ORAL HEALTH AND MAXILLOFACIAL RESEARCH
Jan-Mar 2026, VOL. 3, ISSUE 1, pp. 26-31
https://doi.org/10.61577/ohmr.2026.100005

RESEAPRO JOURNALS

REVIEW

OPEN ACCESS

Dental pulp regeneration and bioengineered teeth in clinical practices: A comprehensive review

Arpan Shrivastava[1], Preeti Upadhyay[2] and Pragya Tripathi[2]

[1]Department of Periodontology and Oral Implantology, Inderprastha Dental College and Hospital, Ghaziabad, Uttar Pradesh
[2]Department of Periodontology, Inderprastha Dental College and Hospital, Ghaziabad, Uttar Pradesh

ABSTRACT

Pulpal necrosis resulting from carious destruction, traumatic injury, or polymicrobial endodontic infection affects millions of patients globally. Conventional endodontic therapy, while effective, affects the tooth biologically by disturbing the neurovascular pulp complex. The emergence of regenerative endodontics and whole-tooth bioengineering acts as an alternative towards biological restoration of the pulp-dentin complex. Existing clinical trials on pulp regeneration are largely based on small sample sizes, short follow-up durations, and absence of standardized histological outcome criteria. The biological difference between true pulp regeneration and non-specific revascularization remains inadequately studied in majority of protocols. Growth factor delivery systems reported in the literature lack long-term pharmacokinetic data within the root canal microenvironment, and scaffold biomaterial studies are predominantly restricted to in vitro or short-term settings without longitudinal functional assessment. A comprehensive narrative review of peer-reviewed literature was conducted using PubMed, Scopus, and Web of Science databases, encompassing publications from 2000 to 2024. Search terms included "dental pulp regeneration," "dental stem cells," "tooth bioengineering," "regenerative endodontics," "scaffold biomaterials," and "clinical trials pulp revascularization." A total of 54 articles were critically studied, including in vitro studies, animal model investigations, and human clinical trials. The review provides a comprehensive, critical study on the current evidence on dental pulp regeneration and whole-tooth bioengineering. It removes the distinctions between pulp revascularization and pulp regeneration, and evaluate the odontogenic, angiogenic, and neurogenic potential of documented stem cell populations including DPSCs, SHED, SCAP, and periodontal ligament stem cells.

KEY WORDS

Regenerative endodontics; Dental pulp cavity; Stem cells; Periodontal ligament; Bioengineering; Biocompatible materials

ARTICLE HISTORY

Received 10 February 2026;
Revised 13 March 2026;
Accepted 20 March 2026

Introduction

Oral diseases act as a major global health concern and is recognized as major contributor to the total percentage of non-communicable diseases. Dental caries and their sequelae, including pulpitis and periapical pathologies, represent the primary causes of dental morbidity and tooth loss. The dental pulp plays a major role in maintaining tooth vitality through sensory, immunological, and reparative functions. However, its rigid dentinal walls limit its capacity to accommodate inflammatory changes, making it vulnerable to irreversible injury following microbial infiltration. Once the inflammatory process exceeds the threshold of reversibility, progressive degeneration of the pulp continues in necrosis [1].

Endodontic diseases are generally microbial in origin, with dental caries identified as the major factor. Progressive carious lesions help bacterial penetration into the pulp chamber, triggering inflammatory responses. Epidemiological evidence mentions pulpal and periapical diseases for a major proportion of dental treatments globally [2].

The global burden of oral diseases remains high despite developments in preventive and therapeutic strategies. According to the World Health Organization (WHO), approximately 3.5 billion individuals were affected by oral diseases in 2019, with untreated dental caries alone impacting nearly 2.5 billion people worldwide. Also, severe periodontal disease affects approximately 1 billion individuals, while complete tooth loss (edentulism) is reported in nearly 350 million people globally [3]. Tooth loss increases with age, with global estimates indicating that approximately 7% of adults and up to 23% of individuals aged over 60 years undergo complete tooth loss. These outcomes are culminative effects of chronic oral pathologies, including untreated caries and pulp-related infections [4]. Studies report that irreversible pulpitis and chronic apical periodontitis register for approximately 34-35% of diagnosed endodontic conditions, making them the most common pathologies. Also, systematic analyses indicate that more than 50% of adults worldwide have undergone at least one endodontic treatment, reflecting the widespread occurrence of pulp-related diseases [5,6]. The number of dental caries continues to rise affecting 2.24 billion individuals globally, with projections suggesting further increases due to population growth and aging [7].

