

Surface Modifications of Dental Implants for Enhanced Antimicrobial Properties: A Literature Review

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Abstract

Dental implants are widely used in modern dentistry for tooth replacement, but bacterial infections such as peri-implant mucositis and peri-implantitis remain significant causes of implant failure. This literature review evaluates the effectiveness of surface modifications and antimicrobial coatings in reducing bacterial colonization and infection on dental implants. A comprehensive search of PubMed and Google Scholar identified 70 relevant studies, of which 56 met the inclusion criteria. The review highlights the use of antimicrobial agents such as silver, zinc, copper, fluorine, and chlorhexidine, as well as surface modifications like dendrimers, titanium dioxide photocatalysts, and ultraviolet treatment. These strategies enhance antimicrobial properties by generating reactive oxygen species, creating super-hydrophilic surfaces, and altering surface characteristics such as roughness, hydrophobicity, charge, and crystalline phase. The findings suggest that these approaches significantly reduce bacterial adhesion and biofilm formation, thereby improving implant success rates. However, further research is needed to assess the long-term clinical performance and stability of these modifications. This review highlights the crucial role of combining advanced surface modification techniques with antimicrobial approaches to improve the performance and safety of dental implants.



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Antibacterial;
 Anti-Adhesion;
 Coating;
 Dental Implants;
 Surface Modification.

Abbreviations

TiO₂

Titanium dioxide

AMPs

Antimicrobial peptides

CHX

Chlorhexidine

UV

Ultraviolet

ROS

Reactive oxygen species

AgNPs

Silver nanoparticles

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Introduction

In dental implantology, bacterial diseases of oral cavities, such as peri-implant mucositis and peri-implantitis, can result in loss of implants. Dental implants offer sub- and supragingivally located surfaces that are available to bacterial colonization. The microbiological findings show clearly that infection represents a possible etiological factor for late changes in implants.¹⁻³ Peri-implant mucositis, characterized by reversible inflammation of the soft tissues around the implant, can progress to peri-implantitis if left untreated. Peri-implantitis involves not only soft tissue inflammation but also bone resorption, leading to implant instability and potential loss.³ Beyond local effects, systemic consequences of bacterial translocation from the oral cavity are increasingly recognized. Bacteria that enter the bloodstream during dental procedures, including dental implant therapy, can potentially lead to severe systemic infections such as infective endocarditis.⁴

Bacteria residing in biofilm such as anaerobic gram-negative species including *Porphyromonas gingivalis*, *Prevotella intermedia*, and *Tannerella forsythia*, along with facultative anaerobes like *Staphylococcus aureus*, are difficult to eliminate using systemic antibiotics. To address this challenge, various anti-adhesive and antimicrobial approaches have been developed to hinder the development of mature biofilms on biomaterial surfaces by minimizing or preventing the initial stages of bacterial attachment and colonization.⁵ It includes surface coatings with dendrimers or polymeric brushes, such as poly(ethylene glycol) layers,^{6,7} surface modifications giving positive charges or turning the surface into a zwitterion layer.^{8,9} titanium implant surface antimicrobial coatings, including ionic antibacterial coating, antibiotic and organic antimicrobial coating, and substrates carrying antibacterial agents,¹⁰ and surface application of silver nanoparticles or a photocatalyst.⁵

Surface antimicrobial coatings encompass various types, such as ionic antibacterial layers, antibiotic or organic-based antimicrobial coatings, and substrates embedded with antibacterial compounds. Additionally, surface treatments utilizing silver nanoparticles or photocatalytic materials have also been used for antimicrobial purposes.⁵

Titanium implant surface modifications can provide antimicrobial materials and offer a means to superim-

pose bacterial adhesion or biosynthesis by changing the surface wettability, texture, crystal morphology, surface potential and other characteristics.¹⁰

The aim of this literature review is to explain the benefits of dental implant surface modifications acting on opportunistic microorganisms and pathogenic bacteria that can lead to an infection and thus to dental implant failure.

