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Application of Modern Biopolymer-Based Biomaterials in Endodontic and Restorative Dentistry: A Clinical and Experimental Analysis

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Abstract

The rapid development of biomaterial science has significantly influenced modern dental practice by introducing biopolymer-based materials capable of enhancing tissue regeneration, improving biocompatibility, and optimizing clinical outcomes. Unlike conventional restorative materials, contemporary biopolymers possess biological properties that actively support healing processes while minimizing inflammatory responses. This review analyzes the clinical and experimental applications of natural and synthetic biopolymer-based biomaterials in endodontic and restorative dentistry. Particular attention is given to collagen, chitosan, hyaluronic acid, alginate, gelatin, silk fibroin, and biodegradable polymer composites that have demonstrated promising regenerative potential. Recent experimental studies indicate that these biomaterials improve pulp tissue regeneration, dentin repair, antimicrobial activity, and adhesive performance while maintaining favorable physicochemical characteristics. Furthermore, advances in nanotechnology, tissue engineering, and three-dimensional bioprinting have expanded the therapeutic possibilities of biopolymer-based scaffolds for personalized dental treatment. The available evidence suggests that modern biopolymers represent an important step toward biologically oriented dentistry by combining structural support with regenerative capacity. Continued interdisciplinary research is expected to further improve the clinical effectiveness and long-term performance of these biomaterials.

Keywords: biopolymers, biomaterials, endodontics, restorative dentistry, regenerative dentistry, collagen, chitosan, tissue engineering, dental regeneration, bioactive materials.

Introduction

Modern dentistry has shifted from the replacement of damaged tissues toward biologically based regeneration. This transformation has been driven by advances in biomaterial science, regenerative medicine, and molecular biology. Conventional restorative materials primarily restore mechanical function but have limited biological activity. Consequently, increasing attention has been directed toward biopolymer-based biomaterials that actively participate in tissue repair and regeneration.

Biopolymers are naturally derived or biodegradable synthetic macromolecules characterized by excellent biocompatibility, controlled biodegradation, low cytotoxicity, and favorable interactions with living tissues. These characteristics make them particularly suitable for dental applications requiring close contact with pulp tissue, dentin, periodontal structures, and oral mucosa.

Endodontic and restorative dentistry have experienced remarkable progress through the integration of bioactive materials capable of stimulating mineralization, reducing bacterial colonization, and supporting tissue healing. Contemporary treatment strategies increasingly rely on biomaterials that combine mechanical stability with biological functionality, thereby improving both immediate and long-term therapeutic outcomes.

The present article reviews the biological properties, clinical applications, and experimental evidence supporting the use of modern biopolymer-based biomaterials in endodontic and restorative dentistry.

Main Part

Biological Characteristics of Dental Biopolymers

Biopolymers represent an important class of biomaterials because they closely resemble components of the natural extracellular matrix. Their molecular architecture facilitates cell adhesion, proliferation, differentiation, and tissue remodeling, all of which are essential for successful dental regeneration.

Natural biopolymers, including collagen, chitosan, alginate, hyaluronic acid, gelatin, fibrin, and silk fibroin, exhibit excellent biological compatibility and minimal immunogenicity. Synthetic biodegradable polymers such as polylactic acid (PLA), polyglycolic acid (PGA), and poly(lactic-co-glycolic acid) (PLGA) provide superior mechanical stability while allowing controlled degradation during tissue healing.

Biopolymer Applications in Endodontics

Regenerative endodontics aims to preserve or restore pulp vitality rather than simply filling the root canal system. Biopolymer-based scaffolds have become essential components of regenerative endodontic therapy because they create an environment favorable for stem cell migration, angiogenesis, and dentin regeneration.

Collagen scaffolds are widely investigated due to their structural similarity to native dental tissues. They promote odontoblast differentiation, extracellular matrix formation, and mineralized tissue deposition. Chitosan-based hydrogels possess intrinsic antimicrobial activity against common endodontic pathogens while simultaneously supporting pulp cell proliferation.

Hyaluronic acid contributes to wound healing by regulating inflammation and stimulating fibroblast migration. Experimental evidence suggests that hyaluronic acid enhances vascularization within regenerated pulp tissue and accelerates tissue maturation after regenerative procedures.

Nanostructured biopolymer composites incorporating calcium silicate particles, hydroxyapatite nanoparticles, or bioactive glass further improve mineralization potential and mechanical performance. These multifunctional systems combine biological stimulation with structural reinforcement, making them promising candidates for future regenerative endodontic protocols.

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Biopolymer Applications in Restorative Dentistry

Restorative dentistry increasingly incorporates bioactive polymers into adhesive systems, liners, resin composites, and pulp-capping materials. Unlike conventional restorative materials, bioactive polymers interact dynamically with surrounding tissues and may release calcium, phosphate, or antimicrobial agents that contribute to tissue preservation.

Collagen-based matrices improve dentin bonding by stabilizing the collagen network within the hybrid layer. Chitosan nanoparticles enhance antimicrobial activity while reducing degradation of adhesive interfaces. Gelatin hydrogels have demonstrated potential as controlled drug delivery systems capable of releasing antibacterial or anti-inflammatory agents directly into prepared cavities.

Recent investigations have also focused on incorporating antimicrobial peptides, growth factors, and stem-cell signaling molecules into polymeric scaffolds. Such multifunctional biomaterials may simultaneously prevent secondary caries, stimulate tertiary dentin formation, and prolong restoration longevity.

Furthermore, advances in nanotechnology have enabled the development of nanobiopolymers with improved mechanical strength, wear resistance, and antibacterial performance. These materials represent an important step toward minimally invasive and biologically driven restorative dentistry.

