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Review

Bio-Futuristic Endodontics: Nanotechnology, Microrobotics, 3D Printing, AI, and Smart Biomaterials for Regenerative Care

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Abstract

Endodontics is undergoing a paradigm shift from conventional root canal therapy toward regenerative and technologically integrated solutions. Persistent biofilms, structural fragility, and loss of vitality after treatment remain major clinical challenges, driving the need for novel strategies. This review provides a comprehensive overview of transformative technologies that are redefining the field, including nanotechnology, microrobotics, 3D printing, artificial intelligence (AI), and environmentally stimuli-responsive biomaterials. Nanotechnology introduces nanoparticles and nanozymes with potent antimicrobial, remineralizing, and regenerative properties, while microrobotic systems offer unprecedented precision in intraradicular navigation, biofilm disruption, and targeted drug delivery. Three-dimensional (3D) printing enables the fabrication of patient-specific scaffolds, canal replicas for training and evaluation, and bioengineered pulp–dentin complexes. Stimuli-responsive hydrogels and smart biomaterials add another dimension by providing controlled, site-specific therapeutic release in response to pH, temperature, redox state, or enzymatic cues. Artificial intelligence further enhances diagnostic accuracy, imaging interpretation, treatment planning, and outcome prediction, and when combined with 3D models, enables the concept of digital twins for personalized endodontic care. Collectively, these advances are converging toward a vision of regenerative and precision endodontics that is minimally invasive, biologically integrative, and sustainable. By synthesizing current progress and future directions, this review outlines a translational roadmap that positions next-generation endodontics within the broader landscape of advanced healthcare materials at the interface of biology, engineering, and digital technology.

Keywords: nanotechnology; microrobotics; stimuli-responsive biomaterials; regenerative endodontics; digital dentistry

1. Introduction: Toward Next-Generation Endodontics

Endodontics has long relied on root canal treatment (RCT) as the gold standard for managing pulp necrosis and irreversible pulpitis. While highly successful, conventional RCT is not without limitations [1]. The procedure eliminates infection but leaves the tooth devitalized, compromising its

biomechanical integrity and long-term survival. Persistent biofilms, intratubular bacteria, and anatomical complexities often resist disinfection, contributing to treatment failures and retreatment needs. Moreover, pulpless teeth lose their innate sensory, immune, and regenerative capabilities, rendering them more susceptible to fracture and structural fatigue. These limitations underscore the urgent need for strategies that restore both biological vitality and mechanical integrity rather than offering only structural repair [2].

Recent advances in biomedical engineering, materials science, and digital technologies are converging to reshape the future of endodontics. Nanotechnology has introduced nanoparticles and nanozymes with antimicrobial, bioactive, and regenerative capabilities [2]. Microrobotics promises unprecedented precision in navigating root canal microanatomy, actively disrupting biofilms, and delivering targeted therapeutics [2]. Three-dimensional (3D) printing and bioprinting enable the fabrication of patient-specific scaffolds, canal replicas, and even bioengineered pulp–dentin complexes [2]. At the same time, environmentally stimuli-responsive biomaterials provide spatiotemporally controlled drug delivery and adaptive scaffolding tailored to the pathological microenvironment [3]. Artificial intelligence (AI) enhances diagnostic accuracy, treatment planning, and imaging interpretation, while regenerative endodontics seeks to restore pulp vitality through cell-based and cell-homing strategies [4,5]. Together, these technologies are redefining endodontics as a digitally integrated, biologically regenerative discipline.

Within this transformation, advanced biomaterials play a central role. Smart hydrogels, bioactive scaffolds, and stimuli-responsive polymers represent a new generation of healthcare materials capable of controlled drug delivery, guided regeneration, and real-time responsiveness to microenvironmental cues. By embedding these innovations into endodontics, the field aligns with the broader progress in advanced healthcare materials, bridging dentistry with regenerative medicine, nanomedicine, and biofabrication [6].

This review provides a comprehensive synthesis of cutting-edge technologies, including nanotechnology, microrobotics, 3D printing, artificial intelligence, and smart stimuli-responsive biomaterials, and critically evaluates their translational potential. By integrating these domains, the article highlights how endodontics can evolve toward regenerative, precision, and sustainable care. Importantly, it positions these developments within the context of advanced healthcare materials, outlining a roadmap that connects biological science, engineering innovation, and clinical translation.

