

Next-Generation Dental Biomaterials: Role of Electrospinning in Regenerative Dentistry

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Abstract

Electrospinning enables the fabrication of extracellular matrix-mimicking nanofibrous scaffolds with high potential for regenerative dentistry, including periodontal regeneration, pulp-dentin complex repair, oral mucosal healing, and dental implant surface modification. This review summarizes recent advances in polymer selection (synthetic for mechanical stability, natural for bioactivity, and hybrids for optimized properties), biofunctionalization with growth factors and antimicrobials, and scaffold design, based on a comprehensive analysis of electrospinning techniques, characterization methods, and preclinical studies. These scaffolds offer high porosity, large surface area, and ECM-like architecture to promote cell adhesion, proliferation, and targeted drug delivery, yielding promising regenerative outcomes in periodontal, endodontic, mucosal, and implant applications. Challenges persist in mechanical durability, reproducibility, scalability, and clinical translation, yet electrospun scaffolds provide a versatile, biomimetic alternative to conventional biomaterials by enabling selective cell responses, enhanced tissue regeneration, and localized therapeutics for improved clinical outcomes.



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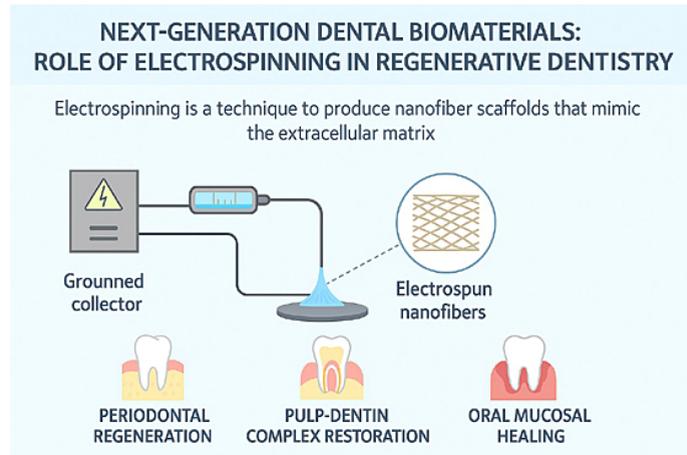
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Abbreviations

| | |
|-------|--|
| ECM | Extracellular Matrix |
| PCL | Polycaprolactone |
| PLA | Polylactic Acid |
| PVA | Polyvinyl Alcohol |
| GTR | Guided Tissue Regeneration |
| DSCs | Dental Stem Cells |
| DPSCs | Dental Pulp Stem Cells |
| SHEDs | Stem Cells from Human Exfoliated Deciduous Teeth |
| SCAPs | Stem Cells from Apical Papilla |
| PDLSs | Periodontal Ligament Stem Cells |

Introduction

Electrospinning is a versatile and advanced fiber fabrication technique that utilizes electrostatic forces to produce continuous nanofibers from polymer solutions or melts. The basic setup comprises a high-voltage power supply, a spinneret or needle, a syringe pump, and a grounded collector. During the process, the polymer solution is ejected through the spinneret under the influence of a strong electric field, forming a charged jet that elongates and solidifies into ultrafine fibers collected on the substrate. Key parameters such as voltage, solution concentration, flow rate, and distance between the spinneret and collector critically influence the morphology and diameter of the resulting nanofibers.¹

Electrospun nanofibers are broadly classified into (1) polymeric, (2) composite, and (3) herbal-incorporated types. Polymeric nanofibers are made from synthetic or natural polymers, composites

involve blending polymers with inorganic or organic additives, while herbal-incorporated nanofibers embed plant extracts or bioactive herbal compounds within the fiber matrix. This versatility allows tailoring of functional properties such as mechanical strength, biocompatibility, and bioactivity for specific biomedical applications.

Unlike traditional fabrication methods such as solvent casting or phase separation, electrospinning provides distinct advantages such as nanoscale diameters, high surface area-to-volume ratios, enhanced porosity, and ECM mimicry, including the ability to produce fibers with nanoscale diameters and high surface area-to-volume ratios, enhanced porosity, and structural mimicry of the native extracellular matrix. Moreover, electrospinning enables facile incorporation of biological molecules and drugs, facilitating controlled release and targeted delivery.

In biomedical fields, electrospinning has garnered significant interest due to its potential to create scaffolds that support cell adhesion, proliferation, and differentiation. In dentistry, electrospun membranes and scaffolds are especially promising for applications such as periodontal regeneration, pulp tissue engineering, and antimicrobial barrier formation, offering innovative solutions to longstanding clinical challenges.² The integration of herbal bioactive agents into electrospun systems further broadens the therapeutic potential by combining natural pharmacological benefits with advanced material properties. Nanofiber scaffolds, known for their ability to support tissue repair and regeneration, have increasingly gained attention and are emerging as promising alternatives for the development of dental materials.