Regenerative dentistry has emerged as an alternative for restoring the functional properties of dental tissues. Under this practice, dental pulp regeneration focuses on re-establishing a vital, vascularized, and innervated pulp-dentin structure using stem cells, growth factors, and biomaterial scaffolds. Whole-tooth bioengineering presents an advanced method that regenerates an entire functional tooth through the recapitulation of embryonic tooth development processes. This involves the interaction of epithelial and mesenchymal stem cells, biomimetic scaffolds, and morphogenetic signalling pathways to generate bioengineered tooth units capable of

***Correspondence:** Dr. Arpan Shrivastava, Department of Periodontology and Oral Implantology, Inderprastha Dental College and Hospital, Ghaziabad, Uttar Pradesh, e-mail: arpanworks828@gmail.com

integration and function within the oral cavity. While pulp regeneration has progressed into early clinical trials, whole-tooth bioengineering remains largely confined to preclinical and experimental models [8].

Earlier, substantial research had been directed toward understanding the biological mechanisms for dental tissue regeneration. Mesenchymal stem cells derived from dental tissues, including dental pulp stem cells (DPSCs), stem cells from human exfoliated deciduous teeth (SHED), and stem cells from the apical papilla (SCAP), have demonstrated potential for odontogenic differentiation and tissue regeneration. These cells show properties such as self-renewal, multilineage differentiation, and immunomodulation, making them suitable candidates for regenerative applications [9].

With stem cells, growth factors such as vascular endothelial growth factor (VEGF), bone morphogenetic proteins (BMPs), and transforming growth factor-beta (TGF-β) play crucial roles in regulating angiogenesis, cell proliferation, and differentiation during pulp regeneration. Biomaterials, including natural polymers like collagen and synthetic polymers such as polylactic-co-glycolic acid (PLGA), have been developed to provide structural support and facilitate regulated delivery of bioactive molecules [10].

Recent studies have also explored cell-free approaches based on endogenous cell homing, as well as advanced bio-fabrication techniques such as three-dimensional bioprinting to improve spatial organization and vascularization of regenerated tissues. Clinical investigations, including early-phase trials using autologous stem cells, have demonstrated the formation of pulp-like tissue with evidence of vascularization and innervation, indicating translational potential [11].

With whole-tooth regeneration, studies have successfully demonstrated the formation of bioengineered tooth structures in animal models through the recombination of epithelial and mesenchymal cells. Developments in induced pluripotent stem cell (iPSC) technology and gene editing tools such as CRISPR-Cas9 have further expanded the opportunities for generating patient-specific dental tissues. However, these methods remain in early developmental stages, with challenges related to morphological control, vascular integration, and functional eruption [12].

Despite progress in regenerative dentistry, its routine clinical application is still limited due to the lack of predictable and functional regeneration of the pulp–dentin complex, particularly in achieving reliable vascularization. Traditional endodontic treatments are effective in removing infections but do not restore the biological functions of the dental pulp. Regenerative methods show variable outcomes and limited control over tissue organization and integration. These challenges are controlled by difficulties associated with stem cell use, including sourcing, handling, and safety concerns, as well as the inability to replicate the natural structure and function of dental tissues in whole-tooth engineering. This review aims to examine the current biological and technological developments in dental pulp regeneration and tooth bioengineering, with a focus on understanding the factors that affect treatment predictability and functional success. By analysing evidence from both preclinical and clinical studies, this review intends to identify existing gaps and guide future research toward developing clinically applicable regenerative therapies.

