Nanomed Res J 11(2):125-132, Spring 2026

REVIEW ARTICLE

Nanomedicine Enabled Prosthodontic Rehabilitation: Synergistic Roles of Dental Implants and Periodontal Surgery in Oral Tissue Engineering

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ARTICLE INFO

Article History:
Received: 2026-02-22
Revised: 2026-05-24
Accepted: 2026-06-01

Keywords:
Nanomedicine
Prosthodontic Rehabilitation
Dental Implants
Periodontal Regeneration
Oral Tissue Engineering

ABSTRACT

Prosthodontic rehabilitation aims to restore oral function and aesthetics; however, long-term clinical success is often compromised by inadequate biomaterial integration, mechanical limitations of conventional prostheses, and the complex regenerative demands of oral tissues. Recent advances in nanomedicine and tissue engineering offer transformative strategies to overcome these challenges by enhancing biomaterial performance, promoting targeted therapeutic delivery, and facilitating biologically driven tissue regeneration. This review explores the synergistic integration of nanotechnology with dental implants and periodontal surgical strategies in the context of oral tissue engineering. Key developments in nano-engineered implant surfaces, bioactive and antibacterial coatings, nanostructured scaffolds, and controlled drug-delivery systems are discussed with emphasis on their roles in improving osseointegration, soft-tissue attachment, and periodontal regeneration. The review also highlights the incorporation of stem cells and growth-factor delivery through nanomaterials to mimic the native oral microenvironment and accelerate healing processes. In addition, current translational barriers including nanomaterial toxicity, manufacturing complexity, regulatory uncertainty, and variability in clinical outcomes are critically evaluated. By synthesizing recent biological, engineering, and clinical evidence, this review underscores the potential of nanomedicine-enabled prosthodontic rehabilitation to shift restorative dentistry toward precision-based, regenerative therapies. Continued interdisciplinary collaboration and standardized safety frameworks are essential to advance these technologies from experimental models to routine clinical practice and to realize their full potential in improving patient outcomes.

How to cite this article
Jafari Z, Tabatabaei H, Damanpak N, Jabbedari MH, Namazikhah MR, Pourseyedi AR. Nanomedicine Enabled Prosthodontic Rehabilitation: Synergistic Roles of Dental Implants and Periodontal Surgery in Oral Tissue Engineering. Nanomed Res J, 2026; 11(2): 125-132. DOI: 10.22034/nmrj.2026.02.002

INTRODUCTION

Prosthodontic rehabilitation constitutes a cornerstone of restorative dental care, emphasizing the restoration of oral function and aesthetics through the use of prosthetic devices. Despite its clinical importance, the field continues to face substantial biological and mechanical challenges that hinder long-term success. Traditional prosthodontic materials frequently fall short in replicating the structural and biochemical

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properties of natural dentition, often leading to premature wear, mechanical failure, and limited biocompatibility [1]. Furthermore, the intricate anatomy of oral tissues including bone, mucosa, and salivary glands complicates tissue integration and regeneration processes [2]. Periodontal diseases exacerbate these difficulties by compromising the supporting structures of teeth and demanding more sophisticated approaches for comprehensive tissue regeneration [3, 4].

The integration of nanomedicine and tissue engineering into oral healthcare introduces transformative possibilities for overcoming these limitations. Nanotechnology enables the creation of dental materials with superior mechanical properties, enhanced aesthetics, and biological affinity, closely mimicking the natural characteristics of teeth [5]. Through advanced diagnostic and therapeutic applications such as targeted drug delivery and antimicrobial coatings, nanomedicine contributes to improved management of periodontal infections and enhanced long-term functionality of prosthetic restorations [3]. Meanwhile, tissue engineering utilizing biomimetic scaffolds, stem cells, and bioactive molecules facilitates the regeneration of compromised oral tissues, promoting integration between prosthetic components and biological structures [2, 6].