In this review, we provide a thorough overview of electrospun nanofibers utilized in the treatment of oral diseases. We begin by discussing the engineering approaches used to create these nanofibers. Next, we explore the biological functions that nanofiber scaffolds can support, such as their ability to deliver cells and/or drugs. Lastly, we highlight potential future directions for scaffold design, fabrication, engineering, and the clinical application of electrospun nanofibers in oral health.

Methods

This study was conducted as a narrative review following the PRISMA guidelines for reporting systematic reviews¹. Relevant literature was searched in PubMed, Scopus, and Web of Science using keywords including “electrospinning,” “dental tissue engineering,” “periodontal regeneration,” “endodontics,” “oral mucosa,” and “implant surface modification.” Studies published in English between 2007 and 2025 were included. Only original research articles, reviews, and preclinical or clinical studies relevant to electrospun nanofibers in dentistry were considered. Exclusion criteria included studies unrelated to dental applications, those not using electrospinning, or those without full-text access.

Results

Electrospun Nanofibrous Membranes: Properties and Characterization

Electrospun nanofibrous membranes possess unique properties that are critical for their performance in

biomedical applications, including dental use. The morphology of these membranes is typically assessed by parameters such as fiber diameter, porosity, and surface area, all of which influence their functional effectiveness. Fiber diameter influences structural integrity, surface area, and drug delivery capacity. Porosity determines fluid permeability and tissue integration capacity, while surface area directly impacts cell adhesion and nutrient exchange.

Mechanical properties like tensile strength and flexibility are fundamental, especially for applications within the oral environment, where dynamic mechanical stresses occur. These properties ensure the membrane can withstand oral forces without failure while maintaining sufficient flexibility to conform to the targeted tissue contours.

Biocompatibility and biodegradability are essential considerations to ensure that the membrane supports tissue regeneration without eliciting adverse immune responses and that it degrades in harmony with new tissue formation.

To thoroughly understand and verify these characteristics, several analytical techniques are employed. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed visualization of the membrane's morphology at high resolution. Fourier-transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) are used to identify chemical compositions and crystalline structures, respectively. Mechanical testing methods quantify the tensile strength and flexibility parameters, thereby furnishing a comprehensive profile of the membrane's physical properties relevant to its intended application.

Electrospinning Polymers used in Dentistry

Electrospinning has emerged as a versatile technology for producing nanofibrous scaffolds with significant potential in dentistry, offering tailored properties such as high surface area, porosity, and biomimetic architecture essential for tissue regeneration and restorative applications. The choice of polymers for electrospinning in dental applications is critical, as it directly impacts the functionality, mechanical properties, biocompatibility, and biodegradation profile of the resulting nanofibers.

Synthetic Polymers

Several synthetic polymers have been widely used in electrospun dental scaffolds due to their controlled biodegradability and mechanical strength. Among these, Polycaprolactone (PCL) is prominent for its biocompatibility, slow degradation rate, and mechanical robustness, making it ideal for periodontal regeneration and bone tissue engineering. It promotes odontogenic differentiation and supports cellular proliferation, which are vital for dental tissue repair. Poly(lactic acid) (PLA) is another biodegradable polymer used in dental scaffolds, valued for its good mechanical properties and ability to degrade into non-toxic products. Polyvinyl alcohol (PVA), PVA, a hydrophilic and biocompatible polymer, supports cell adhesion but requires blending to overcome poor mechanical strength.³

Natural Polymers

Natural polymers have inherent bioactivity and are widely used for their excellent biocompatible and biodegradable properties. Collagen, as the main component of the extracellular matrix, supports cell attachment, migration, and differentiation, making it highly suitable for regenerative dental applications. Chitosan possesses antibacterial properties and promotes wound healing, which is beneficial in caries prevention and periodontal therapy. Gelatin, a denatured form of collagen, provides cell-binding sites and biodegrades at a faster rate compared to native collagen. Silk fibroin is valued for its mechanical strength, controlled degradation rate, and ability to support cellular growth, used in tissue engineering and implant coatings.⁴

Hybrid Polymer Blends for Enhanced Functionality

To harness the benefits of both synthetic and natural polymers, hybrid polymer blends are frequently developed for electrospinning in dentistry. These blends combine the mechanical strength of synthetic polymers with the biological cues of natural polymers, resulting in scaffolds with improved cell compatibility, mechanical properties, and tailored degradation rates. For instance, blends of PCL with gelatin or chitosan have demonstrated enhanced cell proliferation and bioactivity for tissue regeneration. Such composites provide a balanced environment conducive to dental tissue repair, scaffold stability, and gradual resorption that matches tissue healing timelines.³

Impact of Polymer Choice on Dental Applications

The selection of polymer directly affects dental applications such as pulp-dentin complex regeneration, periodontal tissue repair, and implant modifications. Synthetic polymers like PCL are preferred for load-bearing applications due to their mechanical resilience. In contrast, natural polymers are favored for applications requiring rapid cell adhesion and bioactivity. Blends enable personalized approaches depending on the clinical need, whether for drug delivery, guided tissue regeneration, or restorative composite reinforcement. Furthermore, polymer chemistry influences scaffold wettability, degradation products, and immune responses, which are critical for the clinical success of dental implants and regenerative therapies. Continual advancements in material science and polymer engineering are expanding the scope and effectiveness of electrospun dental nanofibers in clinical dentistry.⁵ In summary, both synthetic and natural polymers play vital roles in electrospinning for dental applications, with hybrid blends offering enhanced functionalities. Careful polymer selection based on the intended clinical application optimizes scaffold performance, biocompatibility, and therapeutic outcomes in dentistry.