Biological Structures of Dental Pulp Regeneration

Stem cell sources

Mesenchymal stem cells derived from dental tissues play a central role in regenerative endodontics due to their capacity for self-renewal and multilineage differentiation. Dental pulp stem cells (DPSCs), stem cells from human exfoliated deciduous teeth (SHED), and stem cells from the apical papilla (SCAP) are extensively studied. DPSCs show the ability of differentiation into odontoblast-like cells and contribute to dentin formation, supporting pulp-dentin complex regeneration [13]. SHEDs are characterized by a higher proliferative rate and enhanced angiogenic potential compared to DPSCs, suitable for rapid tissue regeneration [14]. SCAP, located in the apical region of developing teeth, presents strong odontogenic differentiation capacity and are important in root development and maturation. However, the clinical applicability of these cells is influenced by factors, including the availability of donor tissue, ex vivo expansion requirements, and variability in biological performance. Donor-related factors such as age affect stem cell function, with reduced proliferative and differentiation potential observed in cells derived from older individuals [15].

Growth factors and molecular signalling pathways

Growth factors are essential regulators of cellular behaviour during dental pulp regeneration, influencing angiogenesis, cell migration, and differentiation. Vascular endothelial growth factor (VEGF) plays a key role in promoting angiogenesis, which is required for the survival and integration of regenerated pulp tissue. Bone morphogenetic proteins (BMPs), particularly BMP-2 and BMP-7, are involved in odontoblastic differentiation and reparative dentin formation. Basic fibroblast growth factor (bFGF) supports cell proliferation and tissue repair, while transforming growth factor-beta (TGF-β) regulates extracellular matrix formation and cellular differentiation. These signalling molecules act through molecular pathways coordinating tissue regeneration. Controlled delivery of growth factors remains a challenge, as rapid degradation and diffusion limits their therapeutic effectiveness. So, various delivery systems such as hydrogels and nanoparticle-based carriers have been developed for sustainable release [16].

Biomaterials and scaffold design

Scaffolds are a fundamental component of regenerative endodontics, providing a three-dimensional framework that supports cell attachment, proliferation, and tissue formation. These materials are classified into natural, synthetic, and hybrid scaffolds. Natural scaffolds such as collagen and fibrin closely resemble the native extracellular matrix and promote cell adhesion and biocompatibility [17]. Synthetic polymers, polyglycolic acid (PGA) and polylactic-co-glycolic acid (PLGA), offer advantages such as controlled degradation rates and mechanical strength but may lack bioactivity. Hybrid and biomimetic scaffolds, such as decellularized dental pulp matrix (DDPM), combine structural and biochemical cues that closely mimic the natural pulp environment, enhancing regenerative potential. An ideal scaffold should have key properties including biocompatibility, appropriate porosity, and

https://doi.org/10.61577/ohmr.2026.100005

controlled degradation kinetics to match the rate of tissue formation [18] (Table 1).

Table 1. Biomaterials used in regenerative dentistry.

Material Type	Clinical Use	Examples
Hydrogels	Pulp regeneration, periodontal scaffolds	GelMA, Alginate
Bioactive Ceramics	Bone regeneration, ridge augmentation	Hydroxyapatite, β-TCP
Composite Scaffolds	Bone and periodontal tissue repair	PCL–Collagen, PLGA–HA
Exosomes	Pulp angiogenesis, immune modulation	DPSC-derived exosomes
3D Bioprinted Constructs	Tooth bud engineering, complex tissue regeneration	DLP-based, FDM-based constructs

Strategy for Dental Pulp Regeneration

Cell-based regeneration

Cell-based regenerative method involves the transplantation of stem cells into the disinfected root canal space to promote the regeneration of a functional pulp–dentin complex. This utilize either autologous stem cells, derived from the same patient, or allogenic stem cells, obtained from donor sources. Autologous transplantation is preferred due to its reduced risk of immune rejection and better biological compatibility but is limited by the availability of suitable donor tissue and the need for ex vivo cell expansion. Allogenic stem cells offer advantages in accessibility and scalability but may pose risks related to immunogenicity and disease transmission. The mechanism of pulp-dentin complex regeneration involves the differentiation of transplanted mesenchymal stem cells into odontoblast-like cells, along with the formation of vascular and neural networks within the regenerated tissue. These are supported by signaling molecules and the local microenvironment, which together facilitate tissue organization and functional integration [19].