This review aims to provide an in-depth exploration of emerging strategies that combine prosthodontic design with nanomedicine and regenerative technologies. Specifically, it will examine the synergistic roles of dental implants and periodontal surgery in developing next-generation prosthetic therapies enabled by nanomaterials. Key focus areas include the latest innovations in nanotechnology that enhance the durability and functionality of dental prostheses, as well as interdisciplinary approaches integrating bioengineering and pharmacological sciences for precision oral healthcare [5, 7]. By synthesizing contemporary research and clinical evidence, the review seeks to highlight both the promise and challenges associated with these technologies particularly their cost, regulatory barriers, and variability in clinical outcomes and to underscore the need for continued interdisciplinary collaboration to fully realize the potential of nanomedicine-enabled prosthodontic rehabilitation [8, 9].

BIOLOGICAL AND ENGINEERING FOUNDATIONS OF ORAL TISSUE REGENERATION

The integration of nanomedicine in prosthodontic rehabilitation, particularly through dental implants and periodontal surgery, offers a promising avenue for oral tissue engineering. This approach leverages the biological and engineering foundations of oral tissue regeneration to enhance the outcomes of dental treatments. The key biological concepts of bone and periodontal tissue healing, core elements of tissue engineering, and current limitations in conventional implantology and periodontics are crucial to understanding this field.

Bone regeneration in the oral cavity involves a complex interplay of cellular and molecular processes. The balance between bone resorption and formation is critical for maintaining and regenerating alveolar bone and supporting structures around teeth and implants [10]. Periodontal regeneration aims to restore the structure and function of tissues lost due to disease. This process involves the proliferation, migration, differentiation, and synthesis of protein matrices, which are essential for forming new attachment apparatus, including bone, cementum, and periodontal ligament [11].

Stem cells, particularly mesenchymal stem cells (MSCs), are pivotal in regenerating periodontal tissues. They have the potential to differentiate into various cell types necessary for tissue regeneration. Scaffolds provide a structural framework that supports cell attachment and growth. Advances in scaffold design, including the use of synthetic and natural polymers and 3D printing techniques, have improved their effectiveness in tissue [6]. Growth factors such as PDGF, TGF-β, and BMPs play a crucial role in guiding tissue regeneration by promoting cell proliferation and differentiation. The integration of bioactive molecules into scaffolds enhances their regenerative potential [12].

Conventional treatments often fail to achieve complete and predictable regeneration of periodontal tissues. The integration of regenerated tissues and establishing proper vascularization remain significant challenges [6, 13]. Synthetic materials used in traditional therapies do not fully replicate the chemical and structural composition of natural bone, limiting their effectiveness in large or complex defects [14, 15]. Despite advancements, the clinical application of tissue engineering strategies is still in its early stages, with challenges in immune response, regulatory approvals, and long-term efficacy [14, 15].

While the integration of nanomedicine in prosthodontic rehabilitation holds great promise, it is essential to address the existing challenges in tissue engineering. The development of biomimetic scaffolds, improved vascularization techniques, and personalized treatment approaches are critical areas for future research. Collaborative efforts across disciplines will be vital in overcoming these hurdles and unlocking the full potential of tissue engineering in oral health care.

NANOMEDICINE IN DENTISTRY: PRINCIPLES AND MATERIALS

Nanomedicine in dentistry represents a transformative approach that leverages the unique properties of nanotechnology to enhance dental care. This field encompasses a range of applications, from improving the mechanical properties of dental materials to enabling precise drug delivery and tissue regeneration. The integration of nanotechnology into dentistry is poised to revolutionize prosthodontic rehabilitation, particularly through the synergistic roles of dental implants and periodontal surgery in oral tissue engineering. The following sections explore the fundamental principles of nanotechnology relevant to dental applications, the major classes of nanomaterials used, and the critical physicochemical and biocompatibility considerations.