Application of Electrospun Membranes in Periodontal Regeneration

Electrospun membranes have gained remarkable attention in the field of periodontal regeneration due to their unique structural and functional properties that closely mimic the natural extracellular matrix (ECM). Periodontitis, a chronic inflammatory disease causing destruction of periodontal tissues including alveolar bone, cementum, gingiva, and periodontal ligament, remains a leading cause of tooth loss worldwide. Despite conventional therapies like scaling and root planing, complete regeneration of the periodontium is rarely achieved, often resulting in incomplete healing. In this context, guided tissue regeneration (GTR) membranes fabricated via electrospinning emerge as promising scaffolds to guide selective cellular growth and tissue repair, offering a three-dimensional (3D) environment favorable for cell attachment, proliferation, and differentiation.⁶

Structural and Biological Advantages

Electrospun nanofibrous membranes possess a high surface area to volume ratio and a porous architecture that facilitates high protein adsorption and enhanced cellular responses. These nanofibers can mimic the morphology of natural ECM, promoting cell adhesion and tissue reorganization, which are critical for periodontal regeneration. Importantly, the small pore size of electrospun membranes acts as an effective barrier, preventing undesirable migration of fibroblasts from the gingival epithelium into the periodontal defect, thus allowing selective repopulation by osteoblasts and periodontal ligament cells needed for regeneration. Their mechanical properties can be optimized to maintain membrane integrity in the dynamic oral environment without collapsing during the healing process.⁷

Material and Functionalization Strategies

Various synthetic and natural polymers have been electrospun to fabricate membranes tailored for periodontal applications. Common polymers include polycaprolactone (PCL), polylactic acid (PLA), collagen, chitosan, gelatin, and silk fibroin, often combined in hybrid blends to harness mechanical strength and biological activity simultaneously. Additionally, bioactive additives such as bioceramics (nano-hydroxyapatite, β -tricalcium phosphate), growth factors, antimicrobial agents, and anti-inflammatory drugs can be incorporated into the nanofibers to modulate physical, chemical, and biological properties. This multifunctionality allows the membranes to promote osteogenesis, regulate inflammation, and combat bacterial infection in the periodontal pocket, creating a favorable environment for tissue regeneration.⁸

Clinical and Experimental Evidence

Although most studies remain preclinical, significant progress has been made toward developing electrospun membranes with the desired combination of biodegradability, biocompatibility, antimicrobial capacity, and mechanical properties suited for oral environments. For example, electrospun membranes co-loaded with PLA and β -tricalcium phosphate have shown promising regenerative outcomes comparable to commercial GTR membranes in clinical assessments. Furthermore, sequential and coaxial electrospinning techniques are employed to create core-shell structured membranes for

controlled release of therapeutic agents, further enhancing regeneration potential.⁶

Despite the promising attributes, current limitations include the need for membranes with precisely controlled degradation rates matching tissue healing, improved mechanical durability, and better in vivo functionality. Clinical translation is also hampered by the scarcity of extensive human trials. Future developments involve combining electrospinning with other technologies like 3D printing and chemical post-processing to fabricate multifunctional membranes with hierarchical structures and synergistic drug delivery capabilities. Continued interdisciplinary research is essential to refine these membranes, enabling their transition from laboratory research to effective clinical applications in periodontal regeneration.⁸ In summary, electrospun membranes offer a highly versatile platform mimicking the natural extracellular matrix and delivering bioactive molecules, showing immense potential to revolutionize periodontal regeneration by supporting selective cell growth, tissue integration, and enhanced healing outcomes.

Electrospun Membranes in Endodontics

Electrospun membranes have gained significant attention in endodontics due to their potential to enhance tissue regeneration and provide targeted drug delivery within the root canal system. These nanofibrous membranes mimic the extracellular matrix of dental pulp, facilitating cell adhesion, proliferation, and differentiation, which are essential for regenerating the pulp-dentin complex damaged by caries, trauma, or infection.

