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Current State of Advanced Biomaterials and Technologies in the Treatment of Peri-Implantitis: A Review of the Literature

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Abstract

Peri-implantitis remains a challenging biological complication in implant dentistry because predictable disease resolution requires infection control, implant surface decontamination, defect-based treatment planning, and long-term supportive care. Although conventional non-surgical, surgical, resective, and reconstructive approaches may improve selected clinical or radiographic outcomes, long-term stability remains difficult, particularly in advanced defects or around complex implant surfaces. This review of the literature summarizes the current state of advanced biomaterials and emerging technologies for peri-implantitis treatment, with emphasis on their mechanisms, clinical applications, limitations, translational relevance, and future perspectives. A focused literature search was performed in PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. Relevant studies and reviews were identified on peri-implantitis treatment, implant surface decontamination, reconstructive therapy, antimicrobial and bioactive biomaterials, nanoparticles, hydrogels, local drug-delivery systems, laser-assisted therapy, antimicrobial photodynamic therapy, air-abrasive decontamination, electrochemical approaches, cold atmospheric plasma, digital workflows, 3D printing, and artificial intelligence. The reviewed literature indicates that advanced biomaterial-based strategies and emerging technologies are best interpreted as adjunctive platforms rather than replacements for established treatment principles. Laser-assisted therapy, air-abrasive decontamination, and antimicrobial photodynamic therapy have accumulated the most clinical evidence among the reviewed adjunctive technologies, with reported short-term improvements in selected clinical or microbiological outcomes. In contrast, bioactive and antimicrobial membranes, nanoparticles, hydrogels, electrochemical methods, cold atmospheric plasma, and patient-specific 3D-printed scaffolds remain largely preclinical or early translational, with limited direct clinical evidence. Overall, these strategies may support peri-implantitis therapy, but their clinical readiness varies, and their use should remain cautious, adjunctive, and supported by standardized long-term clinical studies.

Keywords: Peri-implantitis, Advanced biomaterials, Implant surface decontamination, Local drug delivery, Emerging technologies.

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1. Introduction

Dental implants are widely used for oral rehabilitation, but biological complications around implants remain an important challenge in contemporary implant dentistry (1,2). Peri-implantitis is a plaque-associated inflammatory condition characterized by inflammation of the peri-implant mucosa and progressive loss of supporting bone (2-4). Its clinical burden is considerable because it may compromise implant function, esthetics, prosthetic prognosis, patient satisfaction, and long-term implant survival (1,3). Although reported prevalence varies by case definition, study design, function time, and diagnostic threshold, recent systematic reviews indicate that peri-implantitis affects a clinically relevant proportion of implant patients, with patient-level

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estimates commonly reported around one-fifth of implant patients (5,6).

Treatment remains difficult because disease resolution requires control of biofilm, implant surface contamination, inflammation, defect morphology, patient-related risk factors, prosthetic accessibility, and long-term supportive peri-implant care (1,7–10). Conventional non-surgical and surgical approaches may improve selected clinical parameters, but predictable and stable outcomes remain challenging, particularly in advanced defects or around rough and threaded implant surfaces (1,7–10). These limitations are mainly related to persistent biofilm on complex implant surfaces, restricted access for decontamination, variability in defect morphology, and the difficulty of achieving true re-osseointegration on previously contaminated surfaces (3,7-12). These challenges provide the rationale for investigating adjunctive biomaterial- and technology-assisted approaches (12-34).

In this review, "advanced biomaterials and technologies" refers to recently developed or actively investigated materials and adjunctive approaches designed to improve antimicrobial control, implant surface decontamination, local drug delivery, defect reconstruction, tissue regeneration, or treatment personalization beyond conventional mechanical debridement and standard reconstructive procedures. These include antimicrobial and bioactive surfaces, nanoparticles, hydrogels, local drug-delivery systems, functionalized membranes and scaffolds, laser-assisted therapy, antimicrobial photodynamic therapy, air-abrasive systems, electrochemical decontamination, cold atmospheric plasma, 3D printing, and digital or artificial intelligence-supported workflows (12-34).

Given the rapid expansion of these approaches, a focused synthesis could help clarify their biological rationale, current clinical relevance, translational gaps, and future research priorities (12-34). By organizing the available evidence on advanced biomaterials, antimicrobial strategies, surface decontamination technologies, local drug-delivery platforms, and digital workflows, this review may help define the current state of the field and guide future research toward more standardized and clinically meaningful treatment protocols. Therefore, this review of the literature aims to summarize the current state of advanced biomaterials and technologies in peri-implantitis treatment, with emphasis on mechanisms of action, clinical applications, limitations, translational relevance, and future directions.

2. Materials and Methods

This literature review was designed to provide a focused overview of advanced biomaterial-based and technology-assisted approaches for peri-implantitis treatment. The scope included studies and reviews addressing peri-implantitis diagnosis and treatment, implant surface decontamination, reconstructive therapy, antimicrobial and bioactive biomaterials, local drug-delivery systems, and emerging digital or device-based technologies (1-4,7-10,12).

A focused literature search was performed using PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. Search terms were combined around peri-implantitis, implant surface decontamination, reconstructive or regenerative therapy, antimicrobial coatings, nanoparticles, hydrogels, local drug delivery, laser therapy, antimicrobial photodynamic therapy, air-abrasive decontamination, electrochemical methods, cold atmospheric plasma, 3D printing, digital workflows, and artificial intelligence.

Eligible publications included clinical guidelines, consensus reports, systematic reviews, meta-analyses, review articles, clinical studies, animal studies, and relevant *in-vitro* studies. Because this article was designed as a review of the literature rather than a systematic review or meta-analysis, no formal PRISMA-based screening, risk-of-bias assessment, certainty-of-evidence grading, or quantitative pooling was performed. The retrieved evidence was qualitatively summarized and organized according to therapeutic target, biomaterial or technology category, clinical relevance, and translational status (1,4,7-10,12).

3. Current treatment concepts and their limitations

Effective management of peri-implantitis typically involves multiple complementary strategies targeting biofilm, surface decontamination, inflammation, defect morphology, prosthetic access, and patient-specific risk factors (1,7-10). Non-surgical therapy, including mechanical debridement, ultrasonic instrumentation, air-abrasive systems, antiseptics, and local antimicrobials, may reduce inflammation in early peri-implant inflammatory conditions and peri-implant mucositis, but its effectiveness in established peri-implantitis is limited, particularly in deep pockets or around rough and threaded implant surfaces (1,7,8).

Surgical access therapy is indicated when non-surgical measures fail or when deep defects exist. Open flap debridement allows direct visualization, granulation tissue removal, and improved surface decontamination (8,9). However, surgical therapy alone does not guarantee bone regeneration or re-osseointegration, and outcomes are influenced by defect morphology, flap stability, and post-operative maintenance (8,9).