Cell homing

Cell-free regenerative strategies are based on endogenous cell homing, where bioactive molecules are used to recruit host stem/progenitor cells into the root canal space to facilitate tissue regeneration. This approach eliminates the need for direct cell transplantation and depends on intrinsic regenerative capacity. Molecules such as stromal cell-derived factor-1 (SDF-1), vascular endothelial growth factor (VEGF), and basic fibroblast growth factor (bFGF) are incorporated into scaffolds or hydrogels to promote cell migration, proliferation, and differentiation. These factors form chemotactic gradient that directs endogenous stem cells toward the site of injury, thus initiating tissue repair [20].

Advanced bio-fabrication

Developments in bioengineering have introduced three-dimensional (3D) bioprinting as an alternative for dental pulp regeneration. This technique ensures precise fabrication of tissue constructs by depositing cells and biomaterials layer-by-layer to replicate the complex architecture of native pulp tissue. Bioink composition is a critical factor in 3D bioprinting and typically includes a combination of stem cells, hydrogels (such as gelatin methacrylate or collagen), and bioactive molecules. These components provide structural support while maintaining cell viability and promoting differentiation. The ability to control spatial distribution of cells and materials allows for the creation of organized tissue structures that closely mimic the natural pulp–dentin interface. Bioprinting improves cell-cell and cell-matrix interactions, which are essential for functional tissue regeneration. Strategies to promote vascularization, such as incorporating endothelial cells or angiogenic growth factors, are being explored to improve nutrient diffusion and tissue survival [21].

Bioengineered Teeth

Tooth germ engineering

Tooth germ engineering is based on developmental biology, the processes that control natural tooth formation during embryogenesis. Tooth development is regulated by reciprocal interactions between oral epithelial cells and neural crest–derived mesenchymal cells, which control cell proliferation, differentiation, and morphogenesis. These interactions are required for the formation of enamel, dentin, and supporting structures. Experimental methods are performed to combine the dissociated epithelial and mesenchymal cells to form bioengineered tooth germ constructs. Preclinical studies have demonstrated that such constructs, when transplanted into animal models, can develop into tooth-like structures with dental tissues, enamel, dentin, and pulp [22].

Induced Pluripotent Stem Cells (iPSCs)

Induced pluripotent stem cells (iPSCs) are produced through reprogramming of somatic cells into a pluripotent state by specific transcription factors. This process helps acquire embryonic stem cell-like properties, like the ability to differentiate into multiple cell lineages. iPSCs have been studied as a potential source of both epithelial and mesenchymal components for tooth development. Studies have proved that iPSCs can be used to differentiate into dental-related cell types, including odontoblast-like and ameloblast-like cells. This provides a significant advantage over mesenchymal stem cells (MSCs), which are generally limited to mesenchymal lineages and lack the ability to generate epithelial components necessary for complete tooth formation [23].

Scaffold-free and organoid-based methods

Scaffold-free method involves use of self-organizing cell systems, referred to as organoids. These depend on the intrinsic ability of stem cells to undergo spatial organization and differentiation that mimics natural tissue development. In dental applications, organoid-based models have been used to generate tooth-like structures by interactions between epithelial and mesenchymal cell populations. One of the major advantages of scaffold-free approaches is their ability to replicate the native microenvironment and cellular interactions observed during tooth development. This reduces the dependence on artificial scaffolds and allows for tissue formation. But issues in controlling the size and shape of the resulting structures, limited reproducibility during experiments, and inadequate vascularization, affecting nutrient diffusion and long-term tissue viability are some major limitations [24].

Gene editing and molecular engineering

Gene editing processes, particularly CRISPR-Cas9, have introduced new domains for targeted modification of genes

https://doi.org/10.61577/ohmr.2026.100005

involved in tooth development and regeneration. It ensures precise editing of specific DNA sequences, allowing for the activation or suppression of genes that regulate odontogenesis. Major genes involved in tooth development include Pax9, Msx1, and BMP4, which play critical roles in early tooth morphogenesis and differentiation. Mutations or dysregulation of these genes are linked with developmental abnormalities. Thus, gene editing aims to improve the regenerative capacity of stem cells and improve the efficiency of bioengineered tooth formation. With its potential, the gene editing application in regenerative dentistry is associated with ethical and translational concerns. These include the risk of off-target effects, unintended genetic modifications, and long-term safety measures [25].