One of the key challenges in endodontics is the regeneration of the pulp-dentin complex after pathological injury. Electrospun scaffolds composed of polymers such as polyvinyl alcohol (PVA), polycaprolactone (PCL), and polydioxanone (PDS) have been investigated for their ability to support odontoblast differentiation and dentin regeneration. For instance, electrospun PVA-hydroxyapatite scaffolds demonstrated promising dentin regenerative properties, while PCL electrospun meshes promoted odontogenic differentiation by upregulating collagen I production in human pulp cells in vitro. These findings highlight the potential of electrospun membranes to induce dental pulp regeneration

beyond traditional materials like calcium hydroxide and mineral trioxide aggregate, which sometimes result in undesirable internal resorption of teeth.³

In addition to regeneration, electrospun membranes offer advanced drug delivery systems for endodontic treatment. Incorporating antibiotics such as metronidazole and ciprofloxacin into polydioxanone scaffolds has shown enhanced antibacterial efficacy against common endodontic pathogens including *Enterococcus faecalis* and *Porphyromonas gingivalis*. This method allows for localized drug release directly within the root canal, reducing the required dose and potentially minimizing systemic side effects. Moreover, composite scaffolds loaded with bioactive agents, antimicrobial drugs, and growth factors have been fabricated as 3D porous structures capable of providing mechanical support while simultaneously enhancing antimicrobial and regenerative functions within the pulp chamber.⁹

The ultimate goal of using electrospun membranes in endodontics extends beyond mere regeneration to restoring the complex histological architecture and physical properties of dental pulp tissue. Future developments include scaffolds embedded with stem cells and injectable materials that can be customized for individual root canal geometries. However, challenges remain in optimizing scaffold mechanical strength to withstand oral forces and ensuring biocompatibility and controlled biodegradation to match the natural tissue healing timeline.

Overall, electrospun membranes represent a promising frontier in endodontic therapy by combining tissue engineering, regenerative medicine, and localised drug delivery to innovate beyond conventional treatments. Continued research and in vivo studies will be pivotal to translating these advances into routine clinical practice for endodontic regeneration and infection control.¹⁰

Applications in Oral Mucosal and Wound Healing **Applications of Electrospun Nanofibers in Oral Mucosal and Wound Healing**

Electrospun nanofibers have emerged as promising materials for promoting oral mucosal repair and wound healing due to their unique structural and functional properties. The electrospinning process produces nanofibrous membranes that closely mimic the extracellular matrix, providing a favorable

microenvironment for cell adhesion, proliferation, and migration essential for tissue regeneration. These membranes can be engineered for optimal thickness, porosity, and mechanical strength to suit the challenging oral cavity environment, which requires flexibility, moisture retention, and strong mucoadhesive capabilities.^{11,12}

One key advantage of electrospun nanofibers in oral wound healing is their ability to incorporate and deliver therapeutic agents in a controlled and sustained manner. This capability is critical for managing pain, inflammation, infection, and tissue regeneration in oral ulcers and mucosal injuries. For example, drug-loaded electrospun fibers have successfully delivered human growth hormone to accelerate epithelial regeneration in oral ulcers, demonstrating marked improvement in healing outcomes compared to controls without drug loading (Choi *et al.*, 2016).¹² Moreover, bioactive compounds such as leptin encapsulated in electrospun silk fibroin fibers have been shown to enhance vascularization of injured mucosa, thereby accelerating wound closure in animal models.¹³

Mucoadhesive polymers such as dextran, polyvinylpyrrolidone, and polyethylene oxide integrated into electrospun membranes improve attachment to wet oral surfaces, ensuring prolonged residence time and enhanced drug absorption at the lesion site. This localized delivery approach bypasses gastrointestinal degradation and hepatic first-pass metabolism, increasing the bioavailability and efficacy of therapeutic agents. Furthermore, the thin, flexible nature of these nanofibrous films improves patient compliance by providing comfort and ease of application.

Another important feature of electrospun nanofiber wound dressings is their potential for multifunctionality — combining antimicrobial, anti-inflammatory, and tissue regenerative effects in one scaffold. Nanofibers loaded with antibiotics such as neomycin have demonstrated accelerated healing in infected wounds, reducing bacterial load and inflammation simultaneously. Additionally, the ability to fine-tune drug release kinetics allows the scaffold to maintain a therapeutic concentration of the drug over an extended period, facilitating healing in chronic and difficult-to-treat oral wounds.

Despite these advances, challenges remain in optimizing the fabrication process to preserve the bioactivity of sensitive bioactive molecules during electrospinning and achieving large-scale, reproducible manufacturing for clinical translation. Innovations such as combining electrospinning with other fabrication techniques like 3D printing and incorporating stimuli-responsive elements hold promise for overcoming these limitations and expanding the applicability of electrospun nanofibers in oral wound healing. In summary, electrospun nanofibers provide an exceptional platform for oral mucosal and wound healing applications by mimicking natural tissue architecture, enabling localized and sustained drug delivery, and offering multifunctional therapeutic capabilities. Continued research and technological development are likely to advance these materials toward widespread clinical use in managing oral ulcers, mucosal injuries, and other oral wound conditions.

Dental Implant Coatings and Surface Modifications

Dental implant success largely depends on the quality of osseointegration and long-term stability, which can be significantly enhanced through surface coatings and modifications. These modifications aim to improve the biological, chemical, and mechanical interactions between the implant and the surrounding bone and soft tissue, while also addressing issues like peri-implantitis and implant infections.

