants, thereby advancing patient care. The most promising direction lies in the development of intelligent, controlled-release coatings capable of responding to environmental stimuli such as pH or temperature changes, ensuring timely antimicrobial defense [109]. Future research should focus on clinical applications of nanocoatings in dental implants, exploring eco-friendly approaches such as green synthesis. Moreover, the possibility of fabricating dental implants entirely from nanomaterials presents an exciting frontier that could redefine the field of restorative dentistry.

CONCLUSION

Zirconia dental implants demonstrate favorable mechanical strength and surface properties that support osseointegration, particularly when combined with advanced surface modification treatments. Surface roughness and bioactive coatings have been shown to enhance cellular adhesion and implant stability; however, they still provide lower removal torque compared with titanium implants. The incorporation of nanotechnology into implant design offers a promising strategy for preventing bacterial colonization and biofilm formation, two major causes of implant failure. Nanocoatings with silver nanoparticles, chitosan, and antibiotic-loaded polymers not only deliver antimicrobial activity but also stimulate bone tissue regeneration. Additionally, intelligent release systems that respond to infection cues provide a targeted approach to infection control while minimizing the risk of antibiotic resistance.

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