Clinical Trails and Human Study

Clinical trials in dental pulp regeneration

Clinical trials of dental pulp regeneration developed from preclinical models to early-phase human trials, focused on stem cell–based regenerative strategies. Most clinical studies have used autologous DPSCs under controlled laboratory conditions and transplanted into disinfected root canals along with scaffolds and growth factors. These studies are typically designed as pilot or phase I/II trials for evaluating safety, feasibility, and preliminary efficacy. Regenerated pulp-like tissue has shown evidence of vascularization and innervation, which are required for restoring pulp vitality [26]. Clinical studies have reported positive responses to electric pulp testing, indicating functional sensory recovery, with radiographic evidence of dentin formation and tissue organization within the root canal. MRI studies have also shown that regenerated tissue provides characteristics like native pulp, resulting in successful tissue integration. Preclinical and translational studies further support the findings, demonstrating that stem cell transplantation results in the formation of vascularized and innervated pulp tissue. Angiogenesis and neurogenesis are considered critical as they support nutrient supply, immune defence, and sensory function within the regenerated tissue. Comparative analysis of available clinical trials indicates that outcomes are favourable in safety and initial functional recovery, but the sample sizes remain small, and long-term follow-up data are limited [27].

Bioengineered teeth in preclinical models

Whole-tooth bioengineering remains in the preclinical stage, with most studies conducted in animal models. Experimental approaches have successfully demonstrated the generation of bioengineered tooth structures through the recombination of epithelial and mesenchymal cells, followed by transplantation into host tissues. These studies have shown that bioengineered tooth units can develop organized structures, including enamel, dentin, pulp, and periodontal ligament, and in some cases, exhibit eruption and functional integration within the oral environment [28]. Transplantation of bioengineered tooth germs in murine models has demonstrated the formation of structurally and functionally comparable teeth, capable of responding to mechanical stimuli and participating in occlusion. These findings highlight the potential of developmental biology–based approaches for complete tooth regeneration. But challenges remain in translating these findings into human applications. One of the primary limitations is the lack of precise control over tooth morphology and size, which is critical for functional and aesthetic integration. Another major challenge is forming functional integration with surrounding tissues, including alveolar bone, periodontal ligament, and neural networks [29].

Challenges and Ethical Considerations

Immunological barriers

One of the primary challenges in regenerative dentistry is the host immune response to transplanted cells and biomaterials. MSCs are considered to have immunomodulatory properties, but the use of allogenic stem cells may trigger immune reactions, leading to reduced cell survival and compromised regenerative outcomes. Immune rejection can result from differences in major histocompatibility complex (MHC) expression and host immune activation, mainly in inflamed or infected environments [30].

Tumorigenicity

The potential for tumour formation is a critical concern in stem cell–based regenerative therapies, particularly with the use of iPSCs. Due to their high proliferative capacity and pluripotency, iPSCs carry a risk of forming teratomas if undifferentiated cells remain after transplantation. Also, genetic and epigenetic changes during the reprogramming process may lead to genomic instability and increase oncogenic potential [31].

Regulatory and clinical approval

The clinical application of regenerative therapies is under strict regulatory rules to ensure safety, efficacy, and quality. Stem cell–based treatments are classified as advanced therapy medicinal products (ATMPs) in many regions and must follow with guidelines related to manufacturing, quality control, and clinical testing. These regulations require good manufacturing practice (GMP) standards, extensive preclinical data, and multi-phase clinical trials before approval. But these requirements create barriers to commercialization and clinical use. High costs associated with cell processing, infrastructure requirements, and regulatory approval processes restricts accessibility and scalability [32].