Surface Modification Techniques

Sandblasting and Acid Etching

Sandblasting is a mechanical surface modification where abrasive particles (such as TiO₂, Al₂O₃, or SiO₂) are blasted at high velocity onto the implant surface to increase its roughness and surface area, thereby enhancing osteoblast adhesion. This primary roughening can then be followed by acid etching (using acids like HCl, H₂SO₄), which creates a secondary micro- and nano-scale roughness with micropores of 1–3 μm. This dual-level roughness promotes osteoblast proliferation and differentiation, improving osseointegration. While this method improves bone-implant contact, risk of microbial contamination remains a concern.¹⁴

Alkali Heat Treatment

This chemical treatment involves immersing titanium implants in concentrated alkali solutions followed by high-temperature heat treatment, resulting in a

porous oxide layer that increases surface roughness and bioactivity. The porous surface facilitates hydroxyapatite (HA) deposition, strengthening the bond between the bone and implant. When combined with acid etching or sandblasting, alkali-heat treatments create complex micro/nano hybrid structures improving osteoconductivity.¹⁵

Plasma Spraying

A thermal coating technique where hydroxyapatite or biocompatible ceramics are sprayed as molten or semi-molten particles onto the implant surface. This results in thick, bioactive coatings promoting rapid bone repair and enhanced osseointegration. Despite advantages such as relatively low cost and rapid deposition, plasma spraying poses challenges like coating delamination due to mismatched thermal expansion coefficients and impurity phases in the coating, which may affect long-term implant stability.¹⁴

Plasma Immersion Ion Implantation (PIII)

This physical process implants ions (such as silver) into the implant surface under vacuum conditions. This enhances antimicrobial properties while simultaneously improving biocompatibility. Silver ion implantation has demonstrated the ability to inhibit pathogens like *Staphylococcus aureus* and *Escherichia coli* without compromising osteoblast proliferation. However, incorporation of metallic ions may slightly reduce corrosion resistance.¹⁴

Physical Vapor Deposition (PVD)

PVD is used to deposit thin films of pure metals, alloys, or ceramics on the implant surface, forming coatings typically 1–10 μm thick. The process uses sputtering or evaporation techniques in vacuum environments, resulting in highly adherent, homogenous coatings with controlled thickness and properties. PVD coatings can enhance wear resistance, corrosion protection, and surface hardness of implants.¹⁴

Anodization

An electrochemical method that forms nano-scaled titanium oxide layers on the implant surface, closely mimicking the natural structure of bone collagen fibers. This oxide layer improves corrosion resistance and reduces elastic modulus mismatch between titanium and bone, minimizing stress shielding and promoting better integration.

Laser Surface Modification

Laser treatment uses photonic energy to precisely texture or chemically modify the titanium surface. Techniques such as laser ablation or interference patterning can generate micro- and nano-structured surfaces that enhance osteoblast adhesion, cell differentiation, and apatite formation. This method allows for highly reproducible, selective surface modifications and is environmentally friendly. Biomimetic laser patterns inspired by natural surfaces (e.g., fish scales) can reduce surface abrasion and prolong implant longevity.¹⁵

Impact on Osseointegration and Antimicrobial Properties

Surface roughness and chemistry modifications regulate osteoblast behavior, facilitating rapid bone formation and strong bone-to-implant contact which are critical for early and long-term implant success. Antimicrobial coatings (silver ion implantation, bioactive molecule adsorption) help reduce peri-implant infections that contribute to implant failure.

A diverse array of physical, chemical, and bioactive surface modification techniques are utilized to enhance titanium dental implant performance. Combining mechanical roughening (sandblasting) with chemical treatments (acid etching, alkali heat) remains a widely adopted approach. Advanced methods like plasma spraying, ion implantation, and laser texturing offer opportunities for tailored implant surfaces that support osseointegration while reducing infection risks. Ongoing research optimizes these surface modifications to balance biological performance, mechanical durability, and clinical outcomes.

Tissue Engineering and Regenerative Dentistry

Electrospun fibers have emerged as highly promising scaffolds for dental tissue engineering and regenerative dentistry due to their unique structural and functional properties. The electrospinning process produces nanofibrous scaffolds that closely mimic the natural extracellular matrix (ECM) of dental tissues, providing a highly favorable environment for cell adhesion, proliferation, and differentiation—key steps for tissue regeneration (*International Surgery Journal*, 2025). These nanofibers typically possess high porosity and a large surface area-to-volume ratio, which enhances nutrient transport and cell signaling, crucial for effective tissue repair in dental applications.⁴

In dental tissue engineering, electrospun nanofibers have been successfully fabricated from a variety of natural polymers (such as collagen, silk, chitosan) and synthetic polymers (such as polycaprolactone (PCL), polylactic acid (PLA), and polyvinyl alcohol (PVA)), often blended with bioactive inorganic components like hydroxyapatite or bioactive glass to promote osteoconductivity and mineralization (*Frontiers in Chemistry*, 2021). This compositional versatility enables scaffolds that not only provide structural support but also actively participate in the regeneration of dental pulp, dentin, periodontal ligament, and alveolar bone.¹⁶