Resective therapy and implantoplasty can improve hygiene access and reduce plaque retention on exposed implant surfaces. Implantoplasty, involving mechanical modification and smoothing of exposed threads, may improve cleanability and maintainability in non-contained or supracrestal defects (35,36).

Conventional reconstructive biomaterials used in peri-implantitis include xenogeneic bone substitutes, alloplastic grafts, composite grafts, and resorbable or non-resorbable barrier membranes (12,37-42). These materials support clot stabilization, defect fill, and space maintenance in intrabony or circumferential defects (8,12,37-42). Their effectiveness depends on defect morphology, graft stability, surface decontamination, flap closure, and supportive maintenance (8,12,37-42). These conventional materials provide the foundation for advanced biomaterial-based strategies (13-19,32).

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4. Advanced and emerging biomaterial-based strategies

4.1. Bioactive and antimicrobial membranes and scaffolds

Bioactive and antimicrobial membranes represent an advanced development of conventional barrier concepts because they aim to combine space maintenance with biological activity (13,14,18). These materials may incorporate antimicrobial agents, nanoparticles, peptides, anti-inflammatory compounds, or regenerative molecules to reduce bacterial colonization and support wound healing in contaminated peri-implant defects (13,14,18). Their potential value is particularly relevant in peri-implantitis, where regenerative materials are placed in previously infected or inflamed sites rather than pristine augmentation sites (12,13). However, antimicrobial or bioactive activity must remain compatible with osteoblasts, fibroblasts, endothelial cells, and normal wound healing because excessive cytotoxicity may impair regeneration despite reducing bacterial load (13,17,18). From a clinical perspective, these materials appear most relevant when they are used to enhance conventional membrane function rather than replace established reconstructive principles (12-14). However, direct clinical evidence for antimicrobial or bioactive membranes in peri-implantitis remains limited compared with conventional graft-and-membrane reconstructive approaches (12-14,18,42).

4.2. Antimicrobial coatings and surface-functionalized materials

Antimicrobial coatings and surface-functionalized materials are designed to reduce bacterial adhesion, inhibit biofilm maturation, or improve host-cell response on implant or biomaterial surfaces (14-16,19). These platforms may include antimicrobial peptides, metallic nanoparticles, polymeric films, calcium phosphate coatings, bioactive glass, or multifunctional coatings that combine antibacterial and osteogenic properties (14-17). At present, antimicrobial coatings and surface-functionalized materials seem more applicable to prevention, next-generation implant surfaces, or preclinical surface-engineering strategies than to routine intraoperative treatment of established peri-implantitis (13-16,19). Their future clinical use will depend on whether stable antibacterial effects can be maintained without impairing osseointegration, soft tissue healing, or long-term surface durability (14-16).

4.3. Nanoparticles and nano-engineered systems

Nanoparticle-based systems have been investigated in peri-implant disease management because they may provide antimicrobial activity, drug delivery, surface functionalization, and modulation of local biological responses (17,18). Metal and metal oxide nanoparticles, including silver, zinc oxide, titanium dioxide, and related nanoformulations, have been studied for antibacterial and antibiofilm effects (17). Nanoparticles may be incorporated into coatings, hydrogels, membranes, scaffolds, or local drug-delivery vehicles to improve retention and sustained therapeutic activity at peri-implant sites (17,18). However, nanoparticle-based systems require careful evaluation because antimicrobial potency may be associated with dose-dependent cytotoxicity, inflammatory effects, or interference with osteogenic cells (17,18). Among advanced biomaterial strategies, nanoparticles have been extensively explored in experimental peri-implant disease models because they can combine antimicrobial activity with drug delivery or surface functionalization (17,18). Nevertheless, their clinical use remains limited by unresolved issues related to dose control, local retention, cytotoxicity, degradation behavior, and long-term tissue compatibility (17,18).

4.4. Hydrogels and local drug-delivery platforms

Hydrogels and advanced local drug-delivery systems are attractive for peri-implantitis therapy because they can deliver antimicrobial, anti-inflammatory, or regenerative agents into irregular peri-implant pockets and defects (18). Injectable or stimulus-responsive hydrogels may improve local retention and controlled release compared with simple irrigation or short-term gel placement (18). These systems may carry antibiotics, antiseptics, nanoparticles, growth factors, or combined therapeutic agents to support early infection control and healing modulation (18). Nevertheless, most hydrogel-based approaches remain preclinical or early translational, and their limited mechanical strength makes them more suitable as delivery vehicles or adjuncts than as standalone regenerative scaffolds (12,18). Their potential advantage lies in improving retention and sustained release of antimicrobial or anti-inflammatory agents within irregular peri-implant pockets and defects (18). Therefore, hydrogels may be more clinically relevant when used as adjunctive delivery systems after mechanical debridement or surgical access, particularly in combination with grafts, membranes, or mechanically stable scaffolds rather than as independent regenerative materials (12,18).

4.5. Smart multifunctional and patient-specific biomaterials

Smart multifunctional biomaterials aim to address several peri-implantitis-related challenges simultaneously, including bacterial control, inflammation modulation, controlled release, osteoconductive support, and regenerative signaling (13,14,18). These platforms may include pH-responsive carriers, enzyme-responsive systems, multilayer coatings, nanoparticle-loaded scaffolds, or bioactive membranes designed to respond to the infected peri-implant microenvironment (13,14,18). Patient-specific 3D-printed scaffolds may also support future defect-adapted regenerative workflows by improving geometric adaptation to complex peri-implant defects (32). However, these materials require validation of biocompatibility, sterilization stability, mechanical behavior, reproducibility, cost-effectiveness, and long-term clinical benefit before routine clinical use can be

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recommended (13,14,18,32). Smart multifunctional and patient-specific biomaterials represent one of the most future-oriented directions in this field. But they currently have less direct clinical evidence than conventional reconstructive biomaterials or commonly used adjunctive technologies (12-19,32). Patient-specific 3D-printed scaffolds may be particularly relevant for complex defect adaptation. However, their current evidence in peri-implantitis remains closer to proof-of-concept or early translational application than routine clinical practice (32).

Table 1. Classification of cutting-edge biomaterials for peri-implantitis treatment.