2. Artificial Intelligence in Endodontics

Artificial intelligence (AI) has rapidly emerged as a transformative force in endodontics, promising to enhance diagnostic precision, treatment planning, and workflow efficiency. This section synthesizes evidence from recent comprehensive reviews to outline the scope, clinical utility, and challenges of AI in endodontics [4,5]. The core strength of AI lies in its ability to process and analyze large volumes of data rapidly [5]. This capability is particularly useful in the interpretation of dental imaging, where AI models can identify patterns and anomalies that might be missed by the human eye [7]. By doing so, AI provides dentists with a powerful tool for accurate diagnosis, acting as a reliable, consistent, and efficient aid. For instance, in detecting early signs of conditions such as dental caries or periodontal disease, AI can analyze 2-dimensional (2D) and 3-dimensional (3D) dental radiographs, ensuring consistency and avoiding subtle signs being overlooked [8]. AI can also assist in treatment planning by suggesting approaches derived from a comprehensive analysis of numerous cases [9].

AI models, particularly those based on convolutional neural networks (CNNs) and artificial neural networks (ANNs), have demonstrated high accuracy across a range of endodontic tasks [10]. Detection and segmentation of periapical and radiolucent lesions and analysis of root canal morphology, prediction of treatment outcomes, detection of vertical root fractures and cracks and detection and classification of dental caries [10]. AI-based tools can identify and segment lesions on periapical and panoramic radiographs with sensitivity and specificity comparable to experienced clinicians. CNNs show especially robust performance, achieving accuracy rates often above 90% in

segmentation and classification tasks [11]. AI facilitates the precise identification of complex root canal configurations, including canal numbers, shapes, curvature, and rare anatomical variants. Deep learning approaches like U-Net and other segmentation networks have been validated for accurate, automated analysis of CBCT and panoramic images [12].

Machine learning models (such as random forest, gradient boosting machines, and XGBoost) have been developed to predict the prognosis of root canal treatments and assess case difficulty using a range of clinical and imaging data. These models support clinicians in making evidence-based decisions and optimizing patient-specific treatment strategies [12]. AI algorithms, including CNN-based classifiers, assist in the radiographic detection of fractures and cracks which may be challenging to identify manually, potentially reducing the rate of missed diagnoses [13].

Systematic reviews and umbrella analyses confirm the significant value of AI in diagnosing and detecting dental caries, with CNNs outperforming traditional diagnostic methods and junior clinicians in many scenarios. AI models excel in image-based caries detection from periapical, panoramic, and intraoral photographs, with high sensitivity, specificity, and area under the curve (AUC) [13]. A comprehensive summary of AI recent applications in endodontics is presented in **Table 1**.

Table 1. Representative AI Applications in Endodontics.

AI Application	Studies
Analysis of Tooth, Root, And Canal Morphology	[14,15], [16–21]
Patient Understanding and Anxiety in Endodontics	[22]
Root Canal Orifice Identification	[23]
Diagnosis, Treatment Planning, And Clinical Decision-Making	[7,9,24],
Caries And Periapical Periodontitis Detection	[8,25],

AI provides reliable, reproducible diagnostic support, reducing human subjectivity in interpreting complex imaging or clinical scenarios [4]. Automated image analysis, lesion detection, and case triage streamline diagnostic and planning processes, saving clinicians' time. Predictive models synthesize a patient's clinical and radiological data to guide individualized treatment and follow-up [10].

Despite significant promise, several barriers to widespread AI adoption persist such as Models must be validated across diverse populations and imaging modalities to ensure consistent performance in real-world settings. Also, the decision-making logic behind complex AI systems can be opaque, making some clinicians hesitant to rely on AI-alone for critical decisions. The use of patient images and data for AI requires robust anonymization and strict regulatory compliance. Successful AI systems depend on large, accurately annotated training datasets, still a limitation for less common conditions and rare anatomical variations [10].

AI must be implemented thoughtfully to avoid reinforcing biases present in training data and to ensure equitable access to technological advances [10]. Ongoing research aims to Develop explainable AI systems for transparent clinical support, Encourage the creation and sharing of large, diverse, well-annotated public datasets, Integrate AI into robotics, practice management, and chairside decision tools, Expand real-world validation studies and develop best-practice regulatory guidelines.

3. Microrobotics for Intraradicular Therapy

Microrobots represent a cutting-edge approach for overcoming the anatomical and microbiological challenges of root canal treatment, enabling active transport, controlled surface contact, and local delivery or triggering of therapy at defined sites that diffusion alone does not reach [26]. because they enable active transport, controlled surface contact, and local delivery or triggering of therapy at defined sites that diffusion alone does not reach [26]. Conventional instrumentation and irrigants often fail to completely disinfect intricate root canal systems, leaving residual biofilms that contribute to persistent infections and treatment failure [27].