Materials and Methods

Scope

This review explores recent advancements in surface modification techniques for dental implants that enhance antimicrobial properties, including ionic antibacterial coating, antibiotics and organic antimicrobial coating and surface modifications, aiming to reduce bacterial adhesion and improve implant success.

Protocol Development

Three authors (Y.R, M.V and D.G) used PICO system to formulate, present and answer the question: How do the surface modifications of dental implants affect the antimicrobial properties in implant patients?

Participants (P)

Patients receiving dental implants.

Intervention or Exposure and Comparison Group (IC)

Surface modifications\coating of dental providing antimicrobial properties. Comparator: implants that did not go through surface modifications or coating prior implantation.

Outcome (O)

Reduction in bacterial adhesion, colonization or biofilm formation.

Eligibility Criteria

Inclusion Criteria

Dental Implantology

Publications In English

Antibacterial or anti-adhesive properties of the dental implant surface

Dental implant surface modification or coating

Exclusion Criteria

No surface modification or coating
No relation to implantology

modifications”, “Antimicrobial effect of dental implant surface coating” and “antimicrobial effect of dental implant surface modifications”.

Search Strategy

Two electronic databases were searched and information gathered from November 2 until December 17, 2024, as shown in table 1. In order to identify articles in the topic of interest, several related terms were used: “Dental implant surface

Publications from 1974 up to 2024 in the interest topic were gathered, duplicates were removed manually, following which the titles and abstracts of the articles were screened independently based on the predefined inclusion and exclusion criteria.

Table 1: Electronic databases and search terms.

| Electronic database | Search term |
|---------------------|--|
| PubMed | “Dental implant surface modifications”, “Antimicrobial effect of dental implant surface coating”, “antimicrobial effect of dental implant surface modifications”. |
| Google Scholar | “Dental implant surface modifications”, “Antimicrobial effect of dental implant surface coating” and “antimicrobial effect of dental implant surface modifications”. |

Data Extraction

Relevant data were individually extracted from the selected articles by three reviewers (Y.R, M.V and D.G) using separate customized charts. Information such as authors' names, year of publication, and other data relevant to the topic were categorized and

assessed within the charts. A condensed overview of the included studies is presented in Table 2, while the complete dataset, detailing all studies and their characteristics, is provided in the Supplementary Material (Table S1).

Table 2: Included study characteristics.

| Type | Number of studies | Key points\ Main findings |
|---|-------------------|--|
| Microbiology | 7 | Investigated microbial causes of implant infections such as peri-implant mucositis and peri-implantitis. Identified contamination sources including implant surfaces, surgical staff, and patient flora. Highlighted systemic risks (e.g., bacteremia, infective endocarditis). |
| Ionic Antibacterial coating | 16 | Explored metallic coatings with Ag, Zn, Cu, and F ions. Silver and zinc coatings showed strong antimicrobial activity through ion release, reactive oxygen species, and photocatalysis while maintaining biocompatibility. Copper exhibited antimicrobial and anti-inflammatory effects. Fluoride coatings (e.g., TiF ₄) inhibited <i>Streptococcus mutans</i> and <i>Bacteroides gingivalis</i> . |
| Antibiotics and organic antibiotics coating | 15 | Studied coatings using antibiotics (amoxicillin, vancomycin, gentamicin, etc.), antimicrobial peptides (AMPs), dextran, polyethylene glycol (PEG), and chlorhexidine. AMPs provided broad-spectrum antibacterial activity with low resistance risk. PEG/dextran coatings reduced protein, platelet, and bacterial |

Surface modifications 25

adhesion. Chlorhexidine coatings achieved sustained antimicrobial release on titanium surfaces. Examined physical and chemical surface treatments such as TiO₂ coatings, UV photo-functionalization, nano structuring, charge alteration, and hydrophilicity tuning. Findings showed that super-hydrophilic, negatively charged, and nano-textured Ti surfaces decrease bacterial adhesion and biofilm formation. The crystalline phase of TiO₂ (anatase, rutile, brookite) influenced photocatalytic antibacterial effects.

