Critical appraisal of treatment modalities for peri-implantitis (Review)

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Abstract. Peri-implantitis is a biofilm-induced, immune-mediated inflammatory condition affecting ~1 in 5 patients bearing implants and remains one of the most clinically unresolved challenges in contemporary implantology. Although multiple therapeutic approaches have been proposed, no universally accepted treatment protocol exists, and the available evidence varies considerably in quality, consistency and long-term predictability. The present critical narrative review, guided by the principles of the Scale for the Assessment of Narrative Review Articles (SANRA), critically evaluates the evidence supporting major treatment modalities for peri-implantitis and synthesizes current knowledge into a clinically applicable, defect-morphology-based decision framework. A topic-specific literature search was independently conducted by two authors across the PubMed/MEDLINE, Scopus and Google Scholar databases for English-language publications from January, 2005 to December, 2025, covering six treatment categories. Non-surgical therapy is an essential, yet insufficient during the first phase, requiring surgical intervention for moderate-to-advanced disease. Within the current comparative evidence, reconstructive therapy exhibits a signal favoring xenogenic over autogenous bone substitutes for contained intrabony defects, although no single graft material has demonstrated consistent superiority across all outcomes. Across both surgical and emerging therapeutic modalities, clinical outcomes appear to be influenced less by the specific decontamination instrument used than by surgical access, defect management, wound stability, and structured supportive maintenance. Emerging approaches, including laser-assisted decontamination, electrochemical disinfection, autologous platelet concentrates and advanced drug-delivery systems, demonstrate biological promise; however, they remain constrained by limited evidence quality, small sample sizes and insufficient long-term follow-up. Overall, peri-implantitis management should evolve from a predominantly reactive treatment model toward a more predictive, preventive, personalized and participatory paradigm, extending the principles of P4 medicine proposed for periodontology to implant care.

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1. Introduction

Dental implants are a cornerstone of contemporary restorative dentistry, and as global placement rates have risen, the long-term biological stability of osseointegrated implants has emerged as a pressing challenge. Chief among the biological complications is peri-implantitis, a biofilm-induced, immune-mediated inflammatory condition affecting the soft and hard tissues around a functioning implant, characterized by inflammation of the peri-implant mucosa and the progressive loss of supporting bone (1).

The epidemiological burden is substantial and is increasing. A 2025 systematic review and meta-analysis conducted under the auspices of the Academy of Osseointegration and the American Academy of Periodontology reported a patient-level peri-implantitis prevalence of ~21%, with peri-implant mucositis affecting almost half of implant-bearing patients (2); a contemporaneous meta-analysis applying the 2017 World Workshop classification reported peri-implantitis in 25.0% of patients and 18.0% of implants (3). The condition is therefore neither rare nor self-limiting, and if inadequately managed,

culminates in irreversible osseous destruction and implant loss.

Despite this, management remains one of the most contested domains in implantology, with no universally accepted protocol. The heterogeneity of interventions, non-surgical mechanical debridement, adjunctive pharmacological agents, resective and regenerative surgery, laser-assisted decontamination, electrochemical disinfection, platelet concentrates and nanomaterial-based drug-delivery systems, reflects not a richness of evidence, but a plurality of incomplete solutions, each constrained by limitations in long-term efficacy, reproducibility, and predictability (4,5). Previous evidence syntheses and clinical guidance, including a systematic review of peri-implantitis therapy and the EFP S3 clinical practice guideline, have addressed established peri-implantitis treatment approaches (4,5); the present review extends this literature by integrating conventional, surgical, biologic, electrochemical and drug-delivery approaches within a single defect-morphology-oriented critical narrative framework, at a time when the evidence base varies widely in quality and translatability.

Accordingly, the present critical narrative review is guided by the principles of the Scale for the Assessment of Narrative Review Articles (SANRA), a validated six-domain quality framework (6). Its objectives are two-fold: To critically appraise the mechanistic rationale, clinical efficacy and limitations of each major treatment modality; and to synthesize this evidence into a coherent, clinically applicable decision-making framework based on disease severity, defect morphology, patient risk profile and evidence quality. The emphasis on disease severity and defect morphology is informed by evidence that these factors influence the selection of surgical peri-implantitis treatment modalities (7). The present review aimed to critically synthesize currently available evidence on conventional, surgical and emerging treatment modalities for peri-implantitis, and to translate these findings into a clinically applicable, defect-morphology-based decision framework.

2. Literature search methods

The present review was conducted in accordance with the principles of SANRA, a validated six-domain framework for transparency and rigor in non-systematic reviews, encompassing justification, objectives, search methodology, referencing, scientific reasoning and the appropriate presentation of endpoint data (6).

Literature search strategy. A literature search was independently conducted by two authors (RC and NS) across the PubMed/MEDLINE, Scopus and Google Scholar databases, restricted to English-language publications from, 2005 to December, 2025, a window selected to span the evolution from evidence-based non-surgical protocols to recent nanomaterial-based drug delivery. PubMed/MEDLINE and Scopus served as primary peer-reviewed databases; Google Scholar was consulted to identify further peer-reviewed records and verify search completeness, with any non-peer-reviewed gray literature screened for background context only and ineligible for inclusion. The search was structured as topic-specific sub-searches across six treatment categories (non-surgical, surgical, laser-assisted, electrochemical, platelet concentrates, drug-delivery systems). Each PubMed sub-search combined Medical Subject Headings (MeSH) with free-text keywords; as Scopus and Google Scholar do not implement MeSH indexing, free-text strings were adapted to each platform while preserving the same conceptual blocks. Representative PubMed/MEDLINE search strings for each treatment category are provided in Table SI; equivalent free-text strings were adapted for Scopus and Google Scholar while preserving the same conceptual blocks. Searches were last updated in April 2026. Records identified across the three databases were exported into Zotero and de-duplicated automatically by DOI and title-author match, with residual duplicates removed manually by cross-checking author, year and journal.

Inclusion and exclusion criteria. Eligible designs included randomized controlled trials (RCTs), systematic reviews and meta-analyses, prospective and retrospective clinical trials, observational studies, case series and reports where mechanistic insight was otherwise unavailable, *in vitro* and *in vivo* experimental studies, narrative reviews and evidence-based guidelines, including the European Federation of Periodontology (EFP) S3-level Clinical Practice Guideline (2023) (https://www.efp.org/education/continuing-education/clinical-guidelines/guideline-on-treatment-of-peri-implant-diseases/). Excluded were non-English publications, abstracts without full text, editorials, letters, opinion pieces unsupported by primary data, studies addressing peri-implant mucositis without reference to peri-implantitis, and studies on implant or prosthetic design without treatment outcomes.