Future Perspectives

Recent advances in regenerative medicine have shown the potential of stem cell-free approaches, mainly those based on secretomes and extracellular vesicles. Stem cell secretomes consist of a complex mixture of growth factors, cytokines, and signalling molecules that control the therapeutic effects of stem cells. Exosomes play a major role in intercellular communication and promote angiogenesis, cell proliferation, and tissue repair. Exosome-based therapy has shown the ability to induce pulp-like tissue formation and enhance vascularization without direct cell transplantation. This offers many advantages, like reduced risk of immune rejection, elimination of tumorigenicity associated with live cells, and simplified storage and handling requirements [33].

The development of smart biomaterials provides a major development in scaffold design for regenerative dentistry. These are engineered to respond to environmental stimuli, such as pH, temperature, or enzymatic activity, ensuring controlled and site-specific delivery of therapeutic agents. Hydrogels, nanoparticles, and composite materials are used to release bioactive molecules, improving regenerative outcomes and reducing the need for repeated interventions [34].

https://doi.org/10.61577/ohmr.2026.100005

The use of artificial intelligence with bioengineering is emerging as promising research to improve the design and predictability of regenerative therapies. AI-based algorithms can analyse large datasets to identify optimal scaffold compositions, structural configurations, and treatment parameters for tissue regeneration. AI-assisted scaffold design helps development of customized biomaterials with enhanced mechanical and biological properties [35].

Conclusion

Regenerative dentistry has developed significantly in recent years, followed by stem cell biology, molecular signalling, and biomaterial science. Evidence from preclinical and early clinical studies supports dental pulp regeneration through the regulated use of mesenchymal stem cells, growth factors, and scaffold systems. These have proved the ability to restore the biological features of the pulp-dentin complex, including vascularization, innervation, and dentin formation, indicating their potential for clinical application. But research gap exists between the status of dental pulp regeneration and whole-tooth bioengineering. Regenerative endodontic procedures, particularly involving cell-based and cell-free strategies, have moved into clinical trials and show promise as alternatives to root canal therapy. But, whole-tooth engineering remains experimental, with evidence from animal models. Future developments in regenerative dentistry are expected to focus on improving the predictability and safety of existing therapies, as well as integrating emerging technologies such as stem cell-free approaches, smart biomaterials, and gene-based strategies. With continued research, regenerative methods have the potential to transition from experimental applications to routine clinical practices. This review examined the biological foundations, present regenerative methods, and clinical approach in both dental pulp regeneration and bioengineered tooth development. By adding the study findings from stem cell research, growth factor biology, scaffold design, and emerging technologies, the review mentions the differential translational status. Further research is required to improve the predictability and safety of regenerative procedures. Development of standardized clinical protocols, long-term evaluation of treatment outcomes, optimization of stem cell-free therapeutic strategies, and enhancement of scaffold design for improved tissue integration are required. In whole-tooth bioengineering, future studies should focus on achieving precise control over tooth morphology, improving vascular and neural integration.

Disclosure Statement

The author does not have conflict of interest in this research.

