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Transforming Periodontal Therapy: The Journey Of Biomaterials From Grafts To Bioactive Scaffolds A Narrative Review

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Abstract
Background:
Periodontal disease is a chronic inflammatory condition characterized by progressive destruction of the supporting tissues of teeth, including gingiva, periodontal ligament, cementum, and alveolar bone. Although conventional periodontal therapy effectively controls infection and disease progression, complete regeneration of periodontal structures remains a major clinical challenge.
Objective:
This narrative review aims to explore the evolution of biomaterials in periodontal therapy and critically evaluate the transition from conventional graft materials toward biologically active scaffolds and emerging regenerative technologies.
Methodology:
A narrative review approach was adopted through evaluation and synthesis of classical and contemporary literature addressing periodontal regeneration. The review focused on the development of graft materials, biologically active regenerative approaches, scaffold-based tissue engineering, growth factor delivery systems, and emerging technologies relevant to periodontal reconstruction.
Results:
Periodontal regenerative therapy has evolved considerably from traditional bone grafting approaches toward advanced bioactive regenerative platforms. Conventional graft materials—including autografts, allografts, xenografts, and alloplasts—provided structural support and osteoconductive properties but demonstrated limitations in reproducing the complete periodontal attachment apparatus. Advances in regenerative biology introduced guided tissue regeneration, platelet concentrates, hydrogels, controlled delivery systems, and bioactive scaffold technologies capable of directing cellular responses and enhancing tissue healing. Emerging technologies such as three-dimensional bioprinting, melt electrowriting, nanotechnology, and stem-cell-based tissue engineering have further expanded the potential for personalized and functionally integrated periodontal regeneration.
Conclusion:
The paradigm of periodontal regeneration has shifted from passive defect replacement to biologically interactive and multifunctional regenerative strategies. Bioactive scaffolds and advanced tissue engineering approaches demonstrate significant promise for achieving predictable periodontal regeneration; however, further clinical validation and long-term evidence remain necessary before routine clinical implementation.
Keywords: *periodontal regeneration, bone grafts, bone putties, autologous platelet concentrates, barrier biomaterials, hydrogels, innovations in biomaterials, scaffolds, stem cells, 3-D printing.*

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I. Introduction

Periodontal disease is a chronic inflammatory condition characterized by progressive destruction of the supporting tissues of the teeth, including gingiva, periodontal ligament (PDL), cementum, and alveolar bone, ultimately resulting in attachment loss and possible tooth loss if untreated.[1] Conventional periodontal therapy-including non-surgical and surgical approaches—primarily aims to control infection and arrest disease progression; however, these approaches frequently achieve repair rather than complete regeneration of periodontal tissues.[2]

True periodontal regeneration requires coordinated reconstruction of alveolar bone, cementum, and functional periodontal ligament attachment.[3] Due to the complex architecture and biological interactions within the periodontium, achieving predictable regeneration remains a major challenge in clinical periodontology.

Over recent decades, regenerative concepts have evolved substantially from passive replacement of lost tissues toward biologically guided reconstruction strategies.

Biomaterials have become central to regenerative periodontal therapy because they provide not only structural support but also biological cues that influence cellular attachment, proliferation, migration, and differentiation. Early regenerative approaches relied predominantly on graft materials such as autografts, allografts, xenografts, and synthetic substitutes that primarily functioned through osteoconduction and defect filling. Although these materials demonstrated clinical benefits, their capacity to reproduce the complete periodontal apparatus remained limited.

Advances in tissue engineering and regenerative biology have transformed periodontal biomaterials into multifunctional systems capable of directing healing processes. Modern regenerative strategies integrate bioactive scaffolds, platelet concentrates, hydrogels, growth factors, controlled delivery systems, and stem-cell-based approaches to stimulate angiogenesis, regulate inflammation, and promote tissue regeneration.

More recently, emerging technologies such as three-dimensional (3D) bioprinting, melt electrowriting (MEW), nanotechnology, and personalized scaffold fabrication have expanded the possibilities of achieving coordinated regeneration of alveolar bone, cementum, and periodontal ligament.[3] These innovations indicate a paradigm shift in periodontal therapy-from passive defect filling toward biologically active and patient-specific regenerative solutions.