Biomaterial category	Main mechanism	Potential clinical application in peri-implantitis	Current evidence / translational status
Bone graft substitutes and reconstructive biomaterials	Provide osteoconductive support, stabilize the clot, maintain defect volume, and support radiographic defect fill.	Contained or circumferential intrabony peri-implant defects; reconstructive surgical therapy after surface decontamination.	Clinically used; evidence supports selected defect-based use, but no graft material is universally superior [10,17-19].
Barrier membranes	Stabilize grafts, exclude rapidly proliferating soft tissue cells, support space maintenance, and protect the regenerative site.	Guided bone regeneration in selected peri-implant defects, especially where graft containment and space maintenance are needed.	Clinical use is established in regenerative surgery, but the additional benefit in peri-implantitis reconstruction remains debated [17,18,23].
Bioactive and antimicrobial membranes	Combine barrier function with antimicrobial, anti-inflammatory, or regenerative activity through incorporated bioactive agents.	Peri-implantitis defects with high contamination risk, membrane exposure risk, or need for enhanced local antimicrobial control.	Promising but mostly preclinical/early translational; cytocompatibility and clinical validation are required [24,25,29].
Antimicrobial coatings and surface modifications	Reduce bacterial adhesion, inhibit biofilm maturation, or deliver local antimicrobial agents from implant or biomaterial surfaces.	Preventive implant-surface design; adjunctive surface-functionalized materials; potential re-osseointegration support.	Strong experimental rationale: many systems remain preclinical or preventive rather than routine intraoperative treatment [24-30].
Nanoparticles and nano-engineered systems	Provide antimicrobial activity, drug delivery, surface functionalization, and modulation of local biological responses.	Local delivery vehicles, nanoparticle-loaded coatings, membranes, hydrogels, or graft adjuncts.	Promising preclinical evidence; clinical use limited by dose, cytotoxicity, release kinetics, and regulatory challenges [28,29].
Hydrogels and injectable platforms	Deliver antimicrobial, anti-inflammatory, or regenerative agents into irregular peri-implant defects; improve local retention.	Adjunctive local drug delivery; irregular peri-implant pockets or defects; combination with grafts or membranes.	Mostly preclinical/early translational; weak mechanical strength limits standalone regenerative use [29].
Local drug-delivery systems	Maintain therapeutic concentrations of antibiotics, antiseptics, anti-inflammatory agents, or biologics at diseased implant sites.	Deep pockets, irregular peri-implant defects, post-debridement antimicrobial support, early healing modulation.	Clinically attractive, but advanced platforms require evidence for sustained release and long-term clinical benefit [24,29].
Smart and multifunctional biomaterials	Combine antimicrobial activity, controlled release, inflammation modulation, osteoconduction, and regenerative signaling.	Complex peri-implantitis defects requiring simultaneous infection control and regenerative support.	Emerging concept; translation depends on safety, reproducibility, sterilization stability, handling, and clinical efficacy [24,25,29].

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Patient-specific scaffolds and 3D-printed biomaterials	Adapt scaffold geometry to defect morphology and combine structural support with bioactive or drug-delivery functions.	Complex or irregular peri-implant defects; future defect-adapted reconstruction and guided regenerative workflows.	Experimental/early translational in peri-implantitis; requires validation of fit, sterility, cost-effectiveness, and clinical benefit [17,43].
Bone graft substitutes and reconstructive biomaterials	Provide osteoconductive support, stabilize the clot, maintain defect volume, and support radiographic defect fill.	Contained or circumferential intrabony peri-implant defects; reconstructive surgical therapy after surface decontamination.	Clinically used; evidence supports selected defect-based use, but no graft material is universally superior [10,17-19].

GBR: guided bone regeneration.

5. Emerging technologies and adjunctive approaches

5.1. Laser-assisted therapy

Laser-assisted therapy has been investigated as an adjunctive approach for implant surface decontamination and peri-implant inflammation control (20,21). Different laser systems, including Er:YAG, diode, CO_2, and Nd:YAG lasers, have been evaluated for their ability to reduce bacterial load, remove granulation tissue, and modify or decontaminate implant surfaces (20,21). The theoretical advantages of laser therapy include antimicrobial activity, hemostasis, selective tissue interaction, and access to complex surface areas that may be difficult to instrument mechanically (20,21).

Among laser systems, Er:YAG lasers have received particular attention because of their ability to ablate hard deposits and decontaminate implant surfaces with relatively limited thermal damage when appropriate parameters are used (20,21). However, laser effects depend strongly on wavelength, energy settings, pulse duration, cooling, distance from the surface, implant surface type, and operator technique (20,21). Excessive energy or inappropriate use may cause surface alteration, heat generation, or damage to peri-implant tissues (20,21). Therefore, laser therapy should be considered a protocol-sensitive adjunct rather than a universally predictable treatment modality (20,21).

Current evidence suggests that lasers may improve selected clinical or microbiological outcomes in some peri-implantitis cases, but their additional benefit over conventional mechanical or surgical therapy remains inconsistent (20,21). Heterogeneity in study design, laser parameters, follow-up periods, and outcome definitions makes direct comparison difficult (20,21). For this reason, laser-assisted therapy should be interpreted as a potentially useful adjunct for surface decontamination or soft tissue management, but not as a standalone solution for advanced peri-implantitis (1,20,21).

5.2. Antimicrobial photodynamic therapy

Antimicrobial photodynamic therapy (aPDT) involves the use of a photosensitizer activated by light of a specific wavelength to generate reactive oxygen species that can damage bacterial cells and disrupt biofilms (22,23). In peri-implantitis treatment, photodynamic therapy has been proposed as an adjunct to mechanical debridement because it may reduce microbial load without relying on systemic antibiotics (22,23). This is clinically relevant because peri-implantitis lesions often contain complex biofilms, and repeated antibiotic exposure may raise concerns about antimicrobial resistance (11,13,22).

The effectiveness of photodynamic therapy depends on the photosensitizer, light wavelength, energy dose, exposure time, oxygen availability, biofilm maturity, and penetration of the photosensitizer into the peri-implant pocket or defect (22,23). Different photosensitizers may show different antimicrobial effects, and incomplete access to mature biofilm can limit treatment efficacy (22,23). Therefore, photodynamic therapy is most rational when used as an adjunct after mechanical disruption of biofilm rather than as a replacement for debridement (7,22,23).

Clinical and systematic review evidence suggests that adjunctive antimicrobial photodynamic therapy may improve some short-term clinical parameters, such as probing depth reduction or bleeding reduction, when compared with mechanical therapy alone in selected cases (22). However, long-term superiority and predictable disease resolution remain uncertain because protocols are heterogeneous and follow-up periods are often limited (22,23). Thus, photodynamic therapy may be useful as a low-invasive antimicrobial adjunct, but its role in advanced peri-implantitis still requires stronger clinical validation (22,23). It may also have a potential adjunctive role in maintenance-oriented protocols, although this application requires further clinical validation (22,23).

5.3. Air-abrasive and air-polishing systems

Air-abrasive and air-polishing systems have been used for biofilm removal and implant surface decontamination around diseased implants (24,25). These systems commonly use powders such as glycine, erythritol, or other low-abrasive particles to disrupt biofilm on implant surfaces and peri-implant tissues (24,25). Their potential advantages include improved access to irregular implant surfaces, reduced mechanical trauma compared with some metal instruments, and usefulness in both non-surgical and surgical settings (24,25).