Study selection and quality assessment. Subsequently, two authors (NS and AT) independently screened the titles and abstracts, resolving discrepancies by consensus; where the two screening authors could not reach consensus at either the title/abstract or full-text stage, a third author (AT or BG) independently reviewed the record and adjudicated by majority decision. Full texts were then assessed and reference lists hand-searched. No review protocol was registered. As a narrative rather than systematic review, the approach carries an inherent risk of selection bias, which was partially mitigated by the independent dual screening described above; no PRISMA flow diagram was generated and no formal risk-of-bias instrument (Cochrane RoB, GRADE, or AMSTAR 2) was applied; quality was appraised narratively, with explicit discussion of study design, heterogeneity, follow-up and sample-size constraints. The evidence-strength descriptors used in the summary tables (high, moderate, low or very low) represent the structured qualitative appraisal of the authors based on study design, consistency across studies, directness to peri-implantitis (as distinct from peri-implant mucositis) and follow-up duration, and are explicitly not formal GRADE certainty ratings. For transparency, the four-tier descriptor was applied using the following internal criteria, considered jointly rather than algorithmically: i) High, consistent findings across multiple RCTs or high-quality systematic reviews directly addressing peri-implantitis, with follow-up of three years or more. ii) Moderate, consistent findings from RCTs or systematic reviews with moderate heterogeneity, follow-up <3 years, or some indirectness (e.g., partial extrapolation from

periodontitis data). iii) Low, findings limited to small RCTs, retrospective studies, or systematic reviews with substantial heterogeneity or high risk of bias. iv) Very low, evidence confined to case series, *in vitro* or preclinical studies, or single small studies without comparator groups. This approach mirrors the general domains considered by GRADE (study design, consistency, directness, precision) in spirit, but was applied narratively by the two lead reviewing authors (RC and NS) rather than through formal certainty-rating software, dual independent GRADE assessment, or a pre-specified algorithm, and should not be interpreted as equivalent to a GRADE rating. A SANRA domain self-assessment, mapping each of the six items to the relevant sections of this review, is provided in Table SII.

Operational definitions. For clarity, the present review adopts the following definitions, applied consistently throughout: Resolution denotes the achievement of the defined clinical endpoint, residual probing pocket depth (PPD) ≤5 mm, no bleeding on probing (BOP) at more than one site and no suppuration (8); disease control denotes the stabilization of clinical parameters and the arrest of further bone loss without necessarily meeting the strict resolution endpoint; success denotes a composite outcome combining resolution or disease control with the absence of complications, as defined by the primary source study; and survival denotes implant retention in function, irrespective of peri-implant health status. As primary studies do not use these terms uniformly, some imprecision inherited from the source literature is unavoidable and is noted where relevant.

3. Non-surgical management

Peri-implantitis management follows a stepwise, phase-based philosophy analogous to periodontitis, in which non-surgical therapy is the essential first phase. Its goals are to reduce peri-implant microbial burden, control modifiable risk factors, establish a stable environment for healing and determine whether surgery is subsequently required. Although non-surgical therapy alone rarely resolves moderate-to-advanced disease, its successful execution is a prerequisite for any surgical phase and a determinant of long-term outcomes (5,8). Irrespective of modality, durable peri-implant health is contingent on self-performed plaque control, adherence to supportive care, and the modification of systemic and behavioral risk factors (9).

Cause-related non-surgical interventions. Effective patient-performed biofilm control is the biological foundation of all professional treatment; structured individualized oral hygiene instruction and motivational support are essential, given the established association between inadequate plaque control and peri-implantitis, particularly in high-risk groups, such as patients with a history of periodontitis, smokers and those with poorly controlled diabetes (2,5,10,11). Addressing modifiable risk factors is equally indispensable: A history of periodontitis and smoking are among the most consistently identified risk factors, and their persistence reduces clinical response and raises recurrence (11); thus, smoking-cessation counseling and periodontal risk assessment need to be incorporated prior to any surgical phase. Unfavorable prosthetic design such as over-contoured restorations, deep mucosal tunnels, cement excess and inadequate embrasures impedes biofilm removal and should be corrected by prosthesis cleaning, modification, or redesign prior to or concurrent with submucosal debridement (5,10).

Mechanical instrumentation. Supra- and submarginal mechanical debridement is the foundational non-surgical intervention; yet, a critical appraisal of the evidence indicates that it is consistently insufficient for resolution in established disease. The biological basis is the threaded, roughened macro- and micro-topography that facilitates osseointegration, but renders submucosal biofilm physically inaccessible to conventional instruments, rendering reliably complete submucosal decontamination difficult with conventional instruments (4,5,12). The available instruments and their critically appraised evidence are compared in Table I.

Adjunctive therapies. The insufficiency of mechanical debridement alone has driven the investigation of chemical, antibiotic and biological adjuncts. Locally administered antiseptics, principally chlorhexidine (CHX), confer only marginal benefit: Controlled studies comparing air-abrasive debridement with and without adjunctive CHX found no significant difference in mean PPD reduction (13), and a double-blind surgical trial found no significant clinical or radiographic advantage for adjunctive CHX implant-surface decontamination (14), reflecting rapid salivary washout and poor biofilm penetration. Locally delivered antibiotics (minocycline, doxycycline) build on early tetracycline-fiber data (15) and yield a modest ~0.6 mm additional PPD reduction with resolution in 20-30% of cases (16). Systemic antibiotics, such as metronidazole alone or with amoxicillin have been associated with greater PPD and BOP reductions, an effect reported to be most evident at modified (rough) surfaces and initially deep sites (17-19), with one meta-analysis reporting PPD and probing attachment level gains of 1.15 and 1.10 mm, respectively, with systemic antibiotics (16). Another meta-analysis identified systemic antimicrobials as the only adjunct with a significant PPD reduction (1.56 mm) and a ~3-fold increase in treatment success (odds ratio, 3.23), albeit with high heterogeneity (20). These benefits need to be weighed critically: Some large antibiotic effects derive from comparators in which control-group debridement performed unusually poorly (21); in the surgical setting, adjunctive systemic antibiotics are frequently administered perioperatively; however, they have demonstrated a clear advantage mainly at modified-surface implants rather than as a routine measure (17); all prescribing needs to be balanced against antimicrobial resistance, since dentistry accounts for ~10% of global antibiotic prescriptions and stewardship principles caution against routine adjunctive use (22). Within a stewardship framework, adjunctive systemic antibiotics are most defensible in a narrow set of circumstances: Modified (rough)-surface implants with deep, actively progressing lesions where mechanical access is inherently limited, and cases refractory to debridement alone with objective clinical or microbiological evidence of ongoing infection (17,20). They should generally be avoided as a routine or first-line adjunct in shallow or slowly progressing lesions, in patients without recognized risk factors for treatment failure, and whenever

Table I. Mechanical instrumentation modalities for non-surgical peri-implantitis therapy.