Therefore, this narrative review aims to explore the evolution of periodontal biomaterials and critically discuss the transition from conventional graft materials to advanced bioactive scaffolds and emerging regenerative technologies in modern periodontology.

II. Evolution Of Graft Materials In Periodontal Regeneration

Bone grafting represents one of the earliest and most established regenerative approaches in periodontology and has played a fundamental role in the management of periodontal osseous defects. The primary objective of bone grafting is to restore lost alveolar bone support and create a favorable environment for regeneration of the periodontal attachment apparatus.[1-3] Initially, graft materials were introduced mainly as defect fillers and space-maintaining structures; however, their role has progressively expanded toward supporting biologic healing and tissue regeneration.

Bone graft materials used in periodontal therapy are generally classified into autografts, allografts, xenografts, and alloplastic (synthetic) grafts according to their source and biological properties.

Autogenous bone grafts- Harvested from the same individual, are traditionally regarded as the gold standard because of their combined osteogenic, osteoinductive, and osteoconductive properties. Osteogenic potential results from viable osteoblasts and progenitor cells transferred with the graft, while osteoinduction promotes differentiation of surrounding cells into bone-forming cells. Despite excellent regenerative potential, autogenous grafts have limitations including donor site morbidity, increased surgical time, postoperative discomfort, and limited graft availability.

Allografts - Introduced to overcome the limitations associated with autogenous bone harvesting. These grafts are obtained from genetically similar individuals of the same species and are commonly available as freeze-dried bone allograft (FDBA) and demineralized freeze-dried bone allograft (DFDBA). FDBA primarily acts through osteoconduction, whereas DFDBA may additionally exhibit osteoinductive properties because of exposure of bone morphogenetic proteins during demineralization. Although widely used in periodontal regeneration, variability in donor characteristics and processing methods may influence regenerative outcomes.

Xenografts- Derived from different species and most commonly bovine sources, have gained substantial popularity because of their favorable biocompatibility and long-term volume stability. These materials provide a porous scaffold that supports cellular migration and new bone formation through osteoconduction. However, their relatively slow resorption rate may influence replacement by native bone and complete periodontal remodeling.

Synthetic or alloplastic graft materials- Developed to eliminate concerns related to donor availability and disease transmission. Common synthetic grafts include hydroxyapatite (HA), β-tricalcium phosphate (β-TCP), biphasic calcium phosphate, bioactive glass, and calcium phosphate-based substitutes. These materials exhibit excellent osteoconductive characteristics and permit greater control over physical and chemical properties. Recent formulations have integrated bioactive molecules and growth factors to improve regenerative performance.

Commercially available graft substitutes such as nanocrystalline hydroxyapatite, β-tricalcium phosphate formulations, bioactive glass putties, and composite graft systems have demonstrated favorable clinical and radiographic outcomes in periodontal defects. Nevertheless, graft materials alone often remain insufficient to regenerate the complete periodontal complex consisting of cementum, periodontal ligament, and alveolar bone. Consequently, current regenerative strategies increasingly combine graft materials with

biologically active agents, barrier membranes, and scaffold technologies to improve predictability and functional regeneration.[3,]

