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Recent Trends in Dental Implant Materials and Surface Modifications: A Literature Review

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Abstract

Introduction: The field of restorative dentistry has been transformed by the invention of dental implants, which provide a lasting remedy to the problem of tooth loss. The effectiveness of these implants is based on their capacity to achieve osseointegration with the surrounding bone tissue, integrating completely within the bone. Optimal osseointegration is attained through the use of biocompatible materials with certain modifications in the material surface that facilitate the adhesion, growth, and multiplication of bone cells, while preventing the colonization by bacteria.Aim of work: To critically examine recent advancements in dental implant materials and surface modification techniques, with a focus on their impact on osseointegration, antibacterial efficacy, and long-term clinical success. Methods: We conducted a comprehensive search in the MEDLINE database's electronic literature using the following search terms: Recent, Trends, Dental, Implant, Materials, and Surface Modifications. The search was restricted to publications from 2016 to 2025 in order to locate relevant content. We performed a search on Google Scholar to locate and examine academic papers that pertain to my subject matter. The selection of articles was impacted by certain criteria for inclusion. Results: The publications analyzed in this study encompassed from 2016 to 2025. The study was structured into various sections with specific headings in the discussion section.Conclusion: In conclusion, modern developments in the field of implant dentistry stem from a more integrated approach to the materials used in implants and their surface modification in order to improve the success rates of these implants. The field of implant dentistry continues to evolve as new strategies for surface engineering, antimicrobial treatments, and even different materials like zirconia are used. Further research and clinical investigations are still needed to make these changes reliable and routine.

Keywords: *Recent, Trends, Dental, Implant, Materials, and Surface Modifications.*

Introduction

Research in dental implantology concentrates on issues concerning the integration of the dental implants into the bone, reducing the rates of bacteria colonization, and prolonging the lifespan of dental implants. Traditionally, dental implants were made from titanium alloys, particularly Ti6Al4V, owing to their excellent mechanical properties and biocompatibility. Increased incidences of peri-implantitis and implant failure have necessitated the investigation of other materials and surface treatment technologies designed to mitigate these risks (Shaikh et al., 2019;

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Łosiewicz et al., 2025).

Achieving proper dental implant functions is critical and resolving these concerns hinges on surface modifications. Sand blasting and acid etching form microscopically rough surfaces which increase the ease with which bone can integrate with the implant (Han et al., 2022). Research has shown that SLA (sandblasting-acidic etching) treated surfaces provide significantly more osseointegration and osteogenic response than smooth untreated surfaces. Moreover, SLA treated surfaces not only enhanced the cellular responses but also inhibited bacterial adhesion more than untreated surfaces when coated with bioactive or nanostructured surfaces (Zhang et al., 2025).

Among the new approaches to developing dental implants is the femtosecond laser surface treatment. Like other laser-based techniques, surface modification with femtosecond lasers improves the accuracy of including surface features at the same time preserving the material's bulk properties. To illustrate, conical microstructures with heightened antibacterial properties against Staphylococcus aureus and Pseudomonas aeruginosa can be seen post femtosecond laser surface texturing on Ti6Al4V alloys (Shaikh et al., 2019). In a parallel study, glass bio-ceramics with laser-modified surfaces also demonstrated complete bacterial rejection (Shaikh et al., 2018).

Recent studies also focus on the intervention of antimicrobial materials onto surfaces of implants. Contact-killing and release-killing infection mitigation is attempted through dual-action mechanisms with nanoparticle and antibiotic coating systems, as well as antimicrobial peptide film composites (Barão et al., 2022). For illustrative purposes, silver nanoparticles are known to possess strong antibacterial effects, but there is concern over cytotoxicity and long-term exposure stability (Kligman et al., 2021).

Zirconia's enhanced aesthetic features and biocompatibility have made it a preferred alternative implant material. Enhanced osseointegration with zirconia implants has prompted modifications to the implant surfaces by acid etching, grit blasting, and laser zirconia treatment. While some evidence suggests improved adherence, proliferation, and differentiation of osteoblasts and fibroblasts due to altered surfaces, consensus on optimal treatment is lacking (Schünemann et al., 2019).