Instrument	Rationale/mechanism	Critically appraised evidence	Role	(Refs.)
Curettes (titanium/plastic)	Manual debridement avoiding metallic surface damage	Modest effect only; BOP reduction 20-50%, PPD reduction ≤1 mm; no resolution as monotherapy	Baseline; insufficient alone.	(21)
Ultrasonic devices	Oscillating tip; alternative/adjunct to manual instrumentation	Effective for mucositis; no clinically meaningful microbiological or clinical change in established peri-implantitis	Adjunct; limited in peri-implantitis.	(65)
Air-abrasive devices (glycine/erythritol)	Low-abrasion powder spray reaching threaded surfaces	Superior BOP reduction vs. curettes; variable PPD effect; powder choice affects cleaning and surface roughness; resolution inconsistent	Optional adjunct; not routinely advised submarginally per EFP S3.	(5,66,67)
Lasers (Er:YAG, diode)	Bactericidal, selective ablation, access to complex topography	Short-term benefit not maintained; no consistent superiority over mechanical debridement (detailed in above in the text)	Not recommended (EFP S3).	(5,39,68)
Oral irrigators/ interdental brushes	Self-administered home biofilm control	Useful adjunct for mucositis and maintenance; sparse evidence for active peri-implantitis	Supportive home care only.	(9)

Role classifications denote the structured qualitative appraisal of the authors and do not constitute formal GRADE certainty ratings. BOP, bleeding on probing; EFP, European Federation of Periodontology; Er:YAG, erbium-doped yttrium aluminum garnet (laser systems detailed above in the text and in Table IV); PPD, probing pocket depth.

debridement quality itself has not first been optimized, since several of the reported antibiotic benefits may reflect comparator debridement that was itself suboptimal rather than a true antibiotic-specific effect (21). Any prescribing decision should be individualized, informed by microbiological sampling where feasible, and should follow institutional or national antimicrobial stewardship guidance rather than generalized protocols. Antimicrobial photodynamic therapy (aPDT) (19), probiotics (23) and 35% phosphoric-acid gel (24) each lack a demonstrated clinical advantage over mechanical debridement. The adjunctive interventions and their critically appraised evidence are compared in Table II.

Critical appraisal, endpoints and decision pathway. A consistent pattern emerges: Although each modality produces statistically measurable improvement, none achieves predictable or complete resolution in moderate-to-advanced disease against the defined endpoint of residual PPD ≤5 mm with no BOP at more than one site and no suppuration (5,8). Reported resolution rates range from 20-30% with local antibiotics to a widely variable 2-65% with systemic antibiotics, reflecting profound heterogeneity in design, baseline severity and debridement quality (20,25). The fundamental constraint is biological rather than technical. The inability of available instrumentation to reliably decontaminate roughened implant surfaces, which defines the ceiling of non-surgical outcomes regardless of adjunct.

Outcomes should be assessed at 6-12 weeks using residual PPD, bleeding tendency, suppuration, oral hygiene and prosthesis cleanability (8). Patients meeting the endpoint enter structured supportive peri-implant care individualized maintenance comprising scheduled recall, professional submarginal biofilm removal, reinforcement of self-performed plaque control and ongoing risk-factor management [associated with 76-100% implant survival at 5 years (5,26)]; those who do not, or who present with moderate-to-advanced bone loss, deep residual pockets, or persistent suppuration, are considered for surgery, as discussed below (Fig. 1).

4. Surgical management

Consistent with the recommendation in the EFP S3 guidelines (https://www.efp.org/education/continuing-education/clinical-guidelines/guideline-on-treatment-of-peri-implant-diseases/) that peri-implantitis therapy begin with a non-surgical step irrespective of presentation severity, surgery is indicated only when non-surgical therapy fails to reach the defined endpoint at the 6-12-week reassessment, as noted above, rather than on the basis of initial presentation alone (5,27-29). Even implants presenting with deep pockets, suppuration and substantial bone loss are expected to undergo an initial non-surgical phase, which reduces biofilm burden, allows the correction of modifiable risk factors and prosthetic deficiencies, and establishes a less inflamed field should surgery subsequently prove necessary (5). A distinct decision precedes this sequence: Upon diagnosis, clinicians should first determine whether the affected implant is treatable at all; implants that are non-maintainable, non-restorable, grossly mobile, or associated with bone loss beyond reconstructive salvage may

Table II. Evidence synthesis for non-surgical adjunctive interventions, mapped to EFP S3 (2023) recommendations.

Intervention	Evidence level	Context (Refs.)	Key findings (Refs.)	EFP S3 recommendation (Refs.)
Local antiseptics (CHX)	Low	Non-surgical (13); surgical-adjunct (14)	Limited benefit beyond debridement; rapid salivary washout	Not recommended routinely (13,14)
Local antibiotics (minocycline/ doxycycline)	Moderate	Non-surgical (15,16)	~0.6 mm extra PPD reduction; 20-30% resolution	Not suggested routinely; possible selective use should be justified clinically (15,16).
Systemic antibiotics (amoxicillin + metronidazole)	Moderate	Non-surgical (18,20); surgical-adjunct (17)	1-1.56 mm PPD reduction; ~3x success odds; AMR concerns; pooled PPD estimate reported with high heterogeneity in the source meta-analysis (20)	Not recommended routinely; selective use only with stewardship justification (17,18,20,22)
aPDT	Low	Non-surgical/ mixed (19)	No consistent benefit over mechanical debridement	Not recommended (19)
Probiotics	Low	Non-surgical (23)	No significant PPD reduction; added economic burden	Not recommended (23)
Phosphoric acid (35% gel)	Low	Surgical-adjunct (24)	Greater bacterial-load reduction; no clinical difference	Not addressed (24)