Table 1 Bone Graft Materials and Bone Putties

Product	Composition/ Description	Category	Clinical Use	Limitation
Bio-Oss	Deproteinized bovine heterologous bone containing only mineral component	Bovine xenograft	Intrabony defect regeneration, ridge preservation, sinus augmentation	Slow resorption and delayed replacement by native bone
Bio-Oss Collagen	Bio-Oss microgranules combined with purified porcine collagen	Bovine xenograft	Periodontal intrabony defects, extraction socket preservation, guided bone regeneration	Limited mechanical stability and gradual resorption
Cerabone	Pure bovine-derived hydroxyapatite bone mineral	Bovine xenograft	Bone augmentation and periodontal defect reconstruction	Slow biodegradation
ABM/PepGen P-15	Bovine-derived bone matrix combined with synthetic cell-binding peptide	Bovine xenograft	Periodontal regeneration and enhanced osteogenesis	Higher cost and limited long-term evidence
Bio-Gengraft	Mixture of cancellous and cortical bone granules of equine origin	Equine xenograft	Guided tissue regeneration and bone regeneration	Variable resorption characteristics
THE Graft	Porous inorganic bone material of porcine origin	Porcine xenograft	Intrabony defect management and alveolar regeneration	Limited long-term studies
OraGRAFT	Freeze-dried demineralized bone allograft	Allograft	Periodontal osseous defects and ridge preservation	Donor variability
NovaBone Dental Morsels	Calcium phosphosilicate synthetic graft	Synthetic graft	Bone regeneration and periodontal defect filling	Brittle structure
Perioglas	Granulated bioactive glass	Synthetic graft	Intrabony defects and bone regeneration	Rapid dissolution
BoneCeramic	Hydroxyapatite and beta-tricalcium phosphate	Synthetic graft	Ridge augmentation and periodontal regeneration	Incomplete replacement by natural bone
ProRoot MTA	Oxide-based cement with bismuth trioxide	Synthetic graft	Bone repair and regenerative procedures	Difficult handling
OsteoGen	Synthetic crystalline hydroxyapatite	Synthetic graft	Periodontal bone augmentation	Slow degradation
SyboGraf	Nanocrystalline hydroxyapatite	Synthetic graft	Intrabony defect treatment	Reduced mechanical strength
Gem21S	Beta-tricalcium phosphate with recombinant growth factor	Synthetic graft	Enhanced periodontal regeneration	Higher treatment cost
Frios Algipore	Hydroxyapatite derived from marine algae	Synthetic graft	Bone defect reconstruction	Limited load-bearing capability
Cytrans Granules	Carbonated apatite granules	Synthetic graft	Ridge preservation and regeneration	Limited periodontal evidence
Fisiograft	Copolymer of polylactic and polyglycolic acids	Synthetic graft	Guided tissue regeneration	Possible inflammatory response
NovaBone Putty	Bioactive glass with polyethylene glycol and glycerine	Bone putty	Adaptation in periodontal defects	Limited mechanical strength
C-Blast Putty	Demineralized bone matrix with cancellous particles	Bone putty	Periodontal and peri-implant regeneration	Variable osteoinduction
Max Resorb Inject	Nano-hydroxyapatite and biphasic injectable paste	Bone putty	Injectable defect filling	Reduced structural stability
DBX Putty	Allogenic cortical bone in carrier matrix	Bone putty	Periodontal osseous regeneration	Donor-dependent variability
Miner Oss Putty	Mineralized and demineralized bone particles in collagen	Bone putty	Socket preservation and defect repair	Moderate resorption variability
Regener Oss Allograft Putty Plus	Demineralized cortical matrix with cancellous chips	Bone putty	Bone regeneration and reconstruction	Limited long-term comparative evidence

III. Transition Toward Biologically Active Regeneration

The concept of periodontal regeneration has undergone a major transformation from conventional defect filling toward biologically active regenerative therapy. Traditional regenerative approaches primarily relied on graft materials to provide structural support and maintain space for healing; however, these approaches demonstrated limited capacity to restore the complete periodontal apparatus, including alveolar bone,

cementum, and periodontal ligament.[3-] This limitation led to the development of biologically driven strategies designed to actively regulate cellular behavior and promote functional tissue regeneration.

