Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

BIOMEDICAL 3D PRINTED SCAFFOLDS FOR ROOT CANAL DISINFECTION AND REGENERATIVE ENDODONTICS: A SYSTEMATIC REVIEW

ABDULRAHMAN IBRAHIM ALQARNI
Biomedical Technology Specialist, Ministry of National Guard Health Affairs, Riyadh, Saudi Arabia.
Email: abdurrahman.Alqarni@gmail.com

ABDULRAHMAN ABDULAZIZ ALASIM
Biomedical Technology Specialist, Ministry of National Guard Health Affairs, Riyadh, Saudi Arabia.
Email: alasim1991@gmail.com

ABDULRAHMAN ABDULLAH ALZAYDAN
Biomedical Technology Specialist, Ministry of National Guard Health Affairs, Riyadh, Saudi Arabia.
Email: abdulrhmanalzidan@gmail.com

ABDULWAHAB DHAFER ALQAHTANI
Resident in Advanced Education of General Dentistry, Ministry of National Guard - Health Affairs, Riyadh, Saudi Arabia. Email: abdulwhabq1@gmail.com

KHALED AJLAN ALSHEHRI
Resident in Advanced Education of General Dentistry, Ministry of National Guard - Health Affairs, Riyadh, Saudi Arabia. Email: khaledshehri16@gmail.com

MARAM SHAYAN ALBAQAMI
Resident in Advanced Education of General Dentistry, Ministry of National Guard - Health Affairs, Riyadh, Saudi Arabia. Email: albaqamimaram422@gmail.com

ALI AHMED ALMUDAWI
Endodontist, Ministry of National Guard - Health affairs, Riyadh, Saudi Arabia.
Email: a.amidawi@gmail.com

Abstract

This systematic review synthesizes available evidence on biomedical 3D-printed scaffolds intended to support root canal disinfection and regenerative endodontics. Regenerative endodontic procedures aim to restore a functional pulp–dentin complex, particularly in necrotic immature teeth, but successful outcomes depend on reducing intracanal microbial load without harming resident or recruited progenitor cells. Emerging additive-manufactured platforms promise tailored architecture, controlled drug release, and improved handling compared with conventional scaffolds. We identified open-access original studies evaluating 3D-printed or 3D-bioprinted constructs relevant to antimicrobial delivery and, or pulp–dentin regeneration. Evidence includes extrusion-printed gelatin hydrogels loaded with quaternary ammonium antimicrobials, and polymer, ceramic or polymer, bioactive composite scaffolds assessed with human dental pulp stem cells. Overall, current data suggest that 3D-printed scaffolds can be engineered to balance cytocompatibility and antimicrobial activity, while promoting odontogenic, osteogenic marker expression and mineralized tissue formation. However, the evidence base largely remains preclinical, with limited direct intracanal regenerative models and scarce clinical translation. Standardized outcome measures, head-to-head comparisons with established disinfection protocols, and well-designed in vivo studies within true endodontic spaces are needed to clarify safety, efficacy, and real-world feasibility.

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

Keywords: 3D Printing; Bioprinting; Regenerative Endodontics; Root Canal Disinfection; Dental Pulp Stem Cells; Hydrogel; Controlled Drug Release; Polycaprolactone; Bioactive Glass.

INTRODUCTION

Regenerative endodontic procedures (REPs) are biologically based strategies designed to replace damaged pulp tissue and enable continued root development in immature permanent teeth with pulp necrosis. Outcomes remain variable, and infection control is repeatedly emphasized as a central determinant of success. As summarized in classic and contemporary overviews, root canal disinfection often requires irrigants and intracanal medicaments that must balance antimicrobial potency with preservation of a microenvironment compatible with stem cell survival and signaling (Lee et al. 2015; Wei et al. 2022). Biomaterial scaffolds constitute a key pillar of the tissue-engineering triad and have been widely explored in regenerative endodontics, with natural and synthetic polymers, hydrogels, and bioactive composites all proposed to support cell migration, angiogenesis, and odontogenic differentiation (Liu et al. 2021). Within this landscape, 3D printing (additive manufacturing) has created new opportunities to fabricate scaffolds with programmable geometry, porosity, and spatial distribution of bioactive agents. Recent dental tissue engineering reviews highlight that 3D-printed constructs offer customization and improved architectural control compared with conventional fabrication methods, suggesting particular value for complex tissues such as the dentin–pulp unit (Zhao et al. 2024).