3.1. Anatomical Targets and Navigation Advances

The porous and tapering architecture of dentin presents formidable barriers: tubule diameters narrow from $\sim 2.5 \mu\text{m}$ coronally to $0.9 \mu\text{m}$ near cementum, with densities reaching 32,000 tubules/ mm^2 at the inner root surface [28–30]. Isthmuses, lateral canals, apical deltas, and C-shaped configurations further complicate disinfection. [31,32]. Magnetically propelled silica–iron helical nanorobots have achieved intratubular insertion depths of $\sim 2 \text{ mm}$, surpassing the reach of NaOCl flushing (submillimeter) or photoacoustic activation ($\sim 0.8 \text{ mm}$) [29]. These microrobots can be field-programmed for distribution, retrieval, and even localized hyperthermia against *E. faecalis* within dentin, establishing new performance benchmarks for intraradicular therapy [28–31].

3.2. Architecture and Actuation Strategies

Advances in microrobot design have focused on magnetic architectures suited for the low-Reynolds-number regime of root canals. Helical swimmers actuated by rotating Helmholtz coils exemplify efficient propulsion, while “TriMag” 3D-printed microrobots integrate actuation, magnetic particle imaging (MPI) visibility, and magnetothermal therapy into a single multifunctional platform. Within dentinal tubules, silica–iron nanorobots display versatile behaviors, rotation for insertion, oscillation for distribution, and field-switching for retrieval, tailored to the anatomical and therapeutic demands of endodontics [29,33–35].

Two-photon polymerization gives precise control over helical and scaffolded geometries at the micrometer scale, which is useful for low-Re locomotion and for tailoring swimmers to confined morphologies like isthmuses in mandibular molars [31,33,35]. In the TriMag approach, the team prints PEG-DA and PETA hydrogels, then performs an in situ reaction that forms Fe_3O_4 and CoFe_2O_4 within the printed network. This sidesteps the common problem of nanoparticle-loaded resins attenuating the laser during printing and avoids thin-film deposition limits, while yielding microrobots that can be actuated, imaged by MPI, and heated magnetothermally [34]. The same paper reports MPI tracking in dense tissue phantoms and ex vivo or in vivo models, together with controlled motion under rotating fields and efficient hyperthermia, illustrating why printed hydrogel helices with embedded magnetic phases are promising for navigation and therapy in complex endodontic spaces [34].

3.3. Imaging, Sensing, and Closed-Loop Control

Real-time localization is critical for clinical translation. Optical coherence tomography (OCT) provides shallow, high-resolution tracking near canal orifices, while X-ray fluoroscopy, enhanced by digital twin overlays, has enabled intuitive navigation of miniature robots under clinical C-arm workflows [36,37]. MRI offers soft-tissue contrast and gradient-based steering at human scale, and ultrasound has recently demonstrated real-time color-flow mapping for microrobot tracking in scattering tissues [38–40]. Together, these modalities define a layered imaging stack suitable for chamber-level guidance and intratubular precision in dental applications [36–41]

3.4. Therapeutic Mechanisms and Anti-Biofilm Strategies

The therapeutic advantage of microrobots lies in mechanochemical synergy. Controllable motion generates shear forces that loosen the extracellular polymeric substance, while catalytic surfaces, such as iron oxide nanozymes, produce reactive oxygen species at acidic biofilm pH, weakening the matrix and killing embedded bacteria. Swarming magnetic collectives can scrub biofilms within tortuous canals, and nanozyme-shelled microcapsules exhibit boundary-following motion for contact-based catalytic disruption. Importantly, these systems selectively target infection-associated cues, sparing adjacent healthy cells and reducing reliance on high-dose, cytotoxic irrigants [26,35].

Persistent intraradicular infection is sustained by biofilms that colonize isthmuses, fins, and dentinal tubules, many of which remain uninstrumented despite advanced file designs and irrigant activation. As a result, irrigant access is limited and biofilm-protected reservoirs persist [42,43]. In this setting, microrobotic and microcollective systems are not merely adjuncts to irrigation and instrumentation but can directly access otherwise unreachable microanatomy, generate local shear and catalytic stresses, and deliver drugs on demand [26,44].

The therapeutic advantage of these platforms lies in mechanochemical synergy. Controllable motion produces shear and contact forces that loosen the extracellular polymeric substance, while magnetically driven swarms and collectives can be steered through tortuous channels where rotating or oscillatory fields translate into near-wall scrubbing and localized mixing that physically erodes the biofilm structure [26,35]. Catalytic interfaces, particularly iron-oxide nanozyme surfaces, add a complementary chemical front by exhibiting peroxidase-like activity that converts peroxides into reactive intermediates at acidic biofilm pH, thereby weakening the matrix and killing embedded bacteria [45,46].