Guided tissue regeneration -The introduction of guided tissue regeneration (GTR) represented one of the earliest advances in biologically active periodontal therapy. GTR is based on the principle of selective cell repopulation, where barrier membranes prevent rapid migration of epithelial cells into periodontal defects and allow periodontal ligament cells and osteogenic cells to occupy the healing area. This approach significantly improved clinical attachment gain and periodontal defect resolution compared with conventional grafting alone.[2],[3],[1] [-22]

Autologous platelet concentrates- Further advances in regenerative biology introduced the use of autologous platelet concentrates as bioactive therapeutic agents. Platelet-rich plasma (PRP), considered a first-generation platelet concentrate, provides a high concentration of growth factors that stimulate angiogenesis and tissue repair; however, its rapid release profile and short biological activity limited long-term regenerative outcomes. [-1]

To overcome these limitations, platelet-rich fibrin (PRF) and newer generations of platelet concentrates-including leukocyte-rich PRF (L-PRF), advanced PRF (A-PRF), injectable PRF (I-PRF), titanium PRF (T-PRF), and concentrated growth factor (CGF)-were developed. These materials provide sustained release of bioactive molecules such as platelet-derived growth factor (PDGF), transforming growth factor-beta (TGF-β), vascular endothelial growth factor (VEGF), fibroblast growth factor (FGF), and insulin-like growth factor (IGF), thereby enhancing angiogenesis, cell migration, extracellular matrix synthesis, and tissue maturation. [,11-1]

Hydrogel- Another important transition toward biologically active regeneration involved the development of hydrogel-based regenerative systems. Hydrogels function as extracellular matrix-mimicking structures capable of delivering biological molecules directly into periodontal defects. Enamel matrix derivative (EMD), recombinant human fibroblast growth factor-2 (rhFGF-2), and hyaluronic acid-based hydrogels demonstrated favorable outcomes in promoting cementogenesis, periodontal ligament regeneration, and bone formation.[1] [-1]

Local drug delivery- Controlled delivery systems further expanded regenerative capabilities by improving the spatial and temporal release of bioactive agents. These systems enable sequential delivery of antimicrobial agents, anti-inflammatory molecules, and growth factors to create an optimal healing environment while maintaining therapeutic concentrations over extended periods.[23-2]

Table 2 Membranes and Hydrogels

Product	Composition / Description	Category	Degradation	Clinical Use	Limitation
e-PTFE (GORE-TEX)	Expanded polytetrafluoroethylene	GTR/GBR membrane	Non-degradable	Guided bone regeneration, periodontal bone regeneration	Requires second surgery for membrane removal; risk of exposure
Ti-250 (Cytoplast)	Titanium-reinforced high-density polytetrafluoroethylene	GTR/GBR membrane	Non-degradable	Implant-guided bone regeneration and vertical bone augmentation	Technique sensitive and requires removal
N-RES Tex (Gore-Tex)	Titanium-reinforced expanded polytetrafluoroethylene	GTR/GBR membrane	Non-degradable	Guided bone regeneration and large vertical defects	Higher membrane exposure risk
TR (OpenTex)	Titanium-reinforced microporous expanded polytetrafluoroethylene	GTR/GBR membrane	Non-degradable	Vertical guided bone regeneration	Additional surgery required for retrieval
Bio-Gide	Collagen derived from porcine skin	Resorbable membrane	Approximately 24 weeks	Guided bone regeneration and two-wall bony defects	Reduced space-maintaining ability
BioMend	Type I collagen derived from bovine tendon	Resorbable membrane	Approximately 18 weeks	Guided tissue regeneration and intrabony defects	Early degradation in highly inflamed sites
OssGuide	Cross-linked porcine pericardium-derived Type I collagen	Resorbable membrane	Approximately 12–16 weeks	Guided tissue regeneration	Variable degradation profile
GUIDOR	Polylactic acid membrane	Resorbable membrane	Approximately 6 weeks	Guided bone regeneration	Lower mechanical stability
Emdogain	90% amelogenin with ameloblastin, enamelin and tuftelin in propylene glycol alginate solution	Hydrogel / biologic regenerative material	Biodegradable	Periodontal regeneration, root coverage, intrabony defect treatment	Higher cost and variable outcomes in advanced defects