Nanotechnology involves the manipulation of materials at the nanoscale (1-100 nm), which allows for enhanced control over material properties and interactions at the molecular level [2, 16]. In dentistry, nanotechnology is applied to improve diagnostics, drug delivery, and the mechanical properties of dental materials. It also plays a role in regenerative medicine, such as tissue engineering and the development of dental implants [2, 17]. Techniques such as the use of nanorobots for precise dental procedures and the development of nanostructured scaffolds for tissue regeneration are examples of how nanotechnology is being integrated into dental practices [18, 19].

Nanoparticles include metallic nanoparticles like silver, zinc oxide, and titanium dioxide, which are used for their antimicrobial properties and ability to enhance the mechanical strength of dental materials. Nanocomposites materials combine nanoparticles with polymers to improve the durability and aesthetic qualities of dental restorations. They are particularly useful in creating dental fillings and prosthetic devices that mimic natural tooth characteristics [20, 21]. Nanofibers and Nanostructured Scaffolds Used in tissue engineering, these materials support cell growth and differentiation, aiding in the regeneration of oral tissues and the integration of dental implants [19].

The high surface-to-volume ratio of nanomaterials enhances their reactivity and bioactivity, which is beneficial for applications like antimicrobial coatings and drug delivery systems [20]. Ensuring that nanomaterials are biocompatible is crucial for their safe use in the oral cavity. This involves assessing their cytotoxicity, potential for causing inflammation, and interactions with oral tissues and biofilms [22]. The lack of standardized synthesis and regulatory frameworks poses challenges for the clinical translation of nanomaterials. Addressing these issues is essential to ensure patient safety and the long-term success of nanotechnology in dentistry.

While nanotechnology offers significant advancements in dental care, it is important to consider the potential risks and challenges associated with its use. Issues such as cytotoxicity, nanoparticle aggregation, and the formation of biologically active protein coronas need to be carefully managed to ensure the safe and effective application of nanomaterials in dentistry. Ongoing research and development are crucial to optimizing these technologies and overcoming the barriers to their widespread adoption in clinical practice.

NANOTECHNOLOGY-ENHANCED DENTAL IMPLANTS

Nanotechnology has significantly advanced the field of dental implants, enhancing their functionality and integration with oral tissues. This progress is primarily achieved through surface nano modifications, antibacterial and bioactive coatings, and drug-releasing systems. These innovations aim to improve osseointegration, mechanical stability, and the overall success of dental implants. The following sections delve into these aspects, supported by clinical and preclinical evidence.

Nano-engineering techniques have been employed to modify the surface characteristics of titanium dental implants, promoting peri-implant osteogenesis and enhancing osseointegration [23, 24]. Techniques such as plasma spraying, anodization, and the application of titanium dioxide nanotubes have been shown to improve the biological performance of implants by mimicking the natural bone formation process at the nanoscale [24]. These modifications facilitate early osseointegration and ensure long-term bone-to-implant contact, reducing the risk of marginal bone loss [25].

The application of antibacterial coatings, such as those incorporating metal nanoparticles or chitosan, has been explored to prevent peri-implantitis and enhance implant longevity [26]. Bioactive coatings, including calcium phosphate nanocrystals, stimulate bone apposition and healing, further supporting osseointegration [27]. Multifunctional coatings that combine antibacterial properties with bioactivity have demonstrated favorable outcomes in increasing implant success rates [28].

Nanotechnology has enabled the development of implants that can release antibiotics or proteins in a controlled manner, enhancing their antibacterial and immunomodulatory functions [8]. Stimuli-responsive systems, which can release therapeutic agents in response to specific environmental triggers, hold promise for advancing implant technology [8]. These systems aim to provide a sustained release of drugs, reducing the risk of infection and promoting tissue integration [29].

In vitro and in vivo studies have shown that nano-modified implant surfaces exhibit excellent biocompatibility, antimicrobial activity, and improved osseointegration. Clinical investigations of micro-roughened surfaces, such as those that are sandblasted or acid-etched, have reported survival rates higher than 95% [30]. Despite promising results, further long-term in vivo studies are necessary to ensure the clinical application and safety of these nanomaterial-modified implants [8].