Aim of Work

The primary objective of this literature review is to analyze new trends in the materials used for dental implants and their surface modifications while paying special attention to osseointegration, antibacterial properties, and the clinical success of the procedure in the long term. It will also consider new techniques such as laser surface texturing, bioactive coating, and other nanostructural modifications which increase the functionality of implants through better biocompatibility and lowered chances of periimplantitis. This review aims to highlight the most influential studies in contemporary implant literature synthesizing evidence from recent research in order to understand the current state and prospects of dental implantology.

Methods

A thorough search was carried out on well-known scientific platforms like Google Scholar and Pubmed, utilizing targeted keywords such as Recent, Trends, Dental, Implant, Materials, and Surface Modifications. The goal was to collect all pertinent research papers. Articles were chosen according to certain criteria. Upon conducting a comprehensive analysis of the abstracts and notable titles of each publication, we eliminated case reports, duplicate articles, and publications without full information. The reviews included in this research were published from 2016 to 2025.

Results

The current investigation concentrated on the the recent trends in dental, Implant materials and surface modifications between 2016 and 2025. As a result, the review was published under many headlines in the discussion area, including: Titanium and Its Alloys: The Gold Standard for Dental Implants, Laser Surface Modification Techniques, Bioactive Coatings: Enhancing Osseointegration, Carbon-Based Coatings Carbon-based materials and Challenges and Future Directions.

Discussion

1. Titanium and Its Alloys: The Gold Standard for Dental Implants

Titanium (Ti) and its alloys, particularly Ti6Al4V, are widely recognized as the industry standard in dental implantology due to their exceptional mechanical strength, biocompatibility, and corrosion resistance. Titanium's elasticity modulus is comparable to bone's, which minimizes stress shielding and improves strain transmission to adjacent tissues. The capacity of Titanium to form an oxide layer contributes to its strong corrosion resistance, especially in the moist, ion-rich environment of the mouth (Albrektsson & Wennerberg, 2019).

It is notable that the alloy Ti6Al4V increases tensile strength and fatigue resistance compared to Titanium's commercially pure form. It contains 6% aluminum and 4% vanadium. Hence, it benefits load-bearing implants utilized in dental and orthopedic procedures (Siemers et al., 2018). Despite these advantages, Titanium and its alloys remain bioinert, not interacting actively with the surrounding biological tissues to enhance osseointegration. These modifications demand strategies aimed at improving the biological response at the bond interface of the bone and implant (Marin & Lanzutti, 2023).

The two most common treatments for surface property modification of Titanium include acid etching and sandblasting. These treatments are effective for increasing surface roughness, improving mechanical interdigitation with the bone, and accelerating osseointegration during the initial phase (Albrektsson & Wennerberg, 2019). In sandblasting, micro pitting with alumina or titanium dioxide particles is further roughened by hydrochloric or sulfuric acid etching. This combination yields topography that is approximately Phoenixed to natural bone and improves osteoblast attachment and proliferation (Stoilov et al., 2022). Regardless of their success, conventional approaches to surface modification have distinct drawbacks.

Surface contamination remains one of the most critical issues. The sandblasting method is known to contaminate surfaces with abrasive particle residue like alumina, which is harmful and can cause inflammation or impede the healing of bones. Furthermore, the methods do not focus on particular regions of the implant; hence, deliberately graded surfaces or bioactive regions intended to provoke stronger biological reactions cannot be created (Omarov et al., 2022).

More recent studies emphasize different approaches of surface modifications like anodization, laser ablation, and bioactive coatings due to the precision and control they offer their functionality. These methods improve osseointegration and aid in greater antimicrobial effectiveness as well as sustained stability of the implants over longer periods. For instance, laser modification creates untouched micro- and nano-scale structures on surfaces that enhance protein adsorption and osteogenic differentiation (Stich et al., 2022).

2. Laser Surface Modification Techniques

Laser surface modification (LSM), which applies to the treatment of surfaces of biomaterials, metals, ceramics and even polymers, is a relatively new procedure that has gained attention. Unlike traditional techniques, LSM is far more precise, thermally damages the workpiece to a lesser extent, enables micro or nano scale feature fabrication, and improves functionality while providing ultra-clean working environments free from any pollutants and contaminants. This approach is frequently adopted in medicine and engineering because in most cases, surface interactions dictate functionality.