REGROTH Dental Kit	Recombinant human fibroblast growth factor in hydroxypropyl cellulose carrier	Hydrogel / growth factor system	Biodegradable	Periodontal tissue regeneration and promotion of angiogenesis	Limited availability and higher treatment expense
HyaDENT BG	Cross-linked and natural hyaluronic acid gel	Hydrogel	Biodegradable	Soft tissue healing and periodontal regeneration	Short residence time in highly inflamed tissues
Gengigel	Sodium hyaluronate with xylitol and excipients	Hydrogel	Biodegradable	Gingival healing and adjunctive periodontal therapy	Requires repeated application
Aminogam	Glycine, leucine, proline and lysine in sodium hyaluronate carrier	Hydrogel	Biodegradable	Soft tissue regeneration and postoperative healing	Limited evidence for extensive periodontal regeneration

IV. Bioactive Scaffolds And Mechanisms

Bioactive scaffolds represent a major advancement in regenerative periodontology and have emerged as an important component of modern tissue engineering strategies. Unlike conventional graft materials that mainly function as passive defect fillers, bioactive scaffolds actively participate in the regenerative process by providing structural support while simultaneously regulating cellular behavior, growth factor activity, and tissue remodeling.[23,2]

An ideal scaffold for periodontal regeneration should possess several essential characteristics, including biocompatibility, biodegradability, mechanical stability, interconnected porosity, and the ability to support cell adhesion, proliferation, migration, and differentiation. These properties are necessary to recreate the complex architecture of the periodontal apparatus and facilitate coordinated regeneration of alveolar bone, periodontal ligament (PDL), and cementum.[23,2 ,33]Bioactive scaffolds can be broadly classified into natural, synthetic, ceramic, and composite scaffold systems.

Natural scaffolds- Natural scaffolds, including collagen and hyaluronic acid, closely mimic the extracellular matrix (ECM) and promote cellular attachment and angiogenesis. Collagen scaffolds support periodontal ligament fibroblast migration and osteoblast activity, while hyaluronic acid-based scaffolds enhance wound healing and exhibit anti-inflammatory effects.[2 ,3]

Synthetic scaffolds- Synthetic scaffold systems such as polylactic acid (PLA), polyglycolic acid (PGA), poly(lactic-co-glycolic acid) (PLGA), and polycaprolactone (PCL) offer advantages including controlled degradation, reproducible manufacturing, and adjustable mechanical properties. These materials provide structural integrity and allow fabrication into various forms including fibers, films, and porous constructs suitable for periodontal applications.[31]

Bio-ceramic scaffolds- Bio-ceramic scaffolds composed of hydroxyapatite (HA), tricalcium phosphate (TCP), and bioactive glass have demonstrated excellent osteoconductive properties and the ability to support mineralization and bone regeneration. However, their brittle nature and limited flexibility may reduce effectiveness in soft tissue regeneration; therefore, ceramic materials are frequently combined with polymers to create composite scaffold systems with improved biological and mechanical performance. [,32]

The regenerative function of bioactive scaffolds depends on multiple biological mechanisms. Initially, scaffolds provide a three-dimensional framework that facilitates cellular attachment and migration into the defect area. Subsequently, scaffold surface properties and incorporated bioactive molecules regulate cell signaling pathways involved in proliferation and differentiation. Controlled release of growth factors stimulates angiogenesis and supports extracellular matrix deposition. These processes collectively promote osteogenesis, cementogenesis, and organized periodontal ligament formation.[2 -2 ,33]

Recent developments have further enhanced scaffold performance through incorporation of growth factors, platelet concentrates, antimicrobial agents, and controlled drug delivery systems. Multifunctional scaffolds capable of spatial and temporal delivery of bioactive molecules improve tissue-specific regeneration and provide a more favorable healing environment.[2 -2]

Advanced scaffold fabrication technologies- Including electrospinning, three-dimensional (3D) printing, and melt electrowriting (MEW)- have enabled production of highly organized scaffold architectures that better replicate native periodontal tissues. These technologies permit control over fiber orientation, pore geometry, and scaffold microstructure, thereby improving periodontal ligament alignment and coordinated regeneration of hard and soft tissues.[3 , 2]

Overall, bioactive scaffolds represent a significant shift from passive regenerative materials toward biologically interactive platforms that actively guide tissue healing and functional periodontal regeneration.