Evidence-level descriptors (high, moderate, low or very low) denote the structured qualitative appraisal of the authors, based on study design, consistency across studies, directness to peri-implantitis and follow-up duration, and do not constitute formal GRADE certainty ratings. EFP S3 recommendation categories are derived from the study by Herrera *et al* (5). AMR, antimicrobial resistance; aPDT, antimicrobial photodynamic therapy; BOP, bleeding on probing; CHX, chlorhexidine; PPD, probing pocket depth.

be considered for explantation independent of, and prior to, the non-surgical-to-surgical sequence described herein (5). Its goals are to resolve inflammation, arrest bone loss, eliminate pathogenic pockets, decontaminate the implant surface under direct vision and where defect morphology permits, regenerate lost bone and, where biologically feasible, promote re-osseointegration (29-31). Success depends not only on technical execution, but also on the quality of the preceding non-surgical phase, the risk profile of the patient and structured post-operative care (29).

Defect morphology and modality selection. A critical determinant of surgical success, insufficiently emphasized, which is largely emphasized in the literature, is osseous defect morphology, which governs both regenerative potential and the appropriateness of each modality. Defects most commonly present with combined intrabony (vertical) and suprabony (horizontal) components, with contained circumferential intrabony defects being the most regeneratively favorable (7). Morphology defined by remaining bony walls, intrabony depth, and the presence of a supracrestal horizontal component should be assessed systematically prior to surgery using periapical radiography and intraoperative inspection. In general, access flap surgery suits shallow defects; resective therapy suits supracrestal horizontal defects in non-aesthetic regions; reconstructive therapy is most predictable for contained three- or four-wall intrabony defects; and combined therapy addresses the mixed-morphology defects that predominate in practice (27). The modalities and their critically appraised evidence are compared in Table III.

Critical appraisal of surgical modalities. Of note, three findings warrant emphasis beyond the tabulated outcomes. First, post-operative soft-tissue recession is a predictable consequence of access flap and resective therapy (0.95-1.9 and ~1.22 mm, respectively) (29,32), and in the anterior aesthetic zone, this can render a functionally successful result cosmetically unacceptable; the likelihood and degree of recession should therefore be discussed explicitly during consent and soft-tissue augmentation considered where aesthetics is paramount (28).

Second, a clinically important and counterintuitive finding is the apparently superior performance of xenogenic over autogenous bone in guided bone regeneration (GBR) within the current comparative evidence. Although recent comparative syntheses suggest a signal favoring xenogenic substitutes over autogenous bone for certain clinical outcomes (notably BOP and PPD reduction), no graft-material-membrane combination has demonstrated consistent superiority across all reconstructive endpoints

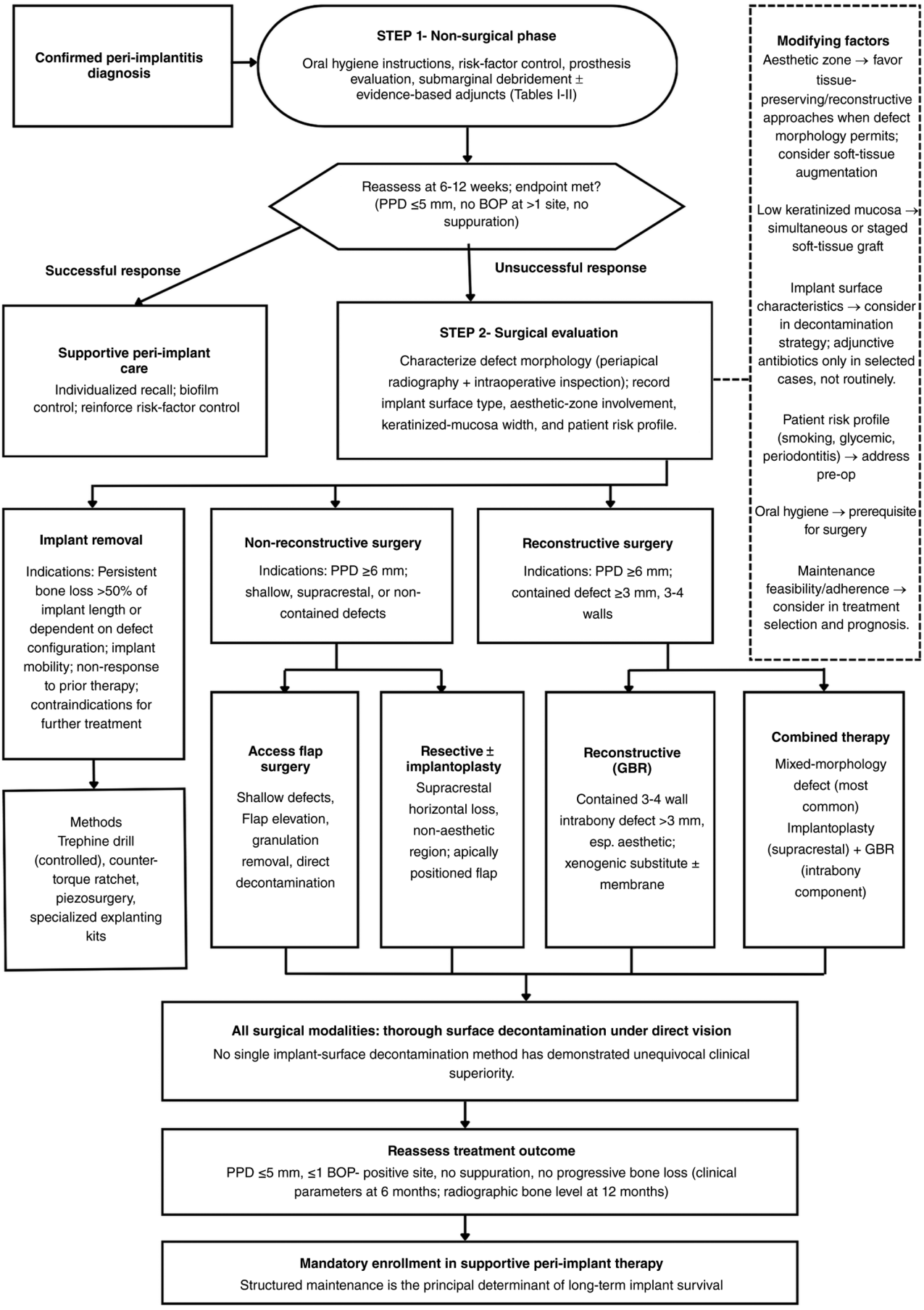

Figure 1. Defect-morphology-based treatment decision algorithm for peri-implantitis, informed by the European Federation of Periodontology (EFP) S3 clinical practice guideline (5) and the Academy of Osseointegration (AO)/American Academy of Periodontology (AAP) 2025 consensus on prevention and management of peri-implant diseases and conditions (76). BOP, bleeding on probing; GBR, guided bone regeneration; PPD, probing pocket depth.