For endodontics, the appeal of 3D-printed scaffolds is twofold. First, they may function as drug-delivery platforms that sustain antimicrobial activity within canal spaces. A recent open-access study explicitly underscores that “a critical determinant of REP success hinges on effective disinfection,” while emphasizing the need to preserve a regenerative niche. (Dallos Ortega et al. 2025). Second, these scaffolds can provide regenerative microenvironments for dental pulp stem cells (DPSCs) and related progenitors, potentially guiding odontogenic marker expression and mineral deposition through tailored mechanical and biochemical cues (Mousavi Nejad et al. 2021; Smaida et al. 2025). Despite growing enthusiasm, the direct evidence linking 3D-printed scaffolds to both intracanal disinfection and functional pulp–dentin regeneration remains emerging. A focused synthesis of open-access original studies is therefore needed to clarify current capabilities, gaps, and research priorities.

METHODS

This systematic review was prepared in accordance with PRISMA 2020 principles. The research question was: What is the current preclinical and clinical evidence for biomedical 3D-printed scaffolds that support root canal disinfection and, or regenerative endodontic outcomes

Search strategy

An electronic search of PubMed, MEDLINE and PubMed Central (PMC), and Scopus was performed alongside additional open-access publisher platforms and indexed databases

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

(Scopus) to identify eligible studies published up to 2025. Search terms combined controlled vocabulary and keywords related to regenerative endodontics and additive manufacturing, including: “regenerative endodontics,” “root canal disinfection,” “dental pulp stem cells,” “3D printing,” “bioprinting,” “hydrogel,” “GelMA,” “polycaprolactone,” “bioactive glass,” and “drug delivery.” We also screened reference lists of key reviews on regenerative endodontics and 3D printing in dental tissue engineering for additional open-access records (Liu et al. 2021; Zhao et al. 2024; Smaida et al. 2025).

Eligibility criteria

Inclusion criteria:

Original research studies. Use of 3D printing, 3D bioprinting to fabricate scaffolds relevant to endodontic disinfection and, or pulp–dentin regeneration. In vitro, ex vivo, or in vivo models using endodontically relevant cells (human DPSCs) or tooth-related regeneration. Full text available through PMC or other open-access sources.

Exclusion criteria:

Reviews, editorials, conference abstracts. Studies focused solely on non-dental bone engineering without a clear rationale for endodontic, pulp–dentin application. Non-open-access full texts.

Study selection and data extraction

Titles, abstracts were screened for relevance, followed by full-text assessment of potentially eligible articles. Data were extracted on scaffold composition, printing method, antimicrobial or regenerative payload, cell sources, experimental model, and main biological outcomes. Given the early-stage nature of the field and heterogeneity in outcomes, a qualitative synthesis was conducted.

Risk of bias, quality considerations

Because included studies were predominantly preclinical, we assessed methodological transparency descriptively (clarity of scaffold fabrication parameters, cell characterization, outcome reporting). Formal meta-analysis was not planned due to expected heterogeneity.

RESULTS

Study selection and overview

The search identified a 4 articles of open-access original studies investigating 3D-printed scaffolds with potential relevance to root canal disinfection and regenerative endodontics. After screening and full-text eligibility assessment, five studies were included in this qualitative synthesis. The included evidence was chiefly preclinical and encompassed extrusion-printed hydrogels designed for antimicrobial delivery and polymer-based or polymer, ceramic scaffolds evaluated with human DPSCs (Cao et al. 2020; Mousavi Nejad et al. 2021; Dallos Ortega et al. 2025; Dawood et al. 2025).

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

Table 1: Characteristics of included studies

Study	Model	3D-printed scaffold, material	Cells, agent	Endodontic relevance	Key outcomes
Cao et al. 2020	In vitro	PLGA, β-TCP and β-TCP scaffolds using two 3DP technologies	Human DPSCs	Proof-of-concept for pulp-related stem cell response	Interconnected porous structure; biocompatibility and osteoconductivity testing with hDPSCs.
Mousavi Nejad et al. 2021	In vitro	PCL, 45S5 Bioglass (for dentin) and HyA-treated PCL (for pulp)	Cell assays + gene expression	Dentin–pulp regeneration concept	Increased hydrophilicity and cell adhesion with HyA; increased DSPP, OCN, DMP-1 expression.
Dallos Ortega et al. 2025	In vitro antimicrobial + cytocompatibility	Gelatin hydrogel scaffolds fabricated with extrusion bioprinting	BDMDAC antimicrobial + primary hDPSCs	Directly targets canal disinfection within REPs	"Excellent antimicrobial efficacy" vs multiple pathogens; >70% hDPSC viability at key BDMDAC loads; 6-month stability after freeze-drying.
Dawood et al. 2025	In vitro	3D-printed PLA discs coated with nHA and naringin	Human pulp stem cells	Regenerative microenvironment model	Highest attachment and calcium deposition on PLA, nHA, NAR vs comparators.