Air-abrasive decontamination may be particularly useful when implant surface geometry limits access for curettes or

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ultrasonic instruments (24,25). However, its effectiveness depends on powder type, particle size, working distance, angulation, pressure, exposure time, and clinical access (24,25). Inappropriate use may cause soft tissue emphysema, surface changes, or incomplete biofilm removal in deep or inaccessible defects (24,25). Therefore, air-abrasive systems require careful technique and should be integrated into a broader decontamination protocol (24,25).

The clinical evidence for air-polishing and air-abrasive methods remains variable (24,25). Available clinical evidence suggests improvements in bleeding, plaque scores, and peri-implant inflammation in selected studies, but predictable resolution of established peri-implantitis is not consistently achieved by air-abrasive therapy alone (7,24,25). These systems are therefore best considered adjunctive tools for biofilm disruption and surface decontamination, especially when combined with surgical access, mechanical debridement, and supportive maintenance (1,7,24,25).

5.4. Electrochemical and electrolytic decontamination

Electrochemical or electrolytic decontamination has emerged as a promising technology for removing biofilm from implant surfaces (26). The principle is based on applying an electrical current or electrochemical process to disrupt biofilm and decontaminate titanium implant surfaces (26). This approach is attractive because it may reach microstructured or rough implant surfaces that are difficult to clean mechanically (26).

Electrochemical decontamination may offer advantages in terms of biofilm disruption without extensive mechanical alteration of the implant surface (26). However, clinical translation requires careful control of current, electrolyte composition, exposure time, safety, tissue compatibility, and device practicality (26). The technology must also be tested under clinically realistic conditions, where implant surfaces are surrounded by inflamed tissues, blood, saliva, bone defects, and limited access (8,26).

Although early evidence is promising, electrochemical decontamination remains less established than conventional mechanical or surgical protocols (26). Its future role may be as an adjunctive intraoperative decontamination method, particularly for rough implant surfaces or complex thread geometries (26). However, robust clinical studies are needed to determine whether improved surface cleaning translates into better disease resolution, bone stability, or reosseointegration (8,26).

5.5. Cold atmospheric plasma

Cold atmospheric plasma is an emerging antimicrobial technology that has been investigated for the decontamination of titanium implant surfaces and disruption of oral biofilms (27-31). Plasma can generate reactive species capable of damaging microbial cells and altering biofilm structure without producing the high temperatures associated with thermal plasma (27-31). This makes it attractive for implant surface decontamination, where antimicrobial activity must be balanced with preservation of surrounding tissues and implant surface integrity (27-31).

In peri-implantitis-related applications, cold atmospheric plasma may be useful because mature biofilms on titanium surfaces can be difficult to remove completely with conventional mechanical methods (7,11,27-31). Plasma-based approaches may also improve surface wettability or biological interaction after decontamination, although the clinical relevance of these effects still requires further investigation (27-31). The technology remains largely experimental or early translational, and standardized clinical protocols have not yet been established (27-31).

Important limitations include device availability, delivery into deep peri-implant defects, exposure time, compatibility with oral fluids, safety for soft and hard tissues, and evidence of long-term clinical benefit (27-31). Its potential value will depend on whether laboratory antimicrobial effects can be translated into predictable clinical improvements in inflammation control, defect stability, and implant survival (1,27-31).

5.6. Digital technologies, 3D printing, and patient-specific planning

Digital technologies may support peri-implantitis treatment by improving diagnosis, defect assessment, surgical planning, prosthetic evaluation, and patient-specific regenerative design (1,8,32-34). Cone-beam computed tomography, intraoral scanning, digital radiographic comparison, and implant-position analysis can help clinicians evaluate bone loss pattern, prosthetic access, implant angulation, and defect morphology (1,8). However, CBCT-based assessment should be used judiciously because radiation exposure, standardized interpretation, and integration with clinical findings remain important considerations (1,8). These factors are important because treatment selection depends heavily on whether the defect is contained, non-contained, esthetically sensitive, maintainable, or surgically accessible (8,12).

Three-dimensional printing and computer-aided design may be useful for future patient-specific regenerative strategies (12,32). Customized scaffolds, membranes, or surgical guides could theoretically improve adaptation to peri-implant defect morphology and support more precise regenerative or resective therapy (12,32). However, most 3D-printed and patient-specific biomaterial approaches remain experimental or early translational in the context of peri-implantitis (12,32). Their clinical adoption will require evidence of safety, sterility, fit accuracy, biological performance, cost-effectiveness, and superiority over conventional materials (12,32).

Artificial intelligence and machine-learning approaches may also contribute to peri-implantitis management by supporting risk assessment, radiographic bone-loss detection, treatment planning, and maintenance scheduling (33,34). However, these tools depend on high-quality datasets, standardized diagnostic criteria, external validation, and clinically interpretable outputs (33,34). At present, digital and AI-based approaches should be considered supportive tools for diagnosis and planning rather than independent therapeutic interventions (33,34). The emerging technologies and

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adjunctive approaches discussed in this section are summarized in Table 2.

6. Clinical evidence and translational relevance

The translational potential of advanced biomaterials and emerging technologies in peri-implantitis treatment varies considerably (1,7-10,12-34). Clinically established interventions include surgical access therapy, implant surface decontamination, conventional reconstructive biomaterials, and selected adjunctive technologies, which have been

Table 2. Emerging technologies and adjunctive approaches in peri-implantitis management.