Results

A Flowchart was constructed using PRISMA flow diagram showing the identification, screening and selection of published materials for this review paper (see Appendix A). A total of 70 articles were found from electronic database search (PubMed and Google Scholar). Overall, 3 duplicates were removed, and 11 articles were excluded based on the inclusion and exclusion criteria. 56 publications were selected for abstract and full text analysis.

Ionic Antibacterial Coating

A total of 16 publications were selected for this review. Among them, five studies focused on silver coatings for implants, six on zinc coatings, three on copper coatings, and two on fluorine coatings. Additionally, four publications did not meet the inclusion criteria and were excluded. The implant is packaged in a sterile, air-tight container, with infections being rare due to strict medical device industry controls.¹⁰ Infections can arise from contaminated implant surfaces, surgical staff, the patient's skin or mucosa, remote infections, contaminated disinfectants, or contact with others post-procedure.^{11,12} Silver (Ag) is a powerful antimicrobial, acting through Ag⁺ ions or "contact killing," which disrupts bacterial cell walls and membranes, leading to cell death.^{13,14} Techniques for silver antimicrobial coatings include plasma spraying and electrochemical deposition.⁹ Radtke *et al.*¹⁵ developed a silver-doped titanium oxide nanotube coating, achieving 97.62% bacterial inhibition via hydroxyl radicals. Silver nanoparticles (AgNPs) enhance antimicrobial effects due to their large surface area and stable oxidative stress reactions.¹⁶ Zinc offers antimicrobial properties through ion, contact, and photocatalytic mechanisms, disrupting bacterial adhesion and membranes.¹⁷⁻²¹ Wang *et al.*²² developed a zinc-doped ZrO₂/TiO₂ coating with strong antimicrobial effects against

Staphylococcus aureus and good biocompatibility. Copper has anti-inflammatory and antimicrobial properties and is safe at proper levels.²³ Jannesari *et al.*²⁴ showed copper ions inhibit bacterial respiration and DNA. Fluorine, zinc, and copper can be added to titanium or hydroxyapatite coatings, with antimicrobial effects from gradual ion release.²⁵ Titanium tetrafluoride (TiF₄) inhibits *Streptococcus mutans* and *Bacteroides gingivalis* on teeth,²⁶ and fluoride ions on titanium surfaces effectively combat peri-implantitis bacteria.²⁷

Antibiotics and Organic Antimicrobial Coating

In the context of antimicrobial coatings, 15 publications were included in the review. Of these, eight studies examined surface treatments using conventional antibiotics and antimicrobial peptides, five focused on dextran and polyethylene glycol (PEG), and two investigated chlorhexidine. One publication did not meet the inclusion criteria and was excluded. Conventional antibiotics are used in controlled release devices but can cause resistance due to an initial burst and prolonged sub-minimal inhibitory concentration (MIC) release.²⁵ To address this, antimicrobial peptides (AMPs) offer broad-spectrum activity and reduce resistance risks by binding to bacterial membranes and targeting intracellular components.²⁸⁻³² Various coating methods, including adsorption and electrospinning, help prevent bacterial colonization on implants.^{33,34} Dextran and PEG coatings inhibit adhesion of proteins, platelets, and several types of bacteria.³⁵⁻³⁸ Ion-implanted surfaces showed 55-80% fewer bacteria than pure titanium.³⁹ Chlorhexidine (CHX) is effective against gram-positive and gram-negative bacteria in oral care.⁴⁰ Wood *et al.*⁴¹ developed a CHX nanoparticle coating with sustained antimicrobial effects against *Streptococcus gordonii* within 8 hours.