Table III. Evidence synthesis for surgical peri-implantitis modalities.

Modality	Primary indication/ procedure	Key outcomes	Evidence source/ follow-up (Refs.)	Evidence level	Notable limitations (Refs.)
Access flap surgery (open flap debridement)	Shallow defects; flap elevation, granulation removal, direct decontamination	53-82% implant success at 1-5 years; arrests bone loss	Narrative reviews synthesizing cohort data, 1-5 years (28,29)	Moderate	Predictable recession 0.95-1.9 mm; limited re-osseointegration (28,29).
Resective therapy (± implantoplasty)	Supracrestal horizontal loss, non-aesthetic zones; pocket elimination, apical flap	Pooled PPD reduction ~2.04 mm (33.4%); a single case series additionally reported 83-87% resolution, ~87% survival[a]	Meta-analysis of RCTs/cohorts (32); single case series, 2-6 years (69)	Moderate	Pooled recession ~1.22 mm; worse on modified surfaces; implantoplasty risks (fracture, thermal damage, Ti particles) (32,69,70).
Reconstructive therapy (guided bone regeneration, GBR)	Contained intrabony defects ≥3 mm, 3-4 walls, adequate keratinized mucosa; grafting ± membrane	MBL gain 1.7-2.1 mm; defect fill ~57%; PPD reduction 2.32-3.16 mm; survival 76-100% at 5 years	Network meta-analysis and systematic reviews, up to 5 years (30,31)	Moderate	No membrane shown superior; exposure risk; less predictable in uncontained defects (30-32,35).
Combined therapy	Mixed suprabony + intrabony defects (most cases); implantoplasty + grafting ± membrane	BOP reduction ~75%; PPD ~2.5 mm; defect fill 52-93%; survival ~90% at 24 mo; resolution 74%	One RCT cohort followed serially at 6 months/ 4 years/7 years[b] (33,34,72); separate 2-year cohort (71)	Moderate	Heterogeneous study designs; no decontamination method shown superior (33,34,71,72).
Supportive peri-implant therapy	All patients post-surgery; individualized recall, biofilm control	Survival 76-100% at 5 years, 70-99% at 7 years; stable bone in majority	Single uncontrolled cohort, n=24, 5 years (26); narrative review (29) and consensus report (70)	Moderate	Compliance-dependent; recall interval not standardized; primary source is a single small uncontrolled cohort, not multiple comparative studies (26,29,33,70).

Evidence-level descriptors (high, moderate, low or very low) denote the structured qualitative appraisal of the authors based on study design, consistency across studies, directness to peri-implantitis and follow-up duration, and do not constitute formal GRADE certainty ratings. [a]The 83-87% resolution and ~87% survival figures derive from a single 32-patient case series (69) without a comparator group; they should be read as very-kow-tier evidence within this otherwise moderate-rated row. [b]Previous studies (33,34,72) report serial follow-up (6 months, 4 years and 7 years) of the same original patient cohort rather than independent studies. RCT, randomized controlled trial; BOP, bleeding on probing; GBR, guided bone regeneration; MBL, marginal bone level; PPD, probing pocket depth; Ti, titanium.

and defect types (30,31). A plausible explanation lies in differing resorption kinetics: Autogenous bone, though osteogenic, may resorb more rapidly and may thus undermine the space-maintaining function important to GBR, whereas xenogenic substitutes may resorb more slowly and better maintain scaffold volume during early healing (30). This challenges the assumption that autogenous bone is the gold standard for peri-implantitis GBR; notably, no

membrane type shows clear superiority, and membrane use carries exposure and morbidity risks (29).

Third, no specific decontamination method used during surgery, whether erbium-doped yttrium aluminum garnet (Er:YAG) laser irradiation or plastic curettes with saline, has demonstrated superiority over the alternatives at up to 7 years of follow-up, based on the limited number of controlled comparisons available (33,34). Surgical success is therefore driven by the quality of access, the completeness of granulation removal, the adequacy of defect management and the integrity of wound closure rather than by the selection of the decontamination instrument (35). Key surface characteristics, however, do modulate outcomes: Modified (rough or textured) surfaces are more difficult to decontaminate and have been associated with poorer resective results and greater disease progression than machined surfaces, and they are also the context in which adjunctive systemic antibiotics show their main effect (17,29). It should also be emphasized that, consistent with systematic-review consensus, no single bone-graft material or barrier-membrane type has demonstrated clear superiority over the alternatives in reconstructive therapy (31). Across all modalities, long-term success is ultimately contingent on enrollment in structured supportive peri-implant therapy; failure to maintain patients post-operatively is among the most significant modifiable risk factors for recurrence and implant loss (26).

Clinical decision pathway. Following reassessment at 6-12 weeks (Fig. 1), patients with persistent PPD >5 mm, ongoing BOP or suppuration, or progressive bone loss are evaluated for surgery, with the preoperative characterization of defect morphology, aesthetic-zone involvement, keratinized-mucosa width and risk factors (27). Shallow supracrestal horizontal loss in non-aesthetic regions indicates resective therapy with implantoplasty; contained three- or four-wall intrabony defects ≥3 mm, particularly in aesthetic regions, indicate reconstructive therapy with xenogenic substitutes with or without a membrane; mixed-morphology defects, the most frequent scenario, indicate combined therapy integrating implantoplasty with GBR (7,27,30,31). Across the available comparative evidence, no decontamination instrument or method has demonstrated superiority over the alternatives, and all patients must enter structured supportive peri-implant therapy immediately after surgery (26).