Technology / adjunctive approach	Main treatment target	Clinical role	Main limitations	Evidence status / key references
Laser-assisted therapy	Biofilm reduction, granulation tissue removal, surface decontamination, soft tissue management.	Adjunct to non-surgical or surgical peri-implantitis therapy; Er:YAG, diode, CO2, and Nd:YAG systems have been investigated.	Protocol-sensitive; outcomes depend on wavelength, energy settings, cooling, implant surface, access, and operator technique.	Clinical/systematic review evidence exists, but additional benefit remains inconsistent [31,32].
Antimicrobial photodynamic therapy (aPDT)	Photosensitizer-mediated generation of reactive oxygen species to damage bacteria and disrupt biofilms.	Low-invasive antimicrobial adjunct after mechanical debridement or during maintenance-oriented protocols.	Depends on photosensitizer, light dose, oxygen availability, biofilm maturity, and access into the defect.	Some short-term clinical benefit reported; long-term superiority remains uncertain [33,34].
Air-abrasive / air-polishing systems	Mechanical biofilm disruption on exposed implant surfaces using low-abrasive powders.	Adjunctive decontamination in non-surgical and surgical settings; useful around complex surface geometry.	Technique-sensitive; depends on powder type, pressure, angulation, distance, exposure time, and access.	More clinically used than many emerging methods, but not sufficient as standalone treatment [9,35,36].
Electrochemical / electrolytic decontamination	Electrical or electrochemical disruption of biofilm on titanium implant surfaces.	Potential intraoperative adjunct for rough or threaded surfaces that are difficult to clean mechanically.	Requires control of current, electrolyte composition, exposure time, tissue safety, and device practicality.	Promising in vitro/early translational evidence; clinical protocols are not yet established [37].
Cold atmospheric plasma	Reactive species-mediated disruption of mature biofilms without high thermal damage.	Cutting-edge antimicrobial decontamination technology for titanium implant surfaces.	Requires validation of delivery into deep defects, exposure time, tissue safety, and long-term clinical effects.	Experimental/early translational; supported by in vitro and in situ titanium biofilm studies [38–42].
Digital imaging and CBCT-based planning	Defect morphology assessment, implant position analysis, prosthetic accessibility evaluation.	Supports defect-based decision-making, surgical planning, and risk assessment.	Requires standardized interpretation, radiation considerations, and integration with clinical findings.	Supportive diagnostic/planning role; not a therapeutic intervention by itself [1,10,17].
3D printing and patient-specific planning	Custom scaffold, membrane, or guide design adapted to defect morphology.	Future patient-specific regenerative or resective workflows in complex peri-implant defects.	Requires validation of fit accuracy, sterility, mechanical behavior, cost, and clinical superiority.	Experimental/early translational in peri-implantitis; related patient-specific scaffold evidence exists [17,43].
Artificial intelligence and machine learning	Risk prediction, radiographic bone-loss detection, treatment planning, and maintenance scheduling.	Potential support for personalized diagnosis and long-term monitoring.	Needs validated datasets, standardized definitions, external validation, and clinically interpretable outputs.	Emerging supportive tool; not a standalone treatment [44,45].

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aPDT: antimicrobial photodynamic therapy, CBCT: cone-beam computed tomography.

evaluated in human studies or systematic reviews (1,7-10,12,37-43).

Clinically adjunctive approaches, such as implantoplasty, reconstructive biomaterials in favorable defects, air-abrasive decontamination, and selected laser or antimicrobial photodynamic therapy protocols, have moderate evidence supporting their use in specific scenarios (8,12,20-25,35,36).

Many antimicrobial coatings, nanoparticles, smart hydrogels, electrochemical methods, cold atmospheric plasma, and patient-specific 3D-printed scaffolds remain primarily preclinical or early translational (13-19,26-34).

Overall, the available evidence supports integration of advanced biomaterials and emerging technologies into evidence-based surgical and supportive protocols (1,8,12-34). Representative clinical, translational, and preclinical studies are summarized in Table 1.

7. Discussion

The reviewed literature indicates that peri-implantitis management is evolving from a primarily mechanical and access-based approach toward integrated, biologically active, and technology-assisted strategies (1,8,12). Limitations of conventional therapy have driven the development of advanced biomaterials and adjunctive technologies to improve antimicrobial control, regenerative potential, and treatment personalization (12-34). This integrated relationship among conventional treatment foundations, advanced biomaterial-based strategies, emerging technologies, clinical relevance, and intended clinical impact is summarized in Figure 1.

No single biomaterial or technology can address all clinical and biological requirements of peri-implantitis treatment (1,8,12). Advanced biomaterials, including bioactive membranes, antimicrobial coatings, nanoparticles, hydrogels, and drug-delivery systems, aim to complement conventional reconstructive therapy and address infection control, regenerative support, and patient-specific needs (13-19,32). Emerging technologies, such as laser-assisted therapy, antimicrobial photodynamic therapy, air-abrasive decontamination, electrochemical methods, cold atmospheric plasma, digital workflows, 3D printing, and AI, may improve decontamination, treatment precision, and personalization (20-34). Their clinical translation depends on standardized protocols, validation, and demonstration of long-term benefit (1,8,20-34). Among the advanced biomaterials, bioactive and antimicrobial membranes have demonstrated promising preclinical outcomes, particularly in enhancing healing and reducing local bacterial load, while nanoparticles and hydrogels have shown strong experimental antimicrobial activity and controlled delivery potential (13-19,32). Smart and patient-specific 3D-printed scaffolds, though still largely preclinical, are highly adaptable for complex defects and may integrate with conventional reconstructive procedures in the near future (32).

Heterogeneity in study design, implant systems, defect morphology, treatment protocols, biomaterials, and outcomes continues to limit direct comparison of interventions and generalizability (1,4,8,12). Most studies still rely on surrogate or short-term outcomes, which do not necessarily reflect durable disease control, implant survival, or re-osseointegration (1,4,8,12). Therefore, future clinical evaluations should prioritize standardized and clinically meaningful long-term endpoints (1,4,8). Laser-assisted therapy and air-abrasive decontamination have accumulated the most clinical evidence to date, with improvements in biofilm disruption and soft tissue management observed in selected clinical scenarios (20-25). In contrast, electrochemical decontamination and cold atmospheric plasma remain largely experimental but may offer adjunctive benefits once standardized protocols and clinical validation are established (26-31). Emerging digital workflows, 3D printing, and AI-supported planning, while primarily translational, hold considerable potential to personalize treatment and improve precision when integrated with conventional approaches (32-34).

Overall, peri-implantitis management is moving toward integrated protocols that combine evidence-based surgical principles with advanced biomaterials, emerging technologies, and personalized supportive care (1,8,12-34). The success of these strategies relies on the ability to translate laboratory and preclinical findings into standardized, reproducible, and clinically validated workflows that ensure long-term inflammation control, defect stabilization, implant survival, and patient-centered outcomes (1,4,8,12).

These observations suggest that integrating biomaterials and emerging technologies with conventional treatment may optimize outcomes, but the current evidence favors laser-assisted therapy, air-abrasive systems, and selected bioactive membranes for early clinical adoption due to their stronger evidence base (13,14,20-25). Conversely, modalities with mostly preclinical support should be considered investigational adjuncts until long-term clinical validation is available.

8. Clinical limitations and future perspectives

The clinical use of advanced biomaterials and emerging technologies in peri-implantitis treatment remains limited by the lack of standardized protocols, heterogeneous study designs, short follow-up periods, and inconsistent outcome measures (1,4,8,12). Many antimicrobial coatings, nanoparticle systems, hydrogels, smart drug-delivery platforms, electrochemical methods, cold atmospheric plasma approaches, and patient-specific scaffold concepts are still supported mainly by preclinical or early translational evidence (13-19,26-34). Therefore, promising laboratory performance should not be interpreted as sufficient evidence for routine clinical use without validation in well-designed clinical studies (1,8,12,13).