Antimicrobial 3D printed scaffolds for intracanal disinfection

Among included studies, the most directly endodontic antimicrobial evidence was provided by Dallos Ortega et al. (2025). The authors fabricated gelatin-based bio-inks incorporating the quaternary ammonium compound BDMDAC and produced extrusion-printed hydrogel scaffolds intended for root canal disinfection in REPs. They emphasized that disinfection must "eliminate microbial contaminants whilst preserving the microenvironment necessary for dental pulp stem cell tissue regeneration." (Dallos Ortega et al. 2025).

Scaffolds containing BDMDAC at defined concentrations demonstrated antimicrobial activity against five bacterial pathogens, including key endodontic organisms. Importantly, cytocompatibility assays using primary human DPSCs from three donors confirmed viability above 70% at optimized concentrations, suggesting a workable therapeutic window for antimicrobial delivery without overtly compromising regenerative cell survival. The study also reported that freeze-dried scaffolds preserved functional stability for at least six months, supporting potential clinical practicality in terms of storage and handling.

This study represents a meaningful step toward printable, shelf-stable, antimicrobial scaffolds that could be inserted into canal spaces after irrigation, potentially reducing

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

dependence on high-dose antibiotic pastes. However, direct intracanal regeneration models and comparative effectiveness against standard REP medicaments were not yet established within this work.

3D-printed scaffolds targeting pulp dentin regeneration

Multiple included studies focused on the regenerative arm of the endodontic challenge. Mousavi Nejad et al. (2021) fabricated two structurally distinct PCL-based scaffolds by 3D printing: a PCL, 45S5 Bioglass composite intended to support dentin regeneration and a hyaluronic acid-treated PCL scaffold aimed at pulp-like tissue support. The authors explicitly state that these constructs were evaluated for dentin and pulp regeneration, respectively. (Mousavi Nejad et al. 2021). Their physicochemical analyses and cell assays suggested that Bioglass enhanced mechanical properties and bioactivity, while hyaluronic acid surface treatment increased hydrophilicity and improved cell adhesion. Notably, both scaffold variants were associated with increased expression of odontogenic-related markers such as DSPP and DMP-1. These findings support the concept that material-specific customization within a printed architecture may allow differential optimization for dentin-facing versus pulp-facing regenerative needs. Cao et al. (2020) also evaluated 3D-printed PLGA, β-TCP and β-TCP scaffolds for biological responses in human DPSCs. They reported highly interconnected porous structures and assessed biocompatibility and osteoconductivity. While framed broadly within dental applications, these data add foundational support for using printed polymer, ceramic constructs with pulp-derived stem cells.

Dawood et al. (2025) presented an in vitro model in which 3D-printed PLA scaffolds coated with nano-hydroxyapatite and naringin promoted higher pulp stem cell attachment and mineral deposition than comparator conditions. This suggests that bioactive surface functionalization can meaningfully modulate stem cell behavior on printed polymer backbones.

Synthesis of findings

Across included studies, 3D printing enabled reproducible macro-architecture and facilitated the integration of antimicrobial compounds, bioactive ceramics, and natural polymer modifiers. Collectively, results support the feasibility of designing scaffolds that either (1) deliver antimicrobials with acceptable cytocompatibility or (2) enhance odontogenic, osteogenic markers and mineralization in pulp-derived stem cell systems.

DISCUSSION

This review highlights an emerging but still limited evidence base for 3D-printed scaffolds at the intersection of root canal disinfection and regenerative endodontics. Traditional REP frameworks emphasize staged disinfection using irrigants and intracanal medicaments followed by induction of a blood clot scaffold or use of bioactive alternatives. Nonetheless, outcomes remain difficult to predict, and persistent infection is a recurring barrier (Lee et al. 2015; Wei et al. 2022). The most clinically aligned advance among included studies is the antimicrobial gelatin scaffold platform described by Dallos Ortega

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

et al. (2025). Their results suggest that quaternary ammonium-loaded, extrusion-printed hydrogels can achieve broad antimicrobial effects while maintaining acceptable DPSC viability. This directly addresses a long-standing tension in REPs: conventional antibiotic pastes may require concentrations that can risk cytotoxicity, whereas a controlled-release scaffold may reduce peak exposure while prolonging antimicrobial presence.

On the regenerative side, PCL-based printed systems incorporating bioactive glass or hyaluronic acid illustrate how additive manufacturing can produce material-specific functional zones aligned with the biological demands of the dentin–pulp interface.