Surface Modifications

Surface modifications emerged as the most extensively studied topic, with 25 publications included in this review. Among these, three studies explored surface treatments with titanium dioxide, three investigated ultraviolet (UV) treatment, four focused on surface roughness, six examined surface charge, three analyzed surface hydrophilicity, and six assessed the impact of surface crystalline phase on antimicrobial properties. Six publications were excluded for not meeting the inclusion criteria. Pure titanium forms a biocompatible and stable titanium dioxide (TiO₂) layer in air, supporting osseointegration and offering antimicrobial properties under certain conditions.⁴² TiO₂ nanotubes reduce bacterial adhesion after UV exposure, while TiO₂ nanoparticles damage bacterial membranes via reactive oxygen species (ROS).⁴³ TiO₂ can also serve as a carrier for sustained drug release,⁹ and UV treatment decreases bacterial adhesion on implants.⁴⁴ Suketa *et al.*⁴⁵ showed that an anatase TiO₂ layer on titanium reduced *Actinobacillus actinomycetemcomitans* and *Fusobacterium nucleatum* viability to under 1% with ultraviolet A (UVA) exposure. UV-induced TiO₂ photo-functionalization creates a super-hydrophilic surface that oxidizes organic impurities for antimicrobial effects.⁴⁶ Protein adsorption on implant surfaces is influenced by hydrophobicity, roughness, and chemical composition, affecting bacterial adhesion.⁴⁷⁻⁵⁰ Bacteria often adhere to protein-coated surfaces, leading to biofilm formation through gene expression changes.⁵¹⁻⁵³ Combining biofilm-disrupting agents with antibiotics may improve outcomes, though this is rarely practiced due to chemical aggressiveness.⁵⁴ Surface smoothness reduces microbial colonization, but nano roughness can enhance protein adsorption and reduce bacterial adhesion.^{5,54} Rough surfaces increases plaque accumulation in dentistry.⁵⁵ Techniques like ion implantation, laser cladding, and anodizing create nano-scale structures.^{56,57} Surface charge and hydrophilicity affect bacterial adhesion; negatively charged and hydrophilic surfaces generally reduce bacterial attachment.^{51,52,57,58} Bacterial adhesion depends on electrostatic interactions and substrate-bacteria physicochemical properties⁵⁹ Gao *et al.*⁶⁰ linked antibacterial effects to electrostatic disturbances causing cell death. Hydrophobic interactions

drive adhesion of pathogens like *Streptococcus aureus* and *Staphylococcus epidermidis*.^{61,62} TiO₂'s crystalline forms like anatase, rutile, and brookite, all contribute to antibacterial properties through photocatalytic activity (PCA).^{54,64-66}

Across all modalities, ion-based coating provided the strongest broad-spectrum antimicrobial effect. Peptide-based coating showed excellent biofilm prevention with a low risk for antibiotic resistance. Surface roughness and charge modification improved early bacterial suppression but required combination with other modalities for stronger antimicrobial performance.

Discussion

Dental implant infections are a rare but serious complication that can arise from various sources, including contaminated implant surfaces, surgical staff, or the patient's own skin. Silver is highly effective in combating microbial contamination through ion release or direct contact killing, and silver-based coatings, including silver nanoparticles, have been developed for enhanced antimicrobial activity. Similarly, other metals like zinc and copper exhibit strong antimicrobial properties through various mechanisms, with some coatings also maintaining biocompatibility. Antimicrobial peptides offer a promising alternative to antibiotics, as they exhibit broad-spectrum activity and are less prone to inducing bacterial resistance. Titanium dioxide, commonly used in implants for its biocompatibility and photocatalytic properties, can also be utilized to reduce bacterial adhesion, especially under ultraviolet light. Furthermore, surface modifications such as nanopatterning and doping with antimicrobial agents can significantly reduce bacterial colonization and biofilm formation, thereby improving the longevity and safety of dental implants.