Another clinical limitation is that the endpoints used to

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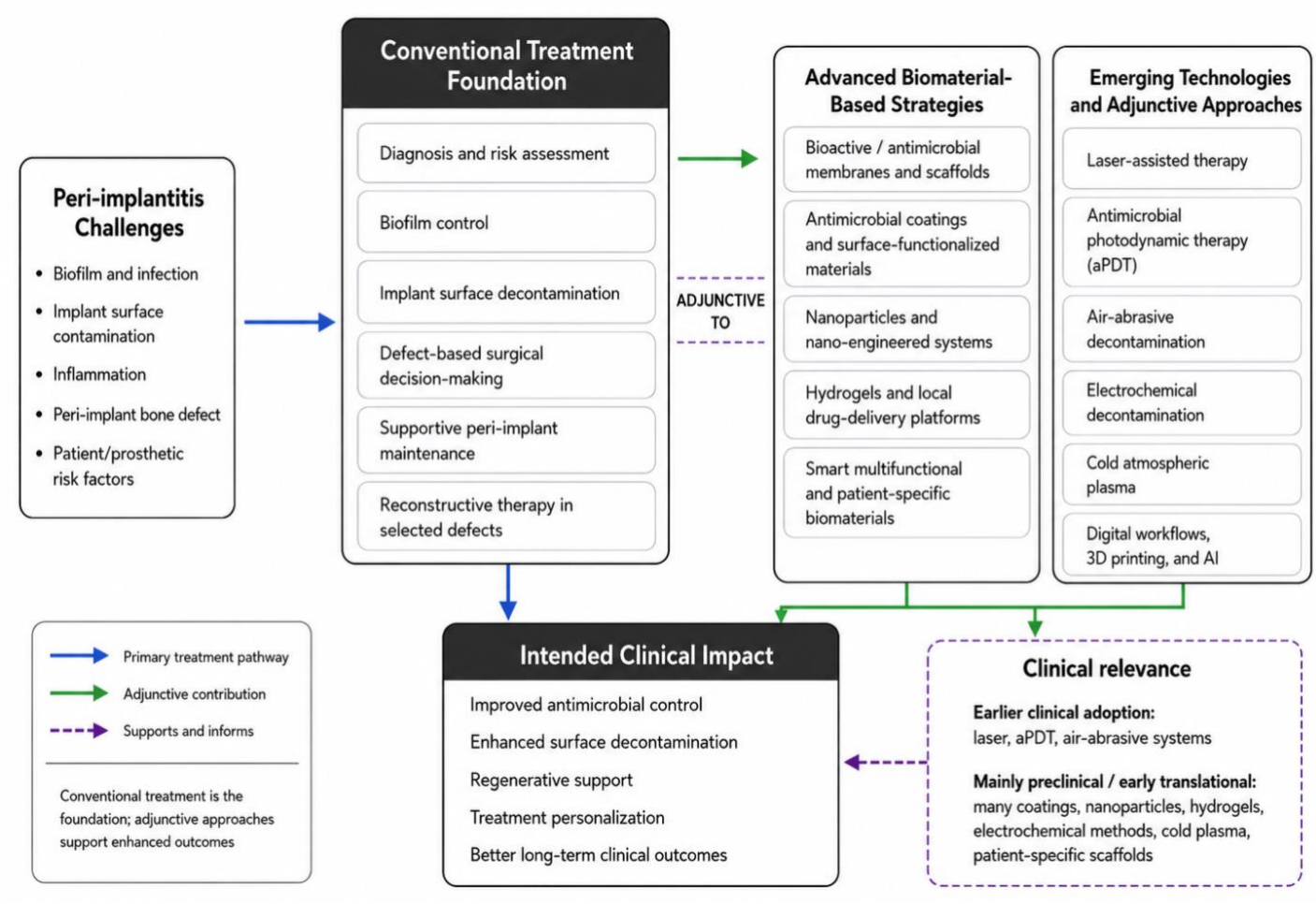


Figure 1. Integrated framework of biomaterials and technologies in peri-implantitis treatment. The figure illustrates conventional treatment as the clinical foundation and presents advanced biomaterial-based strategies and emerging technologies as adjunctive approaches. It also summarizes their intended clinical impact and relative clinical relevance, distinguishing approaches with earlier clinical adoption from those that remain mainly preclinical or early translational.

evaluate these approaches are not always clinically decisive (1,4,8). Short-term reductions in bacterial load, bleeding, probing depth, or inflammatory markers may be useful, but they do not necessarily demonstrate durable disease control, implant survival, recurrence prevention, or true re-osseointegration (1,4,8,12). Future studies should therefore evaluate clinically meaningful outcomes, including absence of suppuration, bleeding reduction, probing depth reduction, radiographic bone stability, recurrence rate, implant survival, patient-reported outcomes, and long-term maintenance success (1,4,8).

Future development should focus on integrated and clinically relevant approaches rather than novelty alone. Among the available adjunctive technologies, laser-assisted therapy, antimicrobial photodynamic therapy, and air-abrasive decontamination are more likely to see earlier and broader clinical use because they already have greater clinical experience and can be incorporated into existing non-surgical or surgical protocols (20-25). However, their use should remain indication-based and protocol-sensitive, as current evidence does not support any single decontamination technology as universally superior for all peri-implantitis defects or implant surfaces (7,9,10,20-25).

Multifunctional biomaterials, including bioactive membranes, antimicrobial coatings, nanoparticles, hydrogels, and smart drug-delivery systems, represent important future directions because they may combine antimicrobial control, healing modulation, and regenerative support in a single platform (13-19). Among these, hydrogels and local drug-delivery systems may be among the more clinically translatable platforms because they can be used as adjunctive carriers within existing treatment workflows rather than requiring complete replacement of current reconstructive procedures (12,18). In contrast, electrochemical decontamination, cold atmospheric plasma, patient-specific 3D-printed scaffolds, and AI-supported workflows remain highly promising but are likely to require more standardization, external validation, device optimization, and long-term clinical evidence before widespread adoption (26-34).

Ultimately, future peri-implantitis management will probably develop through stepwise integration of adjunctive technologies and biomaterial platforms into standardized,

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reproducible, and evidence-based clinical workflows (1,8,12). The success of these approaches should be judged not only by biological plausibility or technical performance, but also by long-term clinical benefit, safety, cost-effectiveness, usability, implant survival, maintenance success, and patient-centered outcomes (1,4,8,13-34).