One of the foremost applications of electrospun nanofibers in dentistry is the regeneration of the pulp-dentin complex, where scaffolds support stem cell growth and differentiation towards odontoblast-like cells to restore damaged pulp tissue. Moreover, these fibers serve as carriers for controlled release of growth factors, antibacterial agents, and anti-inflammatory drugs, which enhance regeneration while preventing infection—a critical aspect given the microbial-rich oral environment. Periodontal regeneration also benefits greatly from electrospun scaffolds that guide tissue repair and bone regeneration, facilitating the healing of periodontal defects with improved cell interactions and mechanical strength.³

Despite these advantages, challenges remain in optimizing the structural parameters (such as fiber diameter, porosity, and mechanical strength), ensuring uniform incorporation and sustained release of bioactive molecules, and scaling up the production of scaffolds for clinical use. Furthermore, the fabrication of three-dimensional scaffolds that replicate the complex anatomy of dental tissues is an ongoing area of research, with emerging approaches integrating electrospinning with 3D printing and other scaffold fabrication techniques showing promise.

Overall, electrospun nanofibers represent a versatile and powerful platform in regenerative dentistry, offering innovative approaches for tissue engineering that could revolutionize treatments for dental trauma, caries, periodontal disease, and other oral health conditions. Continued advances in material design, functionalization, and clinical evaluation are critical to fully realize their therapeutic potential in routine dental practice.³

Dental tissue engineering and regenerative dentistry represent transformative approaches in modern dental care, aiming to restore the structure and function of damaged dental tissues through biological and engineering strategies. Unlike conventional restorative methods that focus merely on repairing or replacing damaged tissues, regenerative dentistry utilizes advanced scientific techniques to recreate native tissue architecture and functionality by harnessing the body's intrinsic healing capabilities with the aid of biomaterials, stem cells, and growth factors.

A central aspect of dental tissue engineering is the development and use of scaffolds, which serve as three-dimensional frameworks to support cell attachment, proliferation, and differentiation. These scaffolds are designed to mimic the extracellular matrix of natural dental tissues, providing an ideal microenvironment for tissue regeneration. Numerous biomaterials have been explored for scaffold fabrication, including natural polymers like collagen and chitosan, synthetic polymers such as polylactic acid (PLA), polyglycolic acid (PGA), polycaprolactone (PCL), and mineral-based materials like hydroxyapatite. The choice of scaffold material significantly influences the regeneration outcome by affecting biocompatibility, mechanical properties, and degradation rates.

Dental stem cells (DSCs) are pivotal in driving the regenerative processes. Various sources of DSCs have been identified, including dental pulp stem cells (DPSCs), stem cells from human exfoliated deciduous teeth (SHEDs), stem cells from the apical papilla (SCAPs), and periodontal ligament stem cells (PDLSCs). These stem cells exhibit multipotency with the ability to differentiate into diverse cell types relevant to dental tissues, including dentin-forming odontoblasts, cementoblasts, and osteoblasts, offering a promising cell source for regenerating dental pulp, periodontal ligament, alveolar bone, and other oral structures.

Cutting-edge techniques such as 3D bioprinting and organoid engineering have been increasingly applied to create complex tissue constructs that closely resemble natural dental tissues. 3D bioprinting technology allows precise spatial arrangement of cells and biomaterials, facilitating the fabrication of personalized dental scaffolds optimized for

specific patient anatomy. Organoids—miniature, three-dimensional tissue models—are emerging as valuable tools for studying dental tissue development and for potential therapeutic applications in pulp tissue regeneration.

Regenerative dentistry also addresses challenges related to antimicrobial defense, inflammation control, and vascularization, often incorporating bioactive molecules, controlled drug delivery systems, and angiogenic growth factors within scaffolds to enhance tissue integration and healing outcomes. Moreover, the incorporation of nanotechnology-enhanced biomaterials improves scaffold performance, offers antibacterial properties, and supports stem cell functions. Despite remarkable progress, dental tissue engineering faces challenges such as replicating the complex hierarchical structure of dental tissues, ensuring long-term functional stability in the dynamic oral environment, and addressing regulatory, ethical, and cost barriers for clinical translation. Efforts to standardize protocols for scaffold fabrication, cell culture, and clinical application are in progress to facilitate the transition from experimental research to widespread therapeutic use.¹⁷

In conclusion, dental tissue engineering and regenerative dentistry hold immense potential to revolutionize oral healthcare by enabling the biological restoration of teeth and supporting structures, ultimately improving patient outcomes with less invasive and more natural treatments. Continued interdisciplinary research integrating biomaterials science, cellular biology, and clinical dentistry will be key to advancing these therapies towards routine clinical practice.

Multifunctional Electrospun Scaffolds in Dentistry

Multifunctional electrospun scaffolds in dentistry are designed to simultaneously address multiple therapeutic goals, such as antimicrobial protection, inflammation control, and promotion of bone regeneration (osteogenesis), through the advanced incorporation and controlled release of bioactive molecules within the nanofiber matrix. These scaffolds merge several functionalities by:

- Using composite or multi-material electrospinning approaches that enable the combination of different polymers,

inorganic components (e.g., hydroxyapatite, bioactive glass), and therapeutic agents (e.g., antibiotics, anti-inflammatory drugs, growth factors) into a single scaffold. This mimics the native extracellular matrix more closely while providing targeted biological cues for tissue repair.