The development of femtosecond lasers is arguably the most important and recent advancements related to LSM. These ultrafast lasers that operate in the 10−15 second range, enable non-thermal ablation processes to occur. During material processing with femtosecond pulses, interactions with the mater results in a surface and volumetric change by generating LIPPS, conical shapes or nano-ripples which significantly alter the morphology and chemistry of the surface (Peng et al., 2018). The modification enhances and promotes cell adhesion, osseointegration and bacterial colonization, which reduces implant rejection and therefore, these changes are advantageous for medical implants.

Biomaterials such as the Ti6Al4V alloys have garnered attention for his surgical and dental applications due to the application of femtosecond lasers. Shaikh et al.

The work of *(2018)* reported that surfaces of Ti6Al4V treated with femtosecond lasers exhibited micro-conical structures having titanium sub-oxide phases (TiOx) enriched layers. Such surface features reduced bacterial adhesion to the surfaces significantly, while increasing the adhesion of mammalian cells, thus accomplishing two beneficial objectives simultaneously. Treatments with lasers have been shown to increase hydrophilic and energetic properties of biomaterials which are critical in determining adsorption and cellular response (Shaikh et al., 2018).

Beyond metals, laser modification is performed on bioactive glasses like 45S5 Bioglass®. These materials constitute bioactives applied in regenerative medicine for bone healing and implants. Strobl et al. (2017) initiated studies proving that the femtosecond laser micro-roughening of 45S5 bioglass enhanced osteoblast adhesion and inhibited adhesion of bacteria. The scientists explained the anti-bacterial action by laser surface texturing which changes the bacterial filament membrane surface without the addition of chemicals, minimizing the chance of developing anti-microbial resistance (Strobl et al., 2017).

LSM also has significant applications in modifying polymers used for vascular and wound-healing instruments. For example, polyetheretherketone (PEEK) is a polymer with outstanding mechanical attributes, but its bioactivity is extremely low. Femtosecond laser etching has been used to etch groove and ridged nanopatterns to the surface of PEEK, leading to high endothelial cell adhesion and proliferation, reduced platelet adhesion, and a critical balance for blood-contacting devices (Huang et al., 2018). Outside biomedical applications, laser surface texturing is extensively used in tribology, where wear and friction resistance are of concern.

Micro-dimples, which laser tech creates to serve as traps for debris and lubricants, have facilitated increases in the tribological performance on some surfaces of aerospace and automotive components. (Seeholzer et al., 2018). These patterns are also important for modulating surface wettability, which has important applications involving controlled interactions with liquids.

From the manufacturing perspective, laser modification of surfaces works with various materials and is scalable. It also provides computer-controlled systems that enhance reproducibility with complex 2D or 3D designs. Lasers can etch, cut, or mark onto any surface; traditional approaches like sandblasting or chemical etching do not provide (Fotovvati et al., 2021).

Adjustment of process parameters like pulse duration, wavelength, energy fluence, and more can lead to unwanted microcracks, melting, or recast layers, leading different materials to differ in desired outcomes. There is also the issue of costly systems, such as the ones using femtosecond lasers, which limit resource-poor places (Fotovvati et al., 2021).

3. Bioactive Coatings: Enhancing Osseointegration

Osseointegration is the biological integration of implanted devices with the bone for effective orthopedic and dental prostheses. The focus of biomaterials sciences has been on improving the integration of coatings that are critical to the proper functioning of the implant. Bioactive coatings serve to interface with living tissue and promote cell attachment, growth, differentiation, and mineralization processes at and around the implant. Out of the numerous investigations conducted, HA and ECM-inspired coatings have demonstrated their effectiveness (Zhu et al., 2021).

HA is bioactive due to its physical and chemical characteristics. As a calcium phosphate ceramic, it constitutes a significant portion of bone and is, therefore, widely used in the field of bio-coating metallic implants. HA is a fundamentally important class of ceramics due to its impressive acceptance by the body and ability to form bonds with bone. In addition, it is a substitute of bone and improves the rate of integration with the surface of the bone and implant. Several studies have shown HA-coated titanium implants exhibit higher rates of osseointegration than uncoated implants as well as improved bone-to-implant contact, which enhances stability (Sirin et al., 2016; Wang et al., 2023; Ziyati et al., 2025). Moreover, the method of applying HA to the surfaces of the implants influences the degree of osseointegration achieved. Plasma spraying remains the standard method for HA coating application.