Integrating modifying factors into the algorithm. As illustrated in Fig. 1, decision-making is primarily organized around defect morphology; however, several patient- and implant-level modifiers should be layered onto this framework in clinical practice rather than applied as an afterthought. Implant surface characteristics influence both instrument selection and expected outcome: Modified (rough or textured) surfaces are harder to decontaminate and respond less predictably to resective therapy, and are also the context in which adjunctive systemic antibiotics show their clearest benefit (17,29); surface type should therefore inform both adjunct selection and outcome expectations, independent of defect morphology. Aesthetic-zone location shifts the risk-benefit balance away from resective approaches, given their predictable recession (0.95-1.9 mm), toward reconstructive or combined therapy with soft-tissue augmentation, even where defect morphology alone may favor a resective approach (28). Adequate keratinized mucosa width supports flap management, wound closure and long-term maintenance; its absence may favor a staged approach incorporating soft-tissue grafting before or during definitive surgery (27). The patient risk profile, namely smoking status, glycemic control, and periodontitis history, should be addressed prior to surgery, since unmodified risk factors reduce the probability of achieving and maintaining the treatment endpoint regardless of the surgical modality selected (11). Finally, adequate self-performed oral hygiene is itself a prerequisite for surgery, not merely a modifier of modality choice: the EFP S3 guideline recommends against performing surgical treatment of peri-implantitis in patients who have not achieved and are not maintaining adequate self-performed oral hygiene (5), and this should be confirmed before surgery is undertaken. The feasibility of structured supportive maintenance remains separately relevant to modality selection: As long-term implant survival across all surgical modalities is contingent on enrollment in supportive peri-implant therapy (26), a patient unable or unwilling to commit to structured recall represents an additional modifier that should temper the choice of more resource-intensive reconstructive or combined approaches in favor of simpler, more maintainable interventions. These modifiers do not replace the defect-morphology-based pathway in Fig. 1, but should be applied concurrently with it.

5. Lasers in the treatment of peri-implantitis

Laser technology has attracted clinical and commercial interest for its theoretically compelling advantages, such as bactericidal decontamination of complex topographies, selective calculus removal, biostimulation and access to areas inaccessible to mechanical instruments (36). A critical appraisal, however, reveals a persistent disconnect between these advantages and clinical outcomes: Across multiple systematic reviews, laser therapy has produced outcomes broadly comparable to, but not consistently superior to conventional mechanical debridement, with no laser system demonstrating long-term superiority (37,38). Given this absence of consistent superiority over conventional therapy, routine adoption should be considered cautiously, particularly in light of the additional equipment requirements involved (4).

Among the laser systems, the Er:YAG has the most extensively studied evidence base rather than a demonstrably superior one: Its wavelength is well absorbed by water and hydroxyapatite, enabling precise ablation with minimal thermal damage under water cooling (39), and a meta-analysis of solid-state lasers showed statistically significant PPD, BOP and clinical attachment level improvements (weighted mean PPD difference., 0.39 mm) that were nonetheless modest, not consistently maintained and broadly comparable to conventional mechanical debridement, supporting at most adjunctive, not standalone use (40). CO_2 lasers have been evaluated mainly as adjuncts for implant-surface decontamination in surgical peri-implantitis therapy; although CO_2 irradiation is largely reflected by titanium, high-energy delivery may still induce temperature rise, with potential for surface alteration and peri-implant tissue damage (41). In one RCT,

Table IV. Evidence synthesis for laser systems in peri-implantitis management.

Laser system	Wavelength	Mechanism	Key clinical outcomes	Evidence level	(Refs.)
Erbium-doped yttrium aluminum garnet (Er:YAG)	2,940 nm	Photomechanical; water/HA absorption	PPD reduction ~0.39-0.65 mm; comparable to conventional at 7 years; adjunct only	Moderate	(33,40)
Carbon dioxide (CO_2)	10,600 nm	Photothermal; bactericidal	Mixed; possible role in deep intrabony defects with GBR; no subgingival fiberoptic access	Low	(37,38,41)
Diode	810-980 nm	Photothermal; pigment absorption	Marginal bone-loss signal in one RCT	Low	(42)
Neodymium-doped yttrium aluminum garnet (Nd:YAG)	1064 nm	Deep photothermal penetration	Inconsistent; documented titanium surface melting/ cracking	Low	(40)
Erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG)	2,780 nm	Photomechanical/ photothermal	*In vitro* and case series only; no controlled evidence	Very low	(37)

Evidence-level descriptors (high, moderate, low or very low) denote the structured qualitative appraisal of the authors based on study design, consistency across studies, directness to peri-implantitis and follow-up duration, and do not constitute formal GRADE certainty ratings. GBR, guided bone regeneration; HA, hydroxyapatite; PPD, probing pocket depth.

adjunctive 810-nm diode laser therapy provided no additional clinical benefit over conventional scaling and was associated with greater marginal bone loss at 6 months (42); their role within aPDT protocols, where the photosensitizer rather than the wavelength is bactericidal, remains very-low-quality evidence (5,43). A strong safety caution applies to the neodymium-doped yttrium aluminium garnet (Nd:YAG) laser: Photothermal damage to titanium surfaces, including melting, cracking, and surface alteration has been reported; thus, its direct application to implant surfaces is generally cautioned against (36,37). Overall, no laser system has demonstrated consistent long-term superiority over conventional debridement, as monotherapy or adjunct (38,44); Er:YAG may serve as a useful adjunct in selected contexts, although technological sophistication should not be conflated with clinical efficacy. In addition, the EFP S3 (2023) guidelines recommend against laser use for non-surgical submarginal instrumentation (5). The principal systems are compared in Table IV.

6. Electrochemical disinfection

Electrochemical disinfection is among the most conceptually innovative decontamination approaches to emerge recently, addressing a persistent challenge: Surface-topology-independent biofilm removal from contaminated titanium without mechanical or thermal damage (45). The GalvoSurge® system, currently the most extensively studied commercial system implementing this principle in peri-implantitis research, loads the contaminated implant as a cathode against a platinized anode in a sodium-formate electrolyte; the process generates hydrogen cations that penetrate the biofilm matrix and hydrogen microbubbles that exert a physical lifting force, detaching biofilm even from thread valleys and micro-roughened areas inaccessible to conventional instruments, independently of implant design (46). A clinically significant advantage is the preservation of surface integrity: Unlike titanium brushes or Nd:YAG irradiation, electrolytic cleaning does not alter implant macro- or micro-topography, maintaining the osseoconductive roughness essential for re-osseointegration (47).