Ionic Antibacterial Coating

Silver (Ag) stands out as the most potent metal against microbes, exerting its antibacterial activity either through the release of Ag⁺ ions or by directly destroying microorganisms upon contact.^{13,14} Various techniques have been developed to create silver-containing antimicrobial coatings, including plasma spraying, electrochemical deposition, sol-gel processes, thermal spraying, co-sputtering, and plasma immersion ion implantation.⁹ Radtke

A *et al.*¹⁵ developed a silver-doped titanium oxide nanotube array coating by immersing the substrate in a silver nitrate solution. This modification effectively suppressed biofilm formation. Silver nanoparticles (AgNPs) have also been recognized as a promising alternative for silver-based antimicrobial coatings. AgNPs provide long-lasting and stable antimicrobial activity through oxidative stress mechanisms and the generation of reactive oxygen species.¹⁶ Similar to silver, zinc exerts its antimicrobial properties through the three mechanisms earlier described.¹⁷⁻¹⁹ Wang *et al.*²² developed a zinc-doped ZrO₂/TiO₂ coating on a Titanium/Aluminum/Vanadium alloy (Ti6Al4V) surface using a combination of magnetron sputtering and microarc oxidation. This coating demonstrated exceptional antimicrobial effectiveness against *Staphylococcus aureus* while maintaining biocompatibility and corrosion resistance. Copper is an inexpensive and readily available metal that has been utilized since ancient times, both in its pure form and as metal compounds, for its anti-inflammatory, antimicrobial, and anti-proliferative properties.²³ At appropriate levels, copper is non-toxic to humans. Research by Jannesari *et al.*²⁴ indicated that copper ions and their superoxide derivatives can disrupt bacterial respiratory processes and cause degradation of bacterial DNA, thus providing significant antimicrobial effects. Elements such as fluorine (F), zinc (Zn), and copper (Cu) can be integrated into titanium or hydroxyapatite coatings through anodic oxidation of their respective ions. The bactericidal action of these ions appears to rely on their gradual release into the surrounding environment, with one proposed mechanism for bacteriostasis being the hydroxylation into highly reactive components.²⁵ In vitro study by Skartveit *et al.*²⁶ demonstrated that titanium tetrafluoride (TiF₄) effectively inhibits the proliferation of *Streptococcus mutans* and *Bacteroides gingivalis* on tooth surfaces. Meanwhile, Yoshinari *et al.*²⁷ successfully introduced fluoride ions to the surface of pure titanium using ion accelerators, achieving effective inhibition of pathogenic bacteria associated with peri-implantitis.

Antibiotics and Organic Antimicrobial Coating

Conventional drug studies have utilized antibiotics such as amoxicillin, vancomycin, gentamicin, tetracycline, minocycline, and cephalothin, incorporated into controlled-release systems. A major issue with these antibiotics is the initial burst release, which is often followed by a sustained release at

levels below the MIC, potentially promoting the development of bacterial resistance over time.²⁵ Due to their tendency to promote drug resistance, the use of antibiotics is limited, whereas the development of AMPs offers a new strategy to address this challenge.²⁸ AMPs are short amphiphilic peptides with broad-spectrum antimicrobial activity. Their positive charge allows them to interact with negatively charged bacterial membranes via electrostatic attraction, ultimately resulting in bacterial cell death.^{29,30} Research has shown that AMPs can penetrate the bacterial cytoplasm to target intracellular components such as DNA, RNA, and proteins, thereby killing bacteria from within and affecting gene expression.^{31,32} Due to their unique antibacterial mechanisms, bacteria find it challenging to develop resistance. Various methods have been employed to coat antimicrobial peptides onto implant surfaces to prevent bacterial colonization, including adsorption, binding, electrospinning, and chemical attachment.^{33,34} Dextran and polyethylene glycol (PEG) surfaces have proven effective at inhibiting protein adhesion, platelet adhesion, bacterial adhesion, and biofilm formation by oral pathogens such as *Staphylococcus aureus*, *Streptococcus sanguinis*, *Lactobacillus salivarius*, *Streptococcus mutans*, and *Streptococcus gordonii*.³⁵⁻³⁸ Bacterial counts on ion-implanted surfaces decreased significantly compared to pure titanium.³⁹ Chlorhexidine (CHX) is a widely utilized surface disinfectant known for its effectiveness against both gram-positive and gram-negative bacteria. Consequently, it is frequently employed for local cleaning and disinfection during oral surgical procedures and oral care.⁴⁰ Wood *et al.*⁴¹ developed a chlorhexamethy hexameta-phosphate nanoparticle coating on pure titanium, with an average particle diameter of 49 nm. This coating demonstrated sustained release of CHX and exhibited antimicrobial activity against the oral primary colonizing bacterium *Streptococcus gordonii* within 8 hours.