References

1. Walsh D, Quigley R, Ekperuoh A, Duncan HF. Objectively Diagnosing Pulpitis: Opportunities and Methodological Challenges in the Development of Point-of-Care Assays. Int J Mol Sci. 2025;27(1):355. https://doi.org/10.3390/ijms27010355
2. Salminen A, Hyvärinen K, Ritari J, Leppilahti JM, Palotie U, Vuollo V, et al. Genome-wide association study of pulpal and apical diseases. Nat Commun. 2025;16(1):6774. https://doi.org/10.1038/s41467-025-61721-1
3. World Health Organization. Global oral health status report: towards universal health coverage for oral health by 2030. World Health Organization; 2022:1-99. Available at: https://www.who.int/publications/i/item/9789240061484
4. Salari N, Darvishi N, Heydari M, Bokaee S, Darvishi F, Mohammadi M. Global prevalence of cleft palate, cleft lip and cleft palate and lip: A comprehensive systematic review and meta-analysis. J Stomatol Oral Maxillofac Surg. 2022;123(2):110-120. https://doi.org/10.1016/j.jormas.2021.05.008
5. Bolado EC, Camacho-Aparicio LA. Prevalence of pulp and periapical diseases in the endodontic postgraduate program at the national autonomous University of Mexico 2014-2019. J Clin Exp Dent. 2023;15(6):e470. https://doi.org/10.4317/jced.60451
6. Go H, Kuboniwa M, Choi YH. Occurrence rate and estimated economic burden of pulp and periapical disease treatment among Korean older adults: a national population-based retrospective study. Epidemiol Health. 2025;47:e2025035. https://doi.org/10.4178/epih.e2025035
7. Li X, Li R, Wang H, Yang Z, Liu Y, Li X, et al. Global burden of dental caries from 1990 to 2021 and future projections. Int Dent J. 2025;75(5):100904. https://doi.org/10.1016/j.identj.2025.100904
8. Amrollahi P, Shah B, Seifi A, Tayebi L. Recent advancements in regenerative dentistry: A review. Mater Sci Eng C. 2016;69:1383-1390. https://doi.org/10.1016/j.msec.2016.08.045
9. Bakopoulou A, About I. Stem cells of dental origin: current research trends and key milestones towards clinical application. Stem Cells Int. 2016;2016(1):4209891. https://doi.org/10.1155/2016/4209891
10. Yadlapati M, Biguetti C, Cavalla F, Nieves F, Bessey C, Bohluli P, et al. Characterization of a vascular endothelial growth factor–loaded bioresorbable delivery system for pulp regeneration. J Endod. 2017;43(1):77-83. https://doi.org/10.1016/j.joen.2016.09.022
11. Bharadwaj RS, Shivakumar AT, Kalgeri SH. Cell Homing: Pioneering Regenerative Solutions in Endodontics. Journal of Preventive, Diagnostic and Treatment Strategies in Medicine. 2025;4(4):297-306. https://doi.org/10.4103/jpdtsm.jpdtsm_134_25
12. Oshima M, Tsuji T. Whole tooth regeneration as a future dental treatment. Engineering mineralized and load bearing tissues. 2015:255-269. https://doi.org/10.1007/978-3-319-22345-2_14
13. Tsutsui TW. Dental pulp stem cells: advances to applications. Stem cells and cloning: advances and applications. 2020:33-42. https://doi.org/10.2147/SCCAA.S166759
14. Wang H, Zhong QI, Yang T, Qi Y, Fu M, Yang XI, et al. Comparative characterization of SHED and DPSCs during extended cultivation in vitro. Mol Med Rep. 2018;17(5):6551-6559. https://doi.org/10.3892/mmr.2018.8725
15. Huang M, Dissanayaka WL, Yiu CK. Exploring the potential of stem cells from the apical papilla (SCAPs) in regenerative medicine: advantages, applications, challenges and opportunities. Stem Cell Res Ther. 2025;16(1):626. https://doi.org/10.1186/s13287-025-04705-8
16. Subbiah R, Guldberg RE. Materials science and design principles of growth factor delivery systems in tissue engineering and regenerative medicine. Adv Healthcare Mater. 2019;8(1):1801000. https://doi.org/10.1002/adhm.201801000
17. Mayya A, Chatra A, Dsouza V, Seetharam RN, Acharya SR, Vasanthan KS. Biomaterials to biofabrication: advanced scaffold technologies for regenerative endodontics. Biomed Phys Eng Express. 2026;12(1):012001. https://doi.org/10.1088/2057-1976/ae2b75