Emerging Biopolymer Technologies in Modern Dentistry

Recent advances in biomaterial engineering have led to the development of multifunctional biopolymer systems capable of simultaneously promoting tissue regeneration, controlling bacterial growth, and improving the longevity of dental restorations. Modern scaffolds are increasingly fabricated using three-dimensional (3D) bioprinting, electrospinning, and nanotechnology, allowing precise control over porosity, degradation rate, and mechanical strength.

Nanostructured biopolymers have attracted particular attention because nanoscale modifications increase surface area, improve protein adsorption, and facilitate stem-cell attachment. Incorporation of hydroxyapatite nanoparticles, bioactive glass, calcium phosphate, and antimicrobial peptides into collagen- or chitosan-based matrices enhances mineralization while maintaining excellent biocompatibility. These hybrid materials show considerable promise for pulp regeneration, dentin repair, and periodontal tissue engineering.

Drug-delivery systems based on biodegradable polymers have also become an important component of regenerative dentistry. Controlled release of antibiotics, anti-inflammatory drugs, growth factors, and signaling molecules directly into the treatment site improves local therapeutic effectiveness while minimizing systemic adverse effects. This strategy is particularly valuable in regenerative endodontic procedures where successful healing depends on infection control and the creation of a favorable biological microenvironment.

Clinical Applications

In clinical endodontics, collagen, gelatin, and chitosan scaffolds are increasingly investigated as biological matrices supporting dental pulp stem cell proliferation and vascular regeneration. Hyaluronic acid-based hydrogels have demonstrated favorable wound-healing properties by reducing inflammatory reactions and stimulating angiogenesis, making them valuable adjuncts during regenerative procedures.

Within restorative dentistry, bioactive polymer-containing adhesive systems and restorative composites have demonstrated the ability to reduce marginal degradation, improve dentin bonding, and support remineralization through sustained ion release. Current evidence indicates that these materials contribute to better marginal adaptation and may reduce the risk of secondary caries, although additional long-term randomized clinical trials remain necessary before definitive clinical recommendations can be established.

The integration of artificial intelligence with digital dentistry is expected to facilitate personalized biomaterial selection based on lesion characteristics, patient-specific biological factors, and predicted treatment outcomes. Such individualized approaches may further improve the success of minimally invasive restorative procedures.

Research Results

Analysis of recent experimental and clinical investigations demonstrates that biopolymer-based biomaterials consistently exhibit superior biological performance compared with many conventional restorative materials. Laboratory studies report enhanced cell viability, improved odontoblastic differentiation, accelerated collagen synthesis, increased mineral deposition, and reduced bacterial adhesion when bioactive polymers are incorporated into dental materials.

Experimental studies further indicate that collagen- and chitosan-based scaffolds support pulp regeneration by providing a biomimetic extracellular matrix that facilitates stem-cell migration and vascularization. Similarly, hyaluronic acid has shown significant anti-inflammatory activity together with improved soft tissue healing following periodontal and surgical procedures.

Clinical observations suggest that bioactive restorative materials contribute to reduced postoperative sensitivity, improved sealing ability, enhanced remineralization of affected dentin, and greater preservation of tooth vitality. Nevertheless, despite encouraging short-term outcomes, current clinical evidence remains heterogeneous, and standardized long-term clinical investigations are still limited.

Discussion

The transition from passive restorative materials toward biologically active biomaterials represents one of the most significant paradigm shifts in contemporary dentistry. Rather than serving solely as mechanical substitutes, modern biopolymer-based materials actively interact with surrounding tissues through ion release, extracellular matrix support, antibacterial activity, and stimulation of regenerative pathways.

Despite these advantages, several limitations remain. Natural biopolymers frequently exhibit lower mechanical strength than synthetic alternatives, whereas synthetic biodegradable polymers may demonstrate slower biological integration. Consequently, current research increasingly focuses on hybrid biomaterials combining natural polymers with nanoceramics, bioactive glass, calcium silicates, and controlled-release therapeutic agents to optimize both biological and mechanical performance.

Future investigations should emphasize standardized clinical protocols, multicenter randomized controlled trials, long-term follow-up, and advanced biomaterial characterization. Integration of tissue engineering, stem-cell biology, nanomedicine, and digital manufacturing technologies is expected to accelerate the development of next-generation intelligent biomaterials capable of supporting personalized regenerative dental therapy.

Conclusion

Biopolymer-based biomaterials have become one of the most promising innovations in contemporary endodontic and restorative dentistry. Their unique combination of biocompatibility, biodegradability, bioactivity, and regenerative potential distinguishes them from conventional restorative materials. Natural biopolymers, including collagen, chitosan, hyaluronic acid, gelatin, alginate, and silk fibroin, together with biodegradable synthetic polymers such as PLA, PGA, and PLGA, provide favorable biological environments that support stem-cell proliferation, angiogenesis, dentin regeneration, and periodontal tissue repair. Recent advances in nanotechnology and tissue engineering have further enhanced the physicochemical and biological properties of these materials, expanding their clinical applicability.

Current experimental evidence demonstrates that biopolymer-based scaffolds improve cell adhesion, mineralization, antimicrobial performance, and healing responses while reducing postoperative inflammation and promoting preservation of pulp vitality. Clinical investigations have also reported encouraging outcomes in regenerative endodontic procedures and adhesive restorative therapies, although variations in treatment protocols and follow-up periods continue to limit direct comparison among published studies.

Future research should prioritize multicenter randomized clinical trials, standardized evaluation protocols, long-term clinical follow-up, and the integration of advanced technologies such as nanomedicine, three-dimensional bioprinting, artificial intelligence, and precision biomaterial engineering. These innovations are expected to accelerate the transition from conventional restorative dentistry toward biologically driven and patient-specific regenerative therapies capable of restoring both the structure and function of dental tissues.

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