Surface Modifications

Pure titanium rapidly develops a thin layer of titanium dioxide (TiO₂) when exposed to air, which exhibits excellent biocompatibility and chemical stability. Additionally, TiO₂ possesses antimicrobial properties under certain conditions.⁴² For instance, TiO₂ nanotubes can significantly inhibit bacterial adhesion post-ultraviolet radiation exposure, while TiO₂ nanoparticles can damage bacterial

membranes by generating ROS.⁴³ Furthermore, TiO₂ can act as a carrier for antimicrobial drugs, allowing for their sustained release from the metal.⁹ Bacterial adhesion and polymerization on implant surfaces significantly decreased after 8 hours of UV treatment.⁴⁴ In research conducted by Suketa *et al.*,⁴⁵ a thin layer of photocatalytic anatase TiO₂ was applied to the surface of pure titanium via plasma source ion implantation followed by annealing. This layer demonstrated a robust photocatalytic reaction under UVA illumination, suppressing the viability of both *Actinobacillus actinomycetemcomitans* and *Fusobacterium nucleatum* to less than 1% under UVA exposure within 120 minutes. The UV light-induced photo-functionalization of TiO₂ eliminates hydrocarbon contamination and results in a super-hydrophilic surface that oxidizes adsorbed organic impurities. This secondary oxidation, initiated by ROS, is believed to be essential for achieving antimicrobial activity.⁴⁶ Protein adsorption is influenced by several factors, including surface hydrophobicity, roughness, porosity, chemical composition, as well as the composition and concentration of the protein solution, salt concentrations, and pH.⁴⁷⁻⁵⁰ The layer of adsorbed proteins is crucial for bacterial adhesion. In reality, bacteria rarely encounter a "clean" surface on an implant. Free-swimming bacteria, in the so-called planktonic state, tend to adhere to these surface-adsorbed proteins.^{51,52} The adhered bacteria can proliferate and attract other bacteria from the surrounding environment. Once a sufficient population of bacteria forms a colony on the surface, they will modify their gene expression patterns. Genes responsible for producing extracellular polymeric substances, vital for biofilm formation, will be activated and expressed.^{52,53} The combined use of biofilm-disrupting agents alongside antibiotics appears to be a more effective strategy; however, this approach is not frequently implemented in practice due to the aggressive nature of the chemicals involved.⁵² It is evident that the topological and chemical properties of a dental implant surface significantly influence the adhesion rate of microorganisms. A completely smooth surface is less prone to microbial colonization compared to a rough surface, which provides a larger area for adhesion and greater adhesive forces generated by microorganisms per unit area.⁵ Although, Puckett *et al.*⁵⁴ noted that surfaces with increased nano roughness exhibit higher surface energy, leading to enhanced protein adsorption and, consequently,