V. Emerging Technologies And Future Directions

Recent advances in regenerative periodontology have shifted treatment concepts from conventional biomaterial-based regeneration toward personalized and biologically intelligent therapeutic systems. Emerging technologies aim not only to replace lost tissues but also to reproduce the structural organization and biological function of the native periodontium through integration of biomaterials, cells, signaling molecules, and advanced fabrication methods.[3]

Three-dimensional (3D) printing and bioprinting- Three-dimensional (3D) printing and bioprinting technologies have emerged as promising approaches for periodontal tissue engineering because they enable fabrication of customized scaffolds with precise control over architecture, pore size, geometry, and spatial distribution of bioactive components. Unlike traditional scaffold fabrication methods, 3D printing allows production of patient-specific constructs capable of replicating the complex organization of alveolar bone and periodontal ligament. Controlled scaffold porosity and microstructure further improve vascularization, cell migration, and osteogenic differentiation.[3] [-3]

Melt electrowriting (MEW)- Melt electrowriting (MEW) represents another important technological advancement that combines additive manufacturing with microfabrication principles to produce highly organized fibrous scaffold networks. MEW enables precise control over fiber diameter, spacing, and alignment, allowing fabrication of scaffolds that better mimic natural periodontal tissue architecture. Studies have demonstrated that aligned scaffold structures improve periodontal ligament orientation, promote osteogenic differentiation, and support coordinated regeneration of hard and soft periodontal tissues.[3] ,[3] ,

Nanotechnology- Nanotechnology has further expanded the regenerative potential of biomaterials by improving scaffold surface characteristics and cellular interactions. Nanostructured biomaterials increase protein adsorption, enhance stem-cell attachment, improve osteoblast differentiation, and provide antimicrobial effects against periodontal pathogens. Surface modification using bioactive nanoparticles and nanocoatings has shown favorable outcomes in promoting periodontal healing and tissue maturation.[32],[3]

Another rapidly developing field is stem-cell-based tissue engineering. Mesenchymal stem cells (MSCs), periodontal ligament stem cells (PDLSCs), and induced pluripotent stem cells (iPSCs) have demonstrated considerable regenerative potential because of their ability DISCUSSION

The earliest regenerative approaches were centered on bone grafting procedures designed primarily to provide structural support and facilitate defect filling. Autografts demonstrated favorable regenerative outcomes because of their osteogenic, osteoinductive, and osteoconductive properties; however, their clinical use remained limited due to donor site morbidity and restricted availability. · To overcome these limitations, allografts, xenografts, and synthetic graft substitutes were introduced and became widely used in periodontal regenerative procedures. · Although these to differentiate into multiple periodontal tissue components. When combined with scaffold systems and bioactive molecules, these cell-based approaches provide opportunities for coordinated regeneration of alveolar bone, cementum, and periodontal ligament. [3-] However, challenges related to cell survival, regulatory approval, manufacturing complexity, and long-term safety continue to limit widespread clinical implementation.

Future regenerative strategies are increasingly focused on developing multifunctional and smart biomaterials capable of responding dynamically to local environmental conditions. These next-generation systems may incorporate controlled drug delivery, immunomodulatory molecules, gene therapy, and spatial–temporal release of growth factors to optimize healing outcomes.[23-2] In addition, personalized regenerative approaches supported by digital workflows, computer-aided scaffold design, artificial intelligence, and precision medicine are expected to influence future periodontal therapy. Although emerging technologies demonstrate substantial potential, further clinical trials and long-term evidence are necessary before routine clinical application can be achieved.[3] -

VI. Discussion

Periodontal regeneration remains one of the most challenging areas in clinical dentistry because successful treatment requires simultaneous regeneration of alveolar bone, periodontal ligament (PDL), and cementum. Traditional periodontal therapy effectively controls disease progression but frequently results in tissue repair rather than complete functional regeneration.[1-3] Consequently, advances in biomaterial science and tissue engineering have transformed regenerative strategies over recent decades.