The *in vitro* evidence is consistent: Electrolytic cleaning achieves the near-complete removal of mature multispecies biofilm, with bacterial reductions >94-99% at higher potentials (48), complete disinfection against most microorganisms (spore-formers more resistant) (49), and a synergistic bioelectric effect when combined with CHX [99.9 and 99.8% reductions in bacterial vitality for (-3 V + CHX) and (-0.75 V + CHX), respectively, vs. 52% with CHX alone] (50). Clinically, the principal clinical evidence is an RCT of 24 patients randomized to electrolytic cleaning alone or combined with powder spray, followed by augmentation and submerged healing. At the 6-month re-entry, bone gain was 2.71-2.81 mm with complete regeneration in half of the implants, and electrolytic cleaning alone matched the combined approach, indicating that, adding powder-spray cleaning to electrolytic decontamination did not provide additional measurable benefit (46). In another RCT, at 18 months, mean PPD decreased from 5.8 to 3.1 mm, BOP decreased from 100 to 35.3% and suppuration decreased from 100 to 11.8% (51), with a recent case series corroborating these gains (52).

The evidence base, while mechanistically compelling, is limited by a small number of controlled studies with modest samples and short follow-up (6-18 months) (46,51); sustained

Table V. Evidence synthesis for autologous platelet concentrates in peri-implantitis.

Generation	Preparation/biology	Critically appraised evidence	Position	(Refs.)
Platelet-rich plasma (PRP)	Double centrifugation with anticoagulant; liquid, no fibrin scaffold	Rapid growth-factor release, poor defect retention; limited, inconsistent, high risk of bias.	Not supported by current evidence.	(54,55)
Platelet-rich fibrin (PRF)	Single spin, no anticoagulant; dense 3D fibrin matrix	Sustained growth-factor release over ~10 days; the most-studied concentrate in peri-implantitis. Limited RCT/CCT evidence suggests improved clinical parameters (PPD, CAL, radiographic bone fill) vs. open-flap debridement alone, but the studies are few, small, and clinically heterogeneous, precluding pooled estimates specific to peri-implantitis.	Most extensively studied concentrate in peri-implantitis; possible adjunct with GBR, though evidence remains limited, small, and heterogeneous	(55-58,73)
Leukocyte platelet-rich fibrin (L-PRF)	Spin preserving buffy-coat leukocytes; mechanically robust membrane	Added antimicrobial/immunomodulatoryeffect; significant PPD/CAL gains; heterogeneous, small studies	Adjunct with GBR; promising.	(54,55)
Concentrated growth factor (CGF)	Variable-speed spin; denser matrix, higher growth-factor load	Higher growth-factor content not consistently superior clinically; case series only	Investigational.	(55)
Injectable platelet-rich fibrin (i-PRF)	Low-speed spin; injectable liquid phase for non-surgical delivery	Single small case series in slight peri-implantitis; PRF + GBR enhanced bone density in one comparative study	Investigational.	(74,75)

Position classifications denote the structured qualitative appraisal of the authors and do not constitute formal GRADE certainty ratings. RCT, randomized controlled trial; CCT, controlled clinical trial; CAL, clinical attachment level; GBR, guided bone regeneration; PPD, probing pocket depth.

resolution at 3-5 years would be required prior to guideline incorporation. All clinical studies evaluate the device only within combined surgical-regenerative protocols, and clinical accessibility is constrained because reaching the contaminated surface generally requires flap reflection and, with cemented prostheses, restoration removal (53). The context with the most supporting evidence is therefore as an adjunct during reconstructive surgery, after flap elevation and granulation removal, before grafting, where direct contact with the exposed surface is achievable.

7. Autologous platelet concentrates

Autologous platelet concentrates rest on a compelling rationale: The concentrated release of endogenous growth factors, such as platelet-derived growth factor, transforming growth factor-β, vascular endothelial growth factor and insulin-like growth factor-1, within the surgical site may accelerate soft-tissue healing, angiogenesis, osteoblastic differentiation and bone regeneration, while avoiding immune rejection and disease transmission (54). This biological elegance, however, is not yet matched by a robust clinical evidence base: The literature is characterized by profound heterogeneity in centrifugation protocols, activation methods, application techniques, defect morphologies and outcome measures that fundamentally limit comparability (55). The generations are compared in Table V.

The fibrin-based second-generation concentrates, platelet-rich fibrin (PRF) and leukocyte-PRF (L-PRF), provide a plausible biological advantage over liquid platelet-rich plasma (PRP), whose absence of a scaffold yields rapid release and poor retention (54); this advantage remains mechanistic rather than demonstrated in comparative clinical outcomes. PRF spontaneously forms a three-dimensional fibrin matrix entrapping platelets, leukocytes and growth factors, enabling the sustained release over a period of ~10 days (56-58). A critical synthesis yields four conclusions: The biological rationale is plausible; the current evidence is nonetheless insufficient to recommend any specific formulation as a standard adjunct, the limiting factor appearing to be study quality rather than biological mechanism (55); PRF and L-PRF are the most extensively studied options for possible adjunctive use with GBR in contained intrabony defects, while concentrated growth factor and injectable PRF remain investigational and PRP is not supported by current data; in addition, centrifugation-protocol heterogeneity, speeds of 700-3,000 rpm across studies, needs to be be resolved (ideally by reporting relative centrifugal force rather than equipment-specific revolutions

Table VI. Advanced drug-delivery platforms under investigation for peri-implantitis.

Platform	Mechanism/rationale	Developmental status	(Refs.)
Polymeric and inorganic nanoparticles	PLGA/chitosan and mesoporous silica carriers; stimulus-responsive, biofilm-penetrating, sustained release	Preclinical; regulatory pathway a major translational barrier.	(59,61)
Hydrogels	Hydrophilic 3D networks combining drug depot, scaffold, and space maintenance; thermosensitive/ antioxidant variants	Early clinical (e.g., doxycycline gels); mechanics-vs-release trade-off.	(59)
Electrospun nanofibers	High surface-area ECM-mimetic membranes; drug-loaded barrier for GBR; pH-responsive release	Preclinical; promising membrane alternative.	(59)
Functionalized implant coatings	Prophylactic; TiO_2 nanotubes, metal nanoparticles, immunomodulatory (M2-polarizing) surfaces	Preclinical/translational.	(61)
Exosome-based delivery	30-150 nm vesicles; potentially low immunogenicity; osteogenic, anti-inflammatory cargo	Proof-of-concept; no clinical studies.	(61)

Developmental-status classifications denote the structured qualitative appraisal of the authors and do not constitute formal GRADE certainty ratings. PLGA, poly(lactic-co-glycolic acid); ECM, extracellular matrix; GBR, guided bone regeneration; TiO_2, titanium dioxide.

per minute) before meta-analytic, guideline-level recommendations become possible.