While nanotechnology has significantly enhanced the capabilities of dental implants, challenges remain in translating these innovations into widespread clinical practice. The complexity of manufacturing and the need for extensive clinical trials to assess long-term safety and efficacy are hurdles that must be overcome. Additionally, the integration of nanotechnology with other fields, such as tissue engineering, could further optimize clinical outcomes, offering exciting possibilities for future advancements in prosthodontic rehabilitation.

NANOMEDICINE-ASSISTED PERIODONTAL REGENERATION AND SURGERY

Nanomedicine has significantly advanced periodontal regeneration and surgery, offering innovative solutions through the use of nanostructured scaffolds, membranes, gels, and drug carriers. These nanomaterials provide a conducive environment for tissue regeneration, enhance the delivery of growth factors and stem cells, and play a crucial role in infection control and guided tissue regeneration. The following sections delve into these aspects, highlighting the synergistic roles of nanotechnology in periodontal surgery and prosthodontic rehabilitation.

Nanostructured scaffolds and membranes are pivotal in periodontal tissue engineering, providing structural support and promoting cellular activities essential for tissue regeneration. Materials like tricalcium phosphate, hydroxyapatite, and polycaprolactone have been explored for their biocompatibility and osteogenic potential, enhancing bone formation and tissue integration. Additionally, 3D-printed scaffolds offer patient-specific solutions, improving structural adaptation to periodontal defects. Hydrogels are favored for their absorption capacity, biodegradability, and mechanical properties, serving as carriers for cell transplantation and drug delivery systems [31]. Nanogels and other nano drug-delivery systems (NDDS) deliver drugs directly to the site of infection, inhibiting bacterial growth and promoting tissue regeneration [32].

Nanomaterials facilitate the controlled release of growth factors, crucial for enhancing tissue healing and functional restoration. Mesoporous silica nanoparticles, for instance, encapsulate growth factors, preserving their bioactivity and ensuring sustained release. This approach enhances the regenerative potential of periodontal treatments by mimicking the physiological microenvironment of periodontal tissues [33]. The integration of stem cells with nanomaterials amplifies regenerative outcomes. For example, nanostructured membranes have been shown to induce bone-forming markers in human mesenchymal stem cells, promoting periodontal tissue regeneration [34]. This synergy between nanomaterials and stem cells is vital for achieving comprehensive periodontal regeneration [6].

Nanomaterials exhibit excellent antibacterial properties, crucial for preventing infections during periodontal regeneration. For instance, bilayer membranes with antimicrobial properties have been developed to combat pathogens associated with periodontitis [34]. Similarly, electrospun membranes with moxifloxacin-loaded nanocarriers provide prolonged infection control, essential for successful tissue regeneration [35]. Nanoengineered membranes with dual drug delivery capabilities enhance GTR by providing both growth factor and antibiotic delivery. This dual function not only supports tissue regeneration but also ensures local infection control, offering a comprehensive approach to periodontal therapy [33].

While nanomedicine offers promising advancements in periodontal regeneration, challenges such as optimizing scaffold degradation, ensuring long-term biocompatibility, and addressing safety concerns remain. The integration of nanotechnology in periodontics requires careful consideration of these factors to ensure successful clinical outcomes. Continued research and interdisciplinary collaborations are essential to overcome these hurdles and fully realize the potential of nanotechnology in periodontal care.

SYNERGISTIC INTEGRATION OF DENTAL IMPLANTS AND PERIODONTAL STRATEGIES

The integration of dental implants with periodontal strategies is a multifaceted approach that combines the strengths of both fields to enhance oral tissue engineering. This synergy is crucial for achieving optimal outcomes in prosthodontic rehabilitation, where the focus is on both functional and aesthetic results. The interplay between implant surfaces and surrounding tissues, co-engineering approaches, and real-world case insights are pivotal in understanding and advancing this integration. Below, each of these aspects is explored in detail.