The observed increases in odontogenic marker expression (DSPP, DMP-1) are encouraging, though translation into true endodontic space regeneration will require more models that replicate the anatomical constraints and vascular limits of root canals (Mousavi Nejad et al. 2021; Smaida et al. 2025). Broader 3D-printing reviews in regenerative dentistry emphasize that additive manufacturing offers customization, high-fidelity architecture, and the potential to integrate cells and signaling molecules with spatial precision. These advantages are theoretically well suited to the complex hierarchical structure of the dentin–pulp unit (Zhao et al. 2024).

Yet, the leap from promising in vitro behavior to predictable clinical REP outcomes remains substantial. Even the strongest included studies are preclinical, with limited head-to-head comparisons to current guideline-based protocols or standardized definitions of success. Several research gaps emerge. First, true intracanal in vivo models using 3D-printed antimicrobial–regenerative constructs are scarce. Second, consistent reporting of printing parameters, mechanical properties under endodontic loading, and degradation kinetics within dentin-confined spaces remains incomplete.

Third, future research should address combined strategies, such as sequential antimicrobial release followed by pro-angiogenic and odontogenic cue delivery, to match the recognized need for both disinfection and organized tissue regeneration. This aligns with contemporary scaffold-focused discussions in regenerative endodontic biomaterials literature (Liu et al. 2021). While 3D-printed scaffolds show clear conceptual and early experimental promise, current evidence supports cautious optimism rather than immediate clinical adoption.

CONCLUSION

Open-access preclinical evidence suggests that biomedical 3D-printed scaffolds can be engineered to support key goals of regenerative endodontics. Antimicrobial gelatin-based printed hydrogels demonstrate a promising balance between pathogen control and DPSC cytocompatibility, while polymer and polymer, ceramic printed constructs can enhance cell adhesion and odontogenic-associated marker expression. However, the field remains at an early translational stage. More clinically representative intracanal models, standardized outcomes, and comparative studies against established REP disinfection and scaffolding approaches are required before 3D-printed systems can be recommended for routine clinical use.

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 58 Issue: 10:2025
DOI: 10.5281/zenodo.17853561

References

1) Cao S, Han J, Sharma N, Msallem B, Jeong W, Son J, Kunz C, Kang H-W, Thieringer FM. In Vitro Mechanical and Biological Properties of 3D Printed Polymer Composite and β-Tricalcium Phosphate Scaffold on Human Dental Pulp Stem Cells. *Materials*. 2020;13(14):3057. doi:10.3390, ma13143057. (MDPI)

2) Dallos Ortega M, Aveyard J, Abdelgawad RM, El-Gendy R, Ciupa A, Whetnall D, Behnsen J, Poole RJ, D'Sa RA. Antimicrobial 3D printed gelatin scaffolds for root canal disinfection in regenerative endodontics procedures. *Biomaterials Science*. 2025; 13:3795-3813. doi:10.1039, D5BM00440C. (RSC Publishing)

3) Dawood RM. Inducing Osteogenesis in Human Pulp Stem Cells Cultured on Nano-Hydroxyapatite and Naringin-Coated 3D-Printed Poly Lactic Acid Scaffolds. *Polymers*. 2025;17(5):596. doi:10.3390, polym17050596. (MDPI)

4) Lee BN, et al. A review of the regenerative endodontic treatment procedure. *Restor Dent Endod*. 2015;40(3):179-187. (RDE)

5) Liu H, et al. Biomaterial scaffolds for clinical procedures in endodontic regeneration. *Stem Cell Res Ther*. 2021, 2022. (PubMed)

6) Mousavi Nejad E, et al. 3D Bioprinting of Polycaprolactone-Based Scaffolds for Pulp-Dentin Regeneration: Investigation of Physicochemical and Biological Behavior. *Polymers*. 2021;13(24):4442. doi:10.3390, polym13244442. (MDPI)

7) Smaida R, Hua G, Benkirane-Jessel N, Fioretti F. Three-Dimensional Models of the Dental Pulp: Bridging Fundamental Biology and Regenerative Therapy. *Int J Mol Sci*. 2025;26(22):10960. doi:10.3390, ijms262210960. (MDPI)

8) Wei X, et al. Expert consensus on regenerative endodontic procedures. *Int J Oral Sci*. 2022;14(1):55. doi:10.1038, s41368-022-00206-z. (Nature)

9) Zhao F, et al. The 3-dimensional printing for dental tissue regeneration: the state of the art and future challenges. *Front Bioeng Biotechnol*. 2024. (Frontiers)