Regardless, the issues of low crystallinity and delamination have led to the exploration of other techniques such as pulsed laser deposition and sol-gel and biomimetic deposition methods (Rafiei et al., 2025). Biomimetic approaches are based on the nucleation of HA crystals, which grow on the implant surface from simulated body fluids (SBF). Such approaches are better from the physiological perspective as they are minimalistic, low-temperature stress, enhancing cellular adhesion and proliferation because of resembling natural bone mineral (Pupilli et al., 2022). Besides HA, there is now more attention paid to the biovital elements like collagen, fibronectin, and growth factors and their incorporation into the coatings. As a result, these biomaterials can offer bioactivity by going beyond osteoconduction because they can attach to cell surface receptors and modulate intracellular pathways associated with bone development. For example, collagen-coated titanium surfaces facilitate the attachment, proliferation, and differentiation of osteoblasts, enhance mineral deposition, and subsequently induce bone formation (Sobczak–Kupiec et al., 2021).

Composite materials that incorporate HA with ECM proteins or peptides from osteoinductive molecules suchas bone morphogenetic proteins (BMPs) and integrin-binding domains serve are examples of innovative bioactive coatings. These multifunctional coatings possess astonishing properties because they combine structural mimicry and bioactive signals capable of directing cellular response. Additionally, nano-HA as well as other nanostructured coatings and nanopatterned surfaces are advantageous due to their area-per-volume ratio. These surfaces are biomimetic and assist in enhancing protein adsorption and cellular interactions (Choy et al., 2017).

Of particular interest, is the glass-ceramic bioactive coatings and silicate-based coatings. They not only bond to bone, but also exhibit angiogenic and osteogenic properties by releasing biologically active ions, including calcium, silicon, and phosphate. Also, bioactive glass coatings exhibited high strength adhesion with glass-ceramic materials and surpassed in expressing key bone formation genes (Al-Harbi et al., 2021).

The clinical application of bioactive coatings is governed by their long-term stability and biocompatibility, as well as their response to mechanical load—delamination and degradation. These criteria help define limits on coating thickness, adhesion, delamination resistance, mechanical strength, and degradation profiles, which are currently being enhanced. Customizing bioactivity also in relation to the patient's age, hormonal status, bone mineral density, and some pathological conditions, like osteoporosis, is intended for future designs of implants (Singh et al., 2023).

4. Carbon-Based Coatings Carbon-based materials

Recent years have seen the application of carbon-containing coatings with graphene and carbon nanotubes (CNTs) as advanced functional materials for use in biomedical engineering. These materials are helpful due to their mechanical, electrical, and biocompatibility properties during the modification of implant surfaces to improve bone integration and colonization by bacteria resistance. Graphene, a carbon allotrope, consists of two-dimensional honeycomb lattices and exhibits extraordinary mechanical strength as well as electric conductivity. Furthermore, it is highly modifiable biomaterial, having 1 Tpa Young's modulus, 1 Tpa voltage, and large surface area (Kim et al., 2024).

Carbon nanotubes (CNTs) are a form of rolled graphene sheets and possess remarkable cylindrical characteristics. In addition to this, CNTs are useful in drug and tissue engineering due to their large length-to-diameter ratio and ability to permeate cell membranes (Maiti et al., 2019). It has been shown that CNT and graphene coatings have hydrophillic properties that enhance the roughness of implant surfaces thereby aiding cell attachement and osseointegration. These coatings also enhanced osseointegration whilst reducing bacterial adhesion (Maiti et al., 2019). With the ability to be functionalized, CNTs and graphene can serve as advanced drug carriers. Such systems can be designed to deliver therapeutics in a controlled manner within tissues or cells, reducing negative effects while optimizing treatment (Zheng et al., 2022).

Carbon-based nanomaterials provide a framework resembling extracellular matrix which supports the proliferation and differentiation of cells. Through scaffolding, neural and bone tissues can be cultivated within frameworks because scaffolds' mechanical properties can be customized specific to those needs (Farjaminejad et al., 2024).

In the biomedical applications, the use of coatings based on carbon has some difficulties. Of primary concern is long-term biocompatibility and possible cytotoxic effects. While some of these effects can be alleviated by functionalizing these materials, their biological interactions in living systems need to be understood better through thorough biological evaluation to reduce the impacts of under-researched biological phenomena (Hassan et al., 2023).