8. Advanced drug-delivery systems

The unifying challenge across all peri-implantitis therapies is achieving sustained, therapeutically effective concentrations of antimicrobial or regenerative agents at the implant surface without systemic administration. Advanced drug-delivery systems represent one of the most direct conceptual responses, potentially providing spatially controlled, temporally sustained, and biologically responsive delivery to the disease site (59); although clinical evidence remains largely absent, the mechanistic rationale addresses core limitations of current therapies, and research output has expanded rapidly over the past decade (60). The principal platforms are compared in Table VI.

Two cross-cutting caveats temper this promise. First, a frequently underacknowledged barrier is the regulatory pathway: Nanoparticle systems raise unique challenges from size-dependent biodistribution, immunogenic degradation products and batch-to-batch variability, requiring substantial development time independent of preclinical efficacy (59). Polymeric carriers use poly(lactic acid) and polycaprolactone, and functionalized coatings may modulate NF-κB signaling and bias macrophages toward the anti-inflammatory M2 phenotype (61); electrospun membranes are positioned as next-generation alternatives to collagen and expanded polytetrafluoroethylene (59). Second, exosome therapy in particular is at proof-of-concept stage, with evidence confined to *in vitro* and small-animal models (61); it is included for its theoretical potential rather than imminent clinical relevance. Collectively, these systems embody a shift from a reactive, procedure-based paradigm toward personalized, biologically targeted, preventively oriented care. This direction aligns with the P4 medicine model-predictive, preventive, personalized and participatory, which has been articulated for periodontology and which we suggest could be extended, by analogy, to peri-implant care (62).

9. Limitations

A transparent appraisal of limitations of both the review process and the evidence base is presented in accordance with SANRA Item 5.

The present review process carries the inherent constraints of narrative methodology: restriction to English-language publications may introduce selection bias (5); the selection, weighting and interpretation of evidence, although structured by SANRA, lack the pre-specified reproducible protocols of a systematic review; thus, unintentional emphasis cannot be excluded (6).

The most consequential limitation of the evidence base, pervading every category reviewed, is profound methodological heterogeneity in diagnostic criteria, baseline severity, implant surfaces, surgical protocols, decontamination methods, follow-up and outcome definitions, which renders direct cross-study comparison unreliable and precludes robust meta-analysis for most comparisons.

Publication bias cannot be excluded, particularly for the emerging modalities discussed in above (electrochemical disinfection, platelet concentrates and advanced drug-delivery systems), where preclinical and early-phase clinical studies reporting favorable outcomes are more likely to be conducted, published and cited than null or negative findings; the promising signals described for these therapies should be interpreted with this caveat in mind. Consequently, the strength of evidence remains low to very low for the majority of adjunctive and emerging modalities (Tables II and IV-VI) in the authors' structured appraisal, reflecting not the absence of effect, but the inability of the current literature to demonstrate consistent, reproducible outcomes; several core interventions, notably

systemic antibiotic adjuncts, reconstructive and combined surgical therapy, and supportive peri-implant maintenance, were appraised as moderate, reflecting a comparatively larger base of controlled studies (Tables II and III), and this distinction should be borne in mind when interpreting the overall evidence landscape; a specific manifestation is the inconsistent adoption of the 2017 World Workshop case definition and resolution criteria as primary endpoints (1,8). Furthermore, the majority of clinical studies systematically exclude the high-risk populations, such as those with diabetes, smokers and those with prior periodontitis, for whom guidance is most needed, creating a mismatch between the evidence and the patients to whom it should be applied (11); the present review also omits a formal comparative health-economic analysis. Finally, the translational barriers limiting advanced drug-delivery systems are scalable reproducible manufacturing, long-term biocompatibility and degradation-product fate, regulatory complexity for biomaterial-drug combination devices and the absence of adapted trial frameworks, which remain insufficiently characterized in the peri-implantitis literature (59), and should be acknowledged to prevent misreading preclinical promise as near-term clinical availability.

10. Conclusion

Peri-implantitis is a complex complication driven by microbial dysbiosis, host susceptibility, and iatrogenic factors, progressing from reversible mucositis to irreversible bone loss (63,64). Affecting ~1 in 5 patients with implants, it is neither rare nor self-limiting. The present SANRA-guided critical narrative review appraised the full therapeutic spectrum, from non-surgical debridement through surgical reconstruction to emerging laser, electrochemical, biologic and nanomaterial-based technologies, and several unifying conclusions emerge. First, no single modality achieves predictable, complete, durable resolution across the severity spectrum; non-surgical therapy is essential, yet insufficient and surgery is required for moderate-to-advanced disease, with a signal favoring xenogenic bone substitutes for contained intrabony defects; however, no single graft material has shown consistent superiority across all reconstructive endpoints. Second, the specific decontamination instrument is a weaker determinant of outcome than surgical access, defect-morphology management and post-operative maintenance. Third, although the emerging therapies exhibit genuine biological promise, they are uniformly constrained by an evidence base limited in quantity, quality and follow-up, and none can currently be recommended as standard care. Fourth, the foundation of long-term success lies not in any single technology, but in continuous supportive maintenance, the control of modifiable risk factors and patient adherence. In essence, peri-implantitis management is increasingly suggested to evolve from a reactive model toward a more predictive and preventive paradigm, consistent with the P4 medicine framework articulated for periodontology (62); future research is warranted to prioritize adequately powered longitudinal trials of combined mechanical-biologic approaches, the universal adoption of standardized diagnostic and resolution thresholds, the inclusion of high-risk populations and host-modulation strategies. The long-term stability of osseointegration is sustained not by implant design alone, but by a harmonized balance of technology, biology and patient-centered care.

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RC and NS were involved in designing the concept of the review followed by conducting the search and drafting the manuscript. AT and BG were involved in manuscript revision and the initial literature search. Data authentication is not applicable. All the authors have read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Use of artificial intelligence tools

During the preparation of this work, AI tools (Claude) were used to improve the readability and language of the manuscript or to generate images, and subsequently, the authors revised and edited the content produced by the AI tools as necessary, taking full responsibility for the ultimate content of the present manuscript.

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