https://doi.org/10.61577/ohmr.2026.100005

18. Wu DT, Munguia-Lopez JG, Cho YW, Ma X, Song V, Zhu Z, Tran SD. Polymeric scaffolds for dental, oral, and craniofacial regenerative medicine. Molecules. 2021;26(22):7043. https://doi.org/10.3390/molecules26227043
19. Gong T, Heng BC, Lo EC, Zhang C. Current advance and future prospects of tissue engineering approach to dentin/pulp regenerative therapy. Stem Cells Int. 2016;2016(1):9204574. https://doi.org/10.1155/2016/9204574
20. Kim D, Kim SG. Cell homing strategies in regenerative endodontic therapy. Cells. 2025;14(3):201. https://doi.org/10.3390/cells14030201
21. Mohd N, Razali M, Ghazali MJ, Abu Kasim NH. Current advances of three-dimensional bioprinting application in dentistry: a scoping review. Materials. 2022;15(18):6398. https://doi.org/10.3390/ma15186398
22. Balic A, Thesleff I. Tissue interactions regulating tooth development and renewal. Curr Top Dev Biol. 2015;115:157-186. https://doi.org/10.1016/bs.ctdb.2015.07.006
23. Kim EJ, Yoon KS, Arakaki M, Otsu K, Fukumoto S, Harada H, et al. Effective differentiation of induced pluripotent stem cells into dental cells. Dev Dyn. 2019;248(1):129-139. https://doi.org/10.1002/dvdy.24663
24. Abdolahinia ED, Golestani S, Seif S, Afra N, Aflatoonian K, Jalalian A, et al. A review of the therapeutic potential of dental stem cells as scaffold-free models for tissue engineering application. Tissue and Cell. 2024;86:102281. https://doi.org/10.1016/j.tice.2023.102281
25. Patel VB, Vanasi M, Dhimole A, Saini RJ. Harnessing CRISPR-Cas9 technology in dentistry: a promising avenue for precision oral health-a literature review. J Oral Med Dent Res. 2024;5(1). https://doi.org/10.52793/JOMDR.2024.5(1)-55
26. Xie Z, Shen Z, Zhan P, Yang J, Huang Q, Huang S, et al. Functional dental pulp regeneration: basic research and clinical translation. Int J Mol Sci. 2021;22(16):8991. https://doi.org/10.3390/ijms22168991
27. Su W, Liao C, Liu X. Angiogenic and neurogenic potential of dental-derived stem cells for functional pulp regeneration: A narrative review. Int Endod J. 2025;58(3):391-410. https://doi.org/10.1111/iej.14180
28. Furquim CP, Kumagai RY, Bustillos-Torrez W, Meza-Mauricio J, Tanaka CJ, Santana V, et al. Whole tooth regeneration: can animal studies be translated into clinical application? Tissue Eng Part C Methods. 2022;28(3):104-112. https://doi.org/10.1089/ten.tec.2022.0022
29. Smith EE, Yelick PC. Progress in bioengineered whole tooth research: from bench to dental patient chair. Curr Oral Health Rep. 2016;3(4):302-308. https://doi.org/10.1007/s40496-016-0110-2
30. Li Y, Jin M, Guo D, Shen S, Lu K, Pan R, et al. Unveiling the immunogenicity of allogeneic mesenchymal stromal cells: Challenges and strategies for enhanced therapeutic efficacy. Biomed Pharmacother. 2024;180:117537. https://doi.org/10.1016/j.biopha.2024.117537
31. Wuputra K, Ku CC, Wu DC, Lin YC, Saito S, Yokoyama KK. Prevention of tumor risk associated with the reprogramming of human pluripotent stem cells. J Exp Clin Cancer Res. 2020;39(1):100. https://doi.org/10.1186/s13046-020-01584-0
32. Musyuni P, Mangla B, Javed S, Kumar P, Ahsan W. Regulatory challenges and opportunities in cell-based therapies: overcoming barriers to advancement and patient care. Regen Med. 2025;20(11):609-624. https://doi.org/10.1080/17460751.2025.2580888
33. Abouelfotouh MM. Advancing Regenerative Medicine: A Comprehensive Review of Cell-Free Therapies. Delta University Scientific Journal. 2025;8(1):40-48.
34. Farjaminejad R, Farjaminejad S, Garcia-Godoy F, Hassani M, Rahimikia K. The Future of Biomaterials in Dentistry: Innovations in Drug Delivery and Regenerative Medicine. J. Appl Dent Oral Sci. 2025;11(4):160-177. https://doi.org/10.1177/30497418251410635
35. Ozieme AD, Adeleye AA, Ajide OO. Artificial Intelligence Driven Optimisation of Scaffold Design and Production in Tissue Engineering: A Critical Review. J Eng Res Rep. 2025;27(12):302-326. https://doi.org/10.9734/jerr/2025/v27i121744

https://doi.org/10.61577/ohmr.2026.100005