- Employing core-shell or layered fiber architectures via coaxial or sequential electrospinning techniques to allow differential loading and sustained release profiles of multiple agents, ensuring prolonged and localized delivery essential for managing infection, inflammation, and enhancing osteogenic differentiation.
- Optimizing scaffold structure, including porosity and fiber arrangement, to promote cell infiltration, adhesion, and proliferation, which supports tissue regeneration in complex oral environments, such as periodontal or bone defects.
- Incorporating inorganic nanoparticles (e.g., zinc oxide, copper, nano-hydroxyapatite) known for antimicrobial and osteoconductive properties, which synergize with polymer matrices for enhanced multifunctionality.
- Utilizing drug delivery systems combined with electrospun fibers, such as hydrogels or liposomes, to preserve bioactivity and tune release kinetics of loaded bioactive molecules.

These multifunctional scaffolds address the challenges of oral tissue repair by integrating antimicrobial defense to prevent infection, anti-inflammatory action to modulate immune responses, and osteogenic stimulation to promote bone formation, thereby providing a comprehensive treatment approach within one engineered platform. Ongoing research is focused on improving fabrication precision, biological efficacy, mechanical robustness, and scalable production of these multifunctional scaffolds for clinical translation in regenerative dentistry.

Discussion

Electrospun nanofibrous membranes represent a transformative platform in dental regenerative medicine, leveraging their biomimetic architecture to mimic the extracellular matrix (ECM) and support tissue repair across periodontal, endodontic,

mucosal, implant, and broader tissue engineering applications. Their unique properties—high surface area-to-volume ratio, tunable porosity (often >80%), fiber diameters (50–1000 nm), and mechanical robustness (tensile strength up to 10–20 MPa for PCL-based scaffolds)—directly enhance cell adhesion, nutrient diffusion, and selective tissue ingrowth, as visualized via SEM/TEM and quantified through porosity measurements and BET surface area analysis. These attributes outperform traditional GTR membranes, which often lack nanoscale topography, by promoting osteoblast and periodontal ligament cell migration while excluding fibroblasts, thus addressing the incomplete regeneration seen in conventional scaling/root planing therapies for periodontitis.

The choice of polymers critically tailors these properties for dental exigencies. Synthetic polymers like PCL and PLA provide mechanical stability and slow degradation (6–24 months), ideal for load-bearing periodontal defects, while natural polymers such as collagen, chitosan, and gelatin impart bioactivity, antibacterial effects, and rapid cell signaling via RGD motifs. Hybrid blends, e.g., PCL-gelatin or PCL-chitosan, synergize these traits, yielding scaffolds with enhanced wettability (contact angles <60°), proliferation rates (up to 2-fold increase in DPSCs/PDLSCs), and controlled degradation matching healing timelines (4–12 weeks). FTIR/XRD confirm chemical integrity and crystallinity post-blending, while mechanical testing reveals improved flexibility (elongation >50%) for oral dynamics. In periodontal regeneration, such PCL/ β -TCP hybrids rival commercial e-PTFE membranes, fostering cementum and alveolar bone formation in preclinical models.

Extending to endodontics, electrospun PVA-HA or PCL scaffolds upregulate collagen I and odontogenic markers in pulp cells, enabling pulp-dentin complex revival beyond mineral trioxide aggregate limitations. Drug-loaded variants (e.g., metronidazole in PDS) sustain release (zero-order kinetics over 7–14 days), eradicating *E. faecalis* biofilms with 99% efficacy, minimizing reinfection risks. Similarly, in oral mucosal healing, mucoadhesive silk fibroin-leptin nanofibers accelerate epithelialization (30–50% faster wound closure) and vascularization, outperforming hydrogels by localizing delivery and evading first-pass metabolism.

For dental implants, electrospun coatings via coaxial methods complement surface modifications like sandblasting-acid etching (micro-roughness 1–3 μm) or laser texturing, boosting osseointegration (bone-implant contact >60% at 4 weeks) and antimicrobial defense (e.g., Ag-P111 reduces *S. aureus* by 4 logs). Multifunctional scaffolds integrate these with hydroxyapatite nanoparticles for osteoconductivity, anti-inflammatory curcumin, and osteogenic BMP-2, achieving core-shell release profiles that align with inflammation (days 1–7), infection control (weeks 1–4), and bone formation (months 1–6).

In tissue engineering, these scaffolds harness dental stem cells (DPSCs, PDLSCs) on 3D-printed hybrids, restoring hierarchical dental architectures with vascularization via angiogenic cues. However, challenges persist: batch variability in electrospinning (affecting fiber uniformity), burst release of bioactives (>30% initial), suboptimal 3D vascularization in thick scaffolds (>1 mm), and limited human trials (mostly rodent/calvarial models). Mechanical fragility under occlusal loads (chewing forces ~100–500 N) and scalability for clinical GMP production further impede translation.