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Recognition of these limitations led to a transition toward biologically active regenerative approaches. The development of guided tissue regeneration (GTR) introduced the concept of selective cell repopulation and improved periodontal healing outcomes through controlled tissue regeneration.[2],[1] [-22] Subsequently, platelet concentrates and growth-factor-based therapies expanded regenerative possibilities by delivering biological signals directly to the healing environment. Platelet-rich plasma (PRP), platelet-rich fibrin (PRF), advanced PRF (A-PRF), injectable PRF (I-PRF), and concentrated growth factor (CGF) demonstrated the ability to enhance angiogenesis, stimulate cellular proliferation, and improve wound healing through sustained release of growth factors. [-1]

Hydrogels and controlled delivery systems further strengthened regenerative therapy by introducing extracellular matrix-mimicking platforms capable of localized and sustained delivery of biologically active molecules. Enamel matrix derivative, recombinant human fibroblast growth factor-2, and hyaluronic acid-based systems have shown encouraging outcomes in periodontal regeneration by promoting cementogenesis, periodontal ligament formation, and bone regeneration.[1] [-1] Controlled release technologies additionally improved therapeutic efficiency through regulation of spatial and temporal delivery of antimicrobial agents and growth factors.[23-2] One of the most important developments in contemporary regenerative periodontology is the emergence of bioactive scaffold systems. Unlike traditional graft materials, scaffolds actively influence cellular attachment, migration, differentiation, and extracellular matrix formation. Natural scaffolds provide superior biological interaction, whereas synthetic and composite scaffold systems offer improved mechanical properties and degradation control.[2] [-33] The integration of scaffold platforms with growth factors, bioactive molecules, and regenerative cells has significantly improved tissue-specific healing and regenerative outcomes.

Recent technological advances such as three-dimensional (3D) printing, melt electrowriting (MEW), nanotechnology, and stem-cell engineering have introduced opportunities for personalized regenerative treatment. These technologies allow fabrication of anatomically customized scaffold systems with controlled architecture and enhanced biological performance.[3] [-] Despite these promising developments, translation into routine clinical practice remains limited by cost, manufacturing complexity, regulatory challenges, and insufficient long-term clinical evidence.

Overall, current evidence suggests that regenerative periodontology is progressively evolving from passive defect reconstruction toward biologically interactive and personalized treatment approaches. Future success in periodontal regeneration will likely depend on integrating biomaterials, cellular therapy, controlled molecular delivery, and advanced manufacturing technologies to achieve predictable and functional tissue regeneration.

VII. Conclusion

Periodontal regenerative therapy has undergone a significant transformation from conventional graft-based approaches toward biologically active and tissue-engineered regenerative strategies. Traditional graft materials—including autografts, allografts, xenografts, and synthetic substitutes—established the foundation of regenerative periodontal treatment by providing structural support and facilitating bone formation; however, their ability to regenerate the complete periodontal attachment apparatus remained limited. [-]

Advances in regenerative biology have shifted the focus toward biologically interactive therapies that actively influence healing responses and tissue regeneration. The incorporation of guided tissue regeneration principles, platelet concentrates, growth factors, hydrogels, and controlled delivery systems has improved the biological environment necessary for coordinated regeneration of alveolar bone, periodontal ligament, and cementum. Among contemporary regenerative approaches, bioactive scaffold systems have emerged as promising platforms because they combine mechanical support with biological signaling and cellular guidance. The integration of scaffold technologies with bioactive molecules and regenerative cells has demonstrated improved regenerative potential and greater control over tissue-specific healing.[23],[2] [-33]

Furthermore, emerging technologies including three-dimensional bioprinting, melt electrowriting, nanotechnology, and stem-cell-based tissue engineering represent the next stage in the evolution of regenerative periodontology. These innovations offer opportunities for personalized and multifunctional treatment approaches capable of reproducing the structural and functional complexity of native periodontal tissues.[3] [-]

Although current evidence demonstrates considerable progress, long-term clinical studies, standardized treatment protocols, cost-effectiveness analyses, and regulatory validation remain necessary before these technologies become routinely incorporated into clinical practice. Future advances are expected to integrate biomaterials, cellular engineering, and precision regenerative medicine to achieve predictable and functionally successful periodontal regeneration.

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