5. Challenges and Future Directions

Although significant advances have been made in dental and orthopedic implants, especially in implant materials and their surface enhancements, much still needs to be done to achieve desirable long-term results. While surface design has improved the integration of bone tissues, how these advantages are accrued over time in real-world clinical practice is still being researched. One of the most important obstacles is the absence of longitudinal clinical trials verifying the endurance and efficacy of the novel surface modifications in vivo (Lopez-Valverde et al., 2021).

The most important issue is the intricate combination of various treatments forming a singular surface. These modifications, including sandblasting, acid-etching, and coating with bioactive molecules or nanostructures, have fostered osseointegration and accelerated healing times (Albrektsson & Wennerberg, 2019). However, when several of these modifiers are used, there is the risk of unpredictable interactions that can result in damaging mechanical strength or biocompatibility. For instance, within specific parameters, hydrophilic surfaces are advantageous for the rapid adsorption of proteins, and cell docking may also lower the threshold for contamination (Zhu et al., 2021). This emphasizes the importance of thorough preclinical studies when technologies are combined. In addition, the current surfaces of implants tend to fall in a middle ground where they can either foster osseointegration while simultaneously facilitating bacterial colonization or vice versa.

The infection of dental implants is heightened due to roughened surfaces increasing bacterial cavities and the likelihood of bone integration (Riool & Zaat, 2022). This has led to investigations of antibacterial coatings incorporating silver, zinc, and antibiotic polymer compounds. Cytotoxicity and antibiotic resistance issues highlighted these solutions, showing there is a need for more permanent approaches (Manivasagam et al., 2022).

The absence of benchmarks hampers biological performance standardization. Use of animal models with low translatability and homogeneous testing frameworks are far too common, invalidating study comparisons and hindering regulatory workflows. Moreover, patients' ages, comorbidities, and medication habits result in variation captured preclinically that are unaccounted for (Al-Zyoud et al., 2023).

In biology, changes in surface geometry translate to changes in fracture toughness and fatigue resistance. Under certain cyclic loading conditions, the mechanical and biological characteristics of nanostructured coatings behave differently, which can result in reduced biological performance (Xu et al., 2022). It continues to be essential for adaptation to mechanical loading to be balanced with biological survivability.

Expedition towards multifunctional surfaces is driven by one strategy aimed at resolving the previously mentioned issues, proposing the embedding of several desirable characteristics onto one surface. This includes providing osseointegration and simultaneously preventing bacterial adhesion, all while maintaining mechanical strength.

For instance, designing layered surface microarchitectures that are reminiscent of trabecular bone structure guides cellular behavior and simultaneously decreases bacterial colonization (Abaricia et al., 2021).

Improvements in nanotechnology and additive manufacturing also pave the way for new personalized implants. Implants designed through 3D printing can have patient-specific shapes and surface features, enhancing overall functionality. Furthermore, innovative implant systems with biosensors are being developed to measure the implant's health and detect early signs of infection or loosening in real-time (Panahi, 2025).

Finally, these innovative technologies require changes to regulatory frameworks and ethical guidelines. There is an urgent multidisciplinary need to define the safety, efficacy, and impact of next-generation materials and implant coatings over time. Material scientists, clinicians, regulatory bodies, industry stakeholders, and court experts must work together to apply laboratory research to clinical settings.

Conclusion

Recent advancements in dental implant materials and surface modification techniques reflect a significant shift toward optimizing biological and mechanical performance. Titanium and its alloys remain the gold standard due to their favorable properties. However, implants femtosecond laser treatments, bioactive coatings and carbon based coatings use nanomaterials is redefining the. They address important problems including early colonization of bacteria and failures within the implan. Active agents that not only stimulate bone formation, but also disable infection reveal new horizons of stimulations their simultaneous implementation permeate. Of critical importance remain the unreserved clinical success issues adherent labs which stem lack uniform standards surface treatment, possible death cell, mechanical weaknesses, rigorous uniform testing, and separated standards still require concentrated efforts much more built that. Now is the time to construct ever precise multi high-performance implants enabled by tightly interfaced fields such as nanotech, additive manufacturing and game-changing diagnostics.

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