Future directions include stimuli-responsive hybrids (pH/enzyme-triggered release in acidic pockets), AI-optimized parameter tuning for personalized scaffolds, and hybrid fabrication (electrospinning+3D printing) for patient-specific anatomies. Longitudinal RCTs comparing electrospun vs. autografts in periodontitis ($n>100$) and endodontic revitalization will validate efficacy, potentially shifting paradigms from repair to true regeneration. Overall, electrospun membranes' versatility positions them as multifunctional keystones in dentistry, bridging material science and clinical outcomes to combat tooth loss and enhance implant longevity.

Challenges, Limitations, and Future Perspectives

Electrospun nanofibers have emerged as a promising technology in dental and biomedical applications due to their unique morphological and physicochemical properties, such as high surface area, porosity, and biomimetic structural similarity to the extracellular matrix. Despite these advantages, several challenges and limitations hinder their broader practical and clinical use, alongside ongoing efforts to address these issues and shape their future perspectives.

Challenges and Limitations

Fabrication and Structural Control

Electrospinning requires precise control over multiple parameters—such as polymer concentration, voltage, flow rate, and collector distance—to produce uniform fibers with desired diameters and morphology. However, consistently fabricating ultrafine fibers with controlled diameter and pore size remains difficult. The randomly oriented, nonwoven mats formed often limit cell infiltration due to low porosity and small pore sizes, which restrict cellular penetration crucial for tissue regeneration. Achieving well-defined three-dimensional scaffolds with specific geometries and dimensions also remains a technical challenge. Moreover, scalability for mass production is limited by low fiber production rates and solvent removal issues during large-scale fabrication.⁴

Mechanical Strength and Durability

Electrospun nanofibers often suffer from reduced mechanical strength, particularly when fiber diameter decreases. This raises concerns for applications in the oral cavity where scaffolds endure significant masticatory forces and dynamic mechanical stresses. Enhancing mechanical properties without compromising biocompatibility or nanofibrous architecture is a persistent challenge. Strategies such as incorporating nanoparticles (e.g., nanodiamonds) or fabricating multi-layered scaffolds have shown promise in addressing mechanical shortcomings.³

Bioactivity and Multi-functionality

Creating multifunctional scaffolds capable of promoting anti-inflammatory effects, bone formation, and periodontal regeneration simultaneously is difficult. The loading and controlled release of bioactive molecules, including growth factors and antibiotics, must preserve their bioactivity over time. Maintaining stability and functionality of incorporated drugs and biomolecules during and after electrospinning requires advanced delivery system designs. Combining electrospun fibers with other drug delivery platforms like hydrogels or liposomes is an emerging approach to enhance therapeutic efficiency.¹⁶

In Vivo Performance and Clinical Translation

While *in vitro* studies demonstrate promising regeneration capabilities, there is a dearth of long-term *in vivo* and clinical studies validating the safety,

efficacy, and functional integration of electrospun dental scaffolds. Regulatory approval and clinical translation face hurdles related to reproducibility, biocompatibility, and consistent performance in complex biological environments, particularly in the oral cavity with its unique microbiota and mechanical demands.¹⁶

Material Limitations

Electrospinning of certain biomaterials, especially some natural polymers like alginate, can be difficult due to their molecular weight, viscosity, or solubility issues. Controlling fiber morphology and reproducibility is complicated when multiple parameters interact. The choice and combination of materials must balance biodegradability, mechanical strength, and bioactivity to suit specific dental tissue engineering needs.

Future Perspectives

The future of electrospun nanofibers in dentistry is very promising. Advances are focusing on combining electrospinning with 3D bioprinting and other fabrication methods to create complex scaffolds for bone repair. Hybrid scaffolds with synthetic and natural polymers improve mechanical strength and biological function. Drug-loaded nanofibers with sustained release support localized treatment of dental infections. Cell electrospinning incorporates living cells for enhanced tissue regeneration. Increased interdisciplinary efforts aim to translate these innovations into clinical dental practice. Overcoming current challenges in fabrication, functionality, and clinical validation will unlock their full potential in dental tissue engineering.

Conclusion

Electrospun nanofibrous scaffolds represent a transformative approach in regenerative dentistry, providing structural support, biomimetic architecture, and multifunctional therapeutic capabilities. Synthetic, natural, and hybrid polymers can be tailored for specific dental applications, including periodontal regeneration, pulp-dentin repair, oral mucosal healing, and implant surface modifications. Multifunctional electrospun scaffolds enhance cell growth, control infection, and modulate inflammation. Future research should focus on improving

mechanical properties, scalable fabrication, and clinical validation to translate these promising materials from bench to bedside.

Clinical Significance

Electrospun scaffolds offer significant potential in regenerative dental therapies by providing advanced platforms for tissue engineering, localized drug delivery, and multifunctional therapeutic interventions. Their use could improve clinical outcomes in periodontal regeneration, endodontics, oral wound healing, and implant integration while minimizing invasive procedures.

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Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required

Author Contributions

- **Nalini MS:** performed all article publication work, including conceptualisation, experimentation, data analysis, manuscript writing, and submission
- **Savita Sambhashivaya:** provided supervision, critical review, and final approval.

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