The success of dental implants largely depends on the osseointegration process, where the implant surface interacts with the bone. Surface treatments such as sandblasting and acid etching enhance this integration by increasing surface roughness, which promotes bone cell attachment [36, 37]. However, soft tissue integration remains a challenge, as the peri-implant soft tissue seal is often inferior to that of natural teeth, leading to potential complications like peri-implantitis [36]. The biologic width, or the space occupied by healthy tissues around implants, is critical for maintaining peri-implant health. The interface between implant materials and peri-implant tissues influences clinical outcomes, with factors such as implant design and surface characteristics playing significant roles [38, 39].

The integration of prosthodontic design with regenerative surgery involves using advanced biomaterials and nanotechnology to enhance tissue regeneration. Innovations in biomaterials, such as bioactive coatings and scaffolds, support both hard and soft tissue regeneration, improving implant stability and aesthetics [40]. Successful integration requires collaboration across disciplines, including periodontics, oral surgery, and prosthodontics. This transdisciplinary approach ensures that all aspects of implant design, placement, and maintenance are optimized for both functional and aesthetic outcomes [40, 41].

Real-world cases demonstrate the effectiveness of combining dental implants with periodontal strategies. For instance, the use of growth factors and stem cells in regenerative therapies has shown promise in enhancing both bone and soft tissue healing, leading to improved implant success rates. The development of new biomaterials and techniques in implant dentistry is a prime example of translational research, where laboratory findings are applied to clinical practice. This approach has led to significant advancements in implant surface design and regenerative strategies, ultimately benefiting patient outcomes [40].

While the integration of dental implants and periodontal strategies offers numerous benefits, challenges remain. The variability in soft tissue response and the complexity of achieving a natural-like peri-implant environment highlight the need for continued research and innovation. Additionally, the interdisciplinary nature of this field necessitates ongoing collaboration and communication among dental professionals to ensure the best possible outcomes for patients. Table 1 summarizes the principal nanomedicine-based approaches that integrate implant surface engineering with periodontal regenerative strategies, outlining their mechanisms, clinical benefits, and current translational limitations.

CHALLENGES, SAFETY, AND TRANSLATIONAL BARRIERS

The integration of nanomedicine in prosthodontic rehabilitation, particularly through dental implants and periodontal surgery, presents numerous challenges and barriers. These

Table 1. Nanomedicine-based strategies integrating dental implants and periodontal regeneration in prosthodontic rehabilitation

Application Area	Nanomaterial / Technology	Mechanism of Action	Clinical Benefit	Current Limitations
Implant surface modification	TiO_2 nanotubes, nano-roughened titanium, anodized coatings	Enhances protein adsorption and osteoblast adhesion; promotes rapid osseointegration	Faster healing, increased implant stability, reduced marginal bone loss	Manufacturing complexity; long-term durability data limited
Antibacterial implant coatings	Silver nanoparticles, chitosan-based nanofilms	Disrupts bacterial membranes; prevents biofilm formation	Reduced peri-implantitis risk; improved implant survival	Potential cytotoxicity; dose optimization needed
Drug-eluting implant systems	Antibiotic- or growth-factor-loaded nanoparticles	Controlled local release of therapeutic agents	Infection control; enhanced bone and soft tissue healing	Limited clinical validation; regulatory challenges
Periodontal scaffolds and membranes	Electrospun nanofibers, nano-hydroxyapatite composites, 3D-printed nanoscaffolds	Provides structural support; promotes cell migration and differentiation	Improved bone and periodontal ligament regeneration	Scaffold degradation control; vascularization issues
Growth factor delivery systems	Mesoporous silica nanoparticles, nanogels	Sustained release of PDGF, BMPs, TGF-β	Accelerated tissue regeneration; improved attachment formation	High cost; stability of bioactive molecules
Stem cell–nanomaterial constructs	Nanostructured membranes with MSCs	Enhances stem cell adhesion and lineage differentiation	Potential for complete periodontal regeneration	Ethical issues; scalability and regulatory approval

challenges are primarily associated with the risks of nanomaterial toxicity, manufacturing complexities, and the need for standardized evaluation and ethical guidelines. Addressing these issues is crucial for the successful translation of nanotechnology into clinical practice.