reduced bacterial adhesion. However, specific threshold values regarding surface roughness that may affect bacterial adhesion remain undefined. In the field of dentistry, a rise in plaque accumulation has been observed with roughness measurements exceeding 0.2 μm .⁵⁵ Various methods are utilized to create nano-scale structures on implant surfaces. Zhang *et al.*⁵⁶ successfully produced a silver-zinc oxide-hydroxyapatite (Ag-ZnO-HA) nanocomposite on Ti6Al4V using laser cladding, which demonstrated excellent antibacterial properties against *Escherichia coli* and *Streptococcus aureus* *in vitro*, along with favorable osteogenesis properties *in vivo*. Most microorganisms possess a charged outer membrane and contain hydrophobic regions, which may contribute to their adhesion to the hydrophobic surfaces of medical implants. Nonetheless, the adhesion of microorganisms typically relies on the formation of a protein layer on the surface, potentially revealing high-affinity adhesion sites.^{51,52} Negatively charged surfaces tend to be less prone to bacterial adhesion than positively charged surfaces, as most bacteria have negatively charged cell walls.^{57,58} The effect of electrical repulsion on bacterial adhesion becomes more pronounced with increased surface hydrophilicity. In terms of surface free energy, the degree of bacterial adhesion can either rise or fall with increasing surface energy of substrates, depending on the physicochemical characteristics of both the substrate and the bacterial strains involved, as well as the aqueous solution utilized.⁵⁹ Gao *et al.*⁶⁰ found that the antibacterial effect observed on the studied surface resulted from electrostatic disturbances that triggered autolytic and/or cellular death mechanisms. Surface hydrophilicity contributes to the interactions between biomaterials and bacteria, but these systems are complex and shaped by various factors, including the implant location and the specific bacterial species and strains involved. Theoretically, hydrophobic bacterial strains are more likely to adhere to biomaterials with hydrophobic characteristics, while hydrophilic species are inclined to attach to hydrophilic surfaces.⁶¹ Hydrophobic interactions are common and play a role in the mechanisms of various microbial adhesion factors, including hydrophobic components of cell membranes and adhesins found on fimbriae or pili.⁶² Research has confirmed that the adhesion of human pathogens such as *Streptococcus aureus* and *Staphylococcus epidermidis* correlates with increased hydrophobicity of the biomaterial surface,

establishing hydrophobicity as a primary driver of bacterial adhesion.⁶³ Concerning the crystalline phases of the surface, titanium dioxide can exist in three forms. The crystalline structure is closely linked to its ability to inhibit bacterial adherence.^{54,64,65} All three forms exhibit photocatalytic activity, which contribute to their antibacterial properties.^{61,64,66}

All included studies were published in English, which may introduce language bias and limit of the findings. The review primarily focused on *in vitro* and some *in vivo* studies, which may not fully reflect clinical outcomes in human subjects. Furthermore, variations in study design, methodologies, and outcome measures among the reviewed studies could impact the consistency and comparability of the results.

Conclusion

This review highlights the critical role of surface modifications and antimicrobial coatings in reducing infections in dental implants. Materials like silver, zinc, copper, and fluorine exhibit strong antimicrobial properties, preventing bacterial growth through ion release, oxidative stress, and photocatalytic activity. Additionally, surface characteristics such as roughness, charge, and crystalline phase significantly influence bacterial adhesion, underscoring the need for optimized implant surface designs. Ultraviolet treatment and titanium dioxide coatings further enhance antimicrobial effects, with titanium dioxide generating reactive oxygen species to disrupt bacterial membranes. Other strategies, including chlorhexidine coatings and controlled-release antibiotic devices, offer infection control but face challenges like bacterial resistance. Meanwhile, alternatives such as dextran and polyethylene glycol coatings effectively reduce biofilm formation and bacterial adhesion, presenting promising solutions for implant-related infections. Despite these advancements, further research is essential to evaluate the long-term stability and performance

of these coatings, particularly under different clinical conditions.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions

- **Yuval Reiser:** Conceptualization, Methodology, Investigation, Writing – Original Draft, Writing-Review and Editing.
- **Marko Vuletić:** Software, Validation, Data Curation, Writing – Original Draft, Writing-Review and Editing.
- **Dragana Gabrić:** Conceptualization, Visualization, Supervision, Validation, Project Administration, Writing-Review and Editing.

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APPENDIX A. PRISMA flowchart.