9. Conclusion

This review indicates that advanced biomaterials and emerging technologies may improve selected aspects of peri-implantitis treatment, particularly antimicrobial control, implant surface decontamination, regenerative support, and treatment personalization (12-34). Among these approaches, laser-assisted therapy, air-abrasive decontamination, and antimicrobial photodynamic therapy appear closest to broader adjunctive clinical use, whereas most advanced coatings, nanoparticles, hydrogels, electrochemical approaches, cold atmospheric plasma, and patient-specific scaffolds remain primarily preclinical or early translational. These strategies should therefore be integrated cautiously within comprehensive, defect-based, risk-oriented, and maintenance-centered protocols, and future studies should prioritize standardized long-term, clinically meaningful outcomes (1,4,8,13-34).

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Ethics
This article is a review of the literature and does not involve direct intervention on human participants, use of identifiable human data, or animal experiments. Therefore, formal ethics committee approval, trial registration, and informed consent are not applicable.

Data availibility
Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Using artificial intelligence (AI)
It is declared by the authors of this manuscript that no generative artificial intelligence (AI) or AI-assisted technologies were used to generate content, ideas, or theories during the writing process of this work.

Author contributions
Mohammad Hossein Rasti: Conceptualization, Methodology, Investigation, Resources, Writing - Original draft, Writing - Review & editing, Visualization
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Conflict of interest
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References
1. Herrera D, Berglundh T, Schwarz F, Chapple ILC, Jepsen S, Sculean A, et al. Prevention and treatment of peri-implant diseases-The EFP S3 level clinical practice guideline. J Clin Periodontol. 2023;50 Suppl 26:4-76. doi:10.1111/jcpe.13823.
2. Berglundh T, Armitage G, Araujo MG, Avila-Ortiz G, Blanco J, Camargo PM, et al. Peri-implant diseases and conditions: consensus report of workgroup 4 of the 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions. J Clin Periodontol. 2018;45 Suppl 20:S286-S291. doi:10.1111/jcpe.12957.
3. Schwarz F, Derks J, Monje A, Wang HL. Peri-implantitis. J Clin Periodontol. 2018;45 Suppl 20:S246-S266. doi:10.1111/jcpe.12954.
4. Renvert S, Persson GR, Pirih FQ, Camargo PM. Peri-implant health, peri-implant mucositis, and peri-implantitis: case definitions and diagnostic considerations. J Clin Periodontol. 2018;45 Suppl 20:S278-S285. doi:10.1111/jcpe.12956.
5. Diaz P, Gonzalo E, Villagra LJG, Miegimolle B, Suarez MJ. What is the prevalence of peri-implantitis? A systematic review and meta-analysis. BMC Oral Health. 2022;22(1):449. doi:10.1186/s12903-022-02493-8.
6. Galarraga-Vinueza ME, Pagni S, Finkelman M, Schoenbaum T, Chambrone L. Prevalence, incidence, systemic, behavioral, and patient-related risk factors and indicators for peri-implant diseases: an AO/AAP systematic review and meta-analysis. J Periodontol. 2025;96(6):587-633. doi:10.1002/JPER.24-0154.
7. Cosgarea R, Sculean A, Shibli JA, Salvi GE. Efficacy of mechanical/physical approaches for implant surface decontamination in non-surgical submarginal instrumentation of peri-implantitis. A systematic review. J Clin Periodontol. 2023;50 Suppl 26:188-211. doi:10.1111/jcpe.13762.
8. Roccuzzo M, Mirra D, Roccuzzo A. Surgical treatment of peri-implantitis. Br Dent J. 2024;236(10):803-808. doi:10.1038/s41415-024-7405-9.
9. Baima G, Citterio F, Romandini M, Romano F, Mariani GM, Buduneli N, et al. Surface decontamination protocols for surgical treatment of peri-implantitis: a systematic review with meta-analysis. Clin Oral Implants Res. 2022;33 Suppl 23:106-114. doi:10.1111/clr.13992.
10. Hart K, Phipps KR, Goffin G, Frantsve-Hawley J. Mechanical and chemical decontamination of implant surfaces in the treatment of peri-implantitis: a systematic review. Clin Exp Dent Res. 2024;10(1):e839. doi:10.1002/cre2.839.
11. Belibasakis GN, Manoil D. Microbial community-driven etiopathogenesis of peri-implantitis. J Dent Res. 2021;100(1):21-28. doi:10.1177/0022034520949851.
12. Monje A, Pons R, Nart J, Figuero E, Sanz-Sanchez I, Ramanauskaite A, et al. Selecting biomaterials in the reconstructive therapy of peri-implantitis. Periodontol 2000. 2024;94(1):192-212. doi:10.1111/prd.12523.