Nanomaterials, due to their small size and high surface area, can interact unpredictably with biological systems, leading to potential toxicity. Cationic nanoparticles, for instance, may cause oxidative stress, while anionic nanoparticles can accumulate in lysosomes, triggering inflammatory responses [2]. The long-term stability of nanomaterials in biological environments is uncertain, raising concerns about their sustained efficacy and safety over time [42]. Traditional preclinical safety tests often fail to predict the unique toxicological profiles of nanomaterials, necessitating the development of new evaluation protocols to ensure their safe application in medical devices and treatments [42, 43].

The manufacturing of nanomedicines involves complex processes that require precise control over material properties to ensure consistency and efficacy. This complexity can lead to high production costs, which may hinder widespread adoption [44]. Regulatory frameworks for nanomedicines are not well-defined, creating significant barriers for manufacturers. The lack of clear guidelines complicates the approval process and increases the risk of non-compliance with safety standards [45, 46]. The absence of a globally synchronized regulatory framework further exacerbates these challenges, as different countries may have varying requirements, leading to delays in the clinical translation of nanomedicines [44, 45].

There is a pressing need for standardized evaluation methods to assess the safety and efficacy of nanomaterials. Current methods are often inadequate for capturing the unique properties of nanomaterials, necessitating the development of new analytical techniques [2]. Ethical considerations are paramount in the deployment of nanotechnology in medicine. Transparent communication and responsible practices are essential to balance innovation with societal well-being [47]. Establishing ethical guidelines and standardized evaluation protocols will help mitigate public concerns and foster trust in nanomedicine applications [47, 48].

While the potential of nanomedicine in prosthodontic rehabilitation is significant, these challenges highlight the need for a concerted effort to address safety, regulatory, and ethical issues. By developing robust evaluation protocols and harmonizing regulatory frameworks, the field can advance towards safer and more effective clinical applications. Additionally, fostering collaboration between researchers, policymakers, and industry stakeholders will be crucial in overcoming these translational barriers.

FUTURE PERSPECTIVES AND CONCLUSIONS

In summary, prosthodontic rehabilitation stands at the intersection of traditional restorative dentistry and modern biomedical innovation. While longstanding challenges such as limited biocompatibility, mechanical fragility, and the complexity of soft and hard tissue integration continue to constrain clinical outcomes, advances in nanomedicine and tissue engineering are paving the way toward more functional, durable, and biologically harmonious solutions. Nanotechnology-driven materials and targeted therapeutic systems are not only enhancing the structural and aesthetic performance of dental prostheses but also revolutionizing the management of periodontal and peri-implant diseases. Concurrently, tissue engineering introduces regenerative approaches that bridge the gap between prosthetic design and biological restoration, fostering improved osseointegration and soft tissue regeneration. As this review underscores, the convergence of prosthodontics, nanoscience, and regenerative medicine holds unparalleled potential to transform oral healthcare. However, realizing this promise requires overcoming key barriers such as high development costs, regulatory complexities, and inconsistent clinical validation. Sustained interdisciplinary collaboration and translational research will therefore be indispensable in advancing nanomedicine-enabled prosthodontic rehabilitation from experimental innovation to standard clinical practice, ultimately enhancing patient outcomes and redefining the future of restorative dentistry.

ACKNOWLEDGEMENTS

The authors utilized artificial intelligence tools, namely Perplexity.ai, to enhance the clarity and language quality of this manuscript throughout its preparation. All suggestions and content provided by the AI were thoroughly reviewed and revised by the authors, who take full responsibility for the accuracy and integrity of the final version.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have disclosed any financial or personal relationships that could potentially influence or bias the work presented.

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