In confined microgeometries, nanozyme-shelled microcapsules and adaptive microcapsule assemblies show precise approach, boundary-following motion, and contact-catalytic disruption of biofilms while sparing healthy cells. Importantly, by selectively targeting infection-associated cues, these systems can reduce reliance on high-dose, cytotoxic irrigants [47,48] [26,35]. Within dentinal tubules, magnetic helical nanobots can be rotated to sweep tubule walls and then retrieved magnetically, extending treatment into the hardest-to-reach recesses that defeat bristle-free irrigant flows [29]. Building on magnetic actuation and bioinspired materials, recent platforms have demonstrated selective engagement of infected surfaces within minutes in complex microenvironments [47,48].

3.5. Targeted Drug Delivery and Regenerative Potential

Microrobots extend beyond disinfection by serving as carriers for drugs, nanoparticles, or biologics. Soft helical microrobots with tunable geometry enable guided delivery of antimicrobials or chemotherapeutics with controlled release [49]. Metal-organic frameworks and engineered hydrogels allow pH-responsive payload release in infected dentin microenvironments [50,51]. Ligand-functionalized microrobots, such as folate-decorated designs, further add molecular specificity [52]. In regenerative applications, hydrogel-based microrobots can deliver growth factors or stem cell-laden scaffolds, degrade after completing their task, and preserve the viability of apical papilla stem cells—shifting their role from microbial “hunters” to regenerative “healers.” [45–47].

3.6. Regenerative Micro-Interventions

Eradication of infection is the prelude to regeneration, not its substitute. Hydrogel microrobots can carry and release growth cues with spatial precision, conform to irregular canal walls, and degrade into biocompatible fragments once their mission ends, which makes them natural candidates for micro-scale regenerative delivery in the root canal space [50]. Building on this, adaptive microcapsule assemblies provide apical access and precise release in branched or curved anatomies,

followed by complete retrieval to leave a clean, modulated microenvironment ready for scaffold or cell therapy [47,48].

Endodontic nanomaterial platforms already support antibacterial action while promoting dentin repair and pulp–dentin complex regeneration, suggesting how microrobotic carriers can be converted from hunters to healers after debridement [53,54]. In this context, peroxidase-like nanozymes offer enzyme-mimetic catalysis that disrupts EPS while limiting collateral damage, and can be integrated into hydrogel/MOF architectures for controlled, pH- or enzyme-responsive release of morphogens (for example, BMPs) or cell-protective factors during early healing [46,50,51]. Catalytically active iron-oxide formulations used during disinfection do not impair the viability of apical papilla stem cells in dental models, preserving the cellular substrate needed for regeneration [45]. Moreover, clinical and ex vivo data indicate that FMX nanozymes not only eradicate recalcitrant endodontic biofilms but also stimulate SCAP proliferation and osteogenic signaling, creating conditions favorable for revascularization and dentinogenesis once a biocompatible scaffold is introduced [45].

From an actuation standpoint, magnetic helical soft microrobots can be dimensioned to maximize apical reach and payload without sacrificing locomotion, a practical consideration when delivering stem-cell aggregates or growth-factor depots through narrow apices [49]. In parallel, advanced materials such as MOFs and smart polymers enable high-capacity loading, stimulus-gated release, and improved biocompatibility of the carrier, aligning with current regenerative protocols that demand sterile, residue-free spaces and temporally staged signaling [50,51].

3.7. Synergy with Current Endodontic Instrumentation and Irrigation

Microrobots are best positioned as finishing adjuncts within contemporary irrigation and instrumentation workflows. Negative-pressure multisonic irrigation can achieve near-complete bacterial reduction even with minimal or no instrumentation, yet scanning electron microscopy still reveals residual organisms, underscoring the need for a micro-level finisher [55]. Shape-adaptive files such as XP Endo improve irrigant distribution in complex mesial systems and increase contact with recesses that standard files miss, thereby creating broader access corridors for subsequent microrobot deployment [42,43]. Given the cytotoxic risks and dentin-weakening associated with high-concentration sodium hypochlorite, a combined protocol that reduces oxidant dose while incorporating catalytic or drug-carrying microrobots is mechanistically attractive and clinically plausible [42,44].

3.8. Materials, Biocompatibility, and Safety Considerations

Safety remains a central priority. Magnetic actuation is favored for its deep tissue penetration and negligible heating. Biocompatible materials, including iron oxides, hydrogels (e.g., GelMA), and soft polymers, provide motility, imaging contrast, and degradability [35,50,51]. Iron oxide nanozymes such as ferumoxytol, already approved for clinical use in medicine, have demonstrated selective antibiofilm activity in endodontic