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13. de Avila ED, van Oirschot BA, van den Beucken JJJP. Biomaterial-based possibilities for managing peri-implantitis. J Periodontal Res. 2020;55(2):165-173. doi:10.1111/jre.12707.
14. Yu YM, Lu YP, Zhang T, Zheng YF, Liu YS, Xia DD. Biomaterials science and surface engineering strategies for dental peri-implantitis management. Mil Med Res. 2024;11(1):29. doi:10.1186/s40779-024-00532-9.
15. Teule-Trull M, Altuna P, Arregui M, Rodriguez-Ciurana X, Aparicio C. Antibacterial coatings for dental implants: a systematic review. Dent Mater. 2025;41(3):229-247. doi:10.1016/j.dental.2024.12.001.
16. Esteves GM, Esteves J, Resende M, Mendes L, Azevedo AS. Antimicrobial and antibiofilm coating of dental implants-past and new perspectives. Antibiotics (Basel). 2022;11(2):235. doi:10.3390/antibiotics11020235.
17. Hosseini Hooshiar M, Shahbazmohamadi S, Zarepour A, Ranjbar M, Salehi R, Mahkam M, et al. Potential role of metal nanoparticles in treatment of peri-implant disease. BioMed Eng OnLine. 2024;23(1):105. doi:10.1186/s12938-024-01294-0.
18. Seoane-Viaño I, Seoane-Gigirey M, Bendicho-Lavilla C, Gigirey LM, Otero-Espinar FJ, Seoane-Trigo S. The integration of advanced drug delivery systems into conventional adjuvant therapies for peri-implantitis treatment. Pharmaceutics. 2024;16(6):769. doi:10.3390/pharmaceutics16060769.
19. Carinci F, Lauritano D, Bignozzi CA, Pazzi D, Candotto V, Santos de Oliveira P, et al. A new strategy against peri-implantitis: antibacterial internal coating. Int J Mol Sci. 2019;20(16):3897. doi:10.3390/ijms20163897.
20. Huang N, Li Y, Li W, Zhao R, Ou Y, Chen J, et al. The clinical efficacy of laser in the nonsurgical treatment of peri-implantitis: a systematic review and meta-analysis. Int J Implant Dent. 2024;10(1):54. doi:10.1186/s40729-024-00570-x.
21. Lin GH, Suarez Lopez Del Amo F, Wang HL. Laser therapy for treatment of peri-implant mucositis and peri-implantitis: an American Academy of Periodontology best evidence review. J Periodontol. 2018;89(7):766-782. doi:10.1902/jop.2017.160483.
22. da Fonseca VCP, Abreu LG, Andrade EJ, Aquino N, Lima RPE. Effectiveness of antimicrobial photodynamic therapy in the treatment of peri-implantitis: systematic review and meta-analysis. Lasers Med Sci. 2024;39(1):186. doi:10.1007/s10103-024-04135-7.
23. Schweigert C, Sahrmann P, Wiedemeier DB, Attin T, Schmidlin PR, Walter C. Influence of the photosensitizer in antimicrobial photodynamic therapy for peri-implantitis: a systematic review. Pharmaceutics. 2024;16(3):307. doi:10.3390/pharmaceutics16030307.
24. Huang N, Li Y, Chen H, Li W, Wang C, Ou Y, et al. The clinical efficacy of powder air-polishing in the non-surgical treatment of peri-implant diseases: a systematic review and meta-analysis. Jpn Dent Sci Rev. 2024;60:163-174. doi:10.1016/j.jdsr.2024.05.003.
25. Bi J, Khoshkam V, Hunter M, Cho C, Kar K. Effect of air polishing on the treatment of peri-implant diseases: a systematic review and meta-analysis. J Oral Implantol. 2023;49(6):616-628. doi:10.1563/aaid-joi-D-23-00114.
26. Koch M, Niedzielska I, Krysiak Z, Hahnel S, Stiesch M, Gollwitzer H, et al. Electrochemical disinfection of dental implants experimentally contaminated with microorganisms as a model for periimplantitis. J Clin Med. 2020;9(2):475. doi:10.3390/jcm9020475.
27. Kamionka J, Matthes R, Holtfreter B, Pink C, Schluter R, von Woedtke T, et al. Efficiency of cold atmospheric plasma, cleaning powders and their combination for biofilm removal on two different titanium implant surfaces. Clin Oral Investig. 2022;26(4):3179-3190. doi:10.1007/s00784-021-04300-0.
28. Haude S, Jablonowski L, Matthes R, Holtfreter B, Kocher T, von Woedtke T, et al. In vitro biofilm removal from TiUnite implant surface with an air-polishing device and cold atmospheric pressure plasma. BMC Oral Health. 2024;24(1):570. doi:10.1186/s12903-024-04230-9.
29. Altenburger MJ, Bergmann M, Antonelli A, Li J, Braun A, Schlagenhauf U, et al. In situ eradication of mature oral biofilm on titanium implant surfaces using cold atmospheric plasma. Dent J (Basel). 2025;13(5):210. doi:10.3390/dj13050210.
30. Idlibi AN, Al-Marrawi F, Hannig M, Lehmann A, Rueppell A, Schindler A, et al. Destruction of oral biofilms formed in situ on machined titanium surfaces by cold atmospheric plasma. Biofouling. 2013;29(4):369-379. doi:10.1080/08927014.2013.775255.
31. Matthes R, Jablonowski L, Holtfreter B, Pitchika V, Kocher T, Ekkernkamp A, et al. Efficiency of biofilm removal by combination of water jet and cold plasma: an in vitro study. BMC Oral Health. 2022;22(1):176. doi:10.1186/s12903-022-02195-1.
32. Ivanovski S, Breik O, Carluccio D, Alayan J, Staples R, Vaquette C. Alveolar bone regeneration using a 3D-printed patient-specific resorbable scaffold for dental implant placement: a case report. Clin Oral Implants Res. 2024;35(12):1655-1668. doi:10.1111/clr.14340.
33. Bonfanti-Gris M, Ruales E, Salido MP, Martinez-Rus F, Ozcan M, Pradies G. Artificial intelligence for dental implant classification and peri-implant pathology identification in 2D radiographs: a systematic review. J Dent. 2025;153:105533. doi:10.1016/j.jdent.2024.105533.
34. Mugri MH. Accuracy of artificial intelligence models in detecting peri-implant bone loss: a systematic review. Diagnostics (Basel). 2025;15(6):655. doi:10.3390/diagnostics15060655.
35. Lima RPE, Abreu LG, Belem FV, Pereira GHM, Brant RA, Costa FO. Is implantoplasty efficacious at treating peri-implantitis? A systematic review and meta-analysis. J Oral Maxillofac Surg. 2021;79(11):2270-2279. doi:10.1016/j.joms.2021.06.015.
36. Dasgupta D, Kaur H, Kumar M, Bhanot R, Dahiya V, Kumar A. Efficacy of implantoplasty in management of peri-implantitis: a systematic review. J Indian Prosthodont Soc. 2023;23(3):210-217. doi:10.4103/jips.jips_133_23.
37. Ramanauskaite A, Sculean A, Cafferata EA, Schwarz F. Biomaterials for reconstructive treatment of peri-implantitis. J Periodontal Res. 2025. doi:10.1111/jre.13414.
38. Friedmann A, Jung R, Bilhan H, Al Ghawi-Begovic H, Kauffmann F, Diehl D. Reconstructive surgical therapy of

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peri-implant defects with ribose cross-linked collagen matrix and crosslinked hyaluronic acid - a prospective case series. Clin Oral Investig. 2024;28(10):536. doi:10.1007/s00784-024-05942-6.
39. Mordini L, Sun N, Chang N, De Guzman JP, Generali L, Consolo U. Peri-implantitis regenerative therapy: a review. Biology (Basel). 2021;10(8):773. doi:10.3390/biology10080773.
40. Castro F, Bouzidi AS, Fernandes JCH, Bottino MC, Fernandes GVO. Bone tissue regeneration in peri-implantitis: a systematic review of randomized clinical trials. Saudi Dent J. 2023;35(6):589-601. doi:10.1016/j.sdentj.2023.05.022.
41. Rakasevic D, Scepanovic M, Mijailovic I, Misic T, Janjic B, Soldatovic I, Markovic A. Reconstructive peri-implantitis therapy by using bovine bone substitute with or without hyaluronic acid: a randomized clinical controlled pilot study. J Funct Biomater. 2023;14(3):149. doi:10.3390/jfb14030149.
42. Cho YJ, Jeong YT, Woo HN, Cho HW, Kang MG, Hwang SM, et al. Reassessing the use of membranes in peri-implantitis surgery: a systematic review and meta-analysis of in vivo studies. J Funct Biomater. 2025;16(7):262. doi:10.3390/jfb16070262.
43. Cheng J, Chen L, Tao X, Qiang X, Li R, Ma J, et al. Efficacy of surgical methods for peri-implantitis: a systematic review and network meta-analysis. BMC Oral Health. 2023;23(1):227. doi:10.1186/s12903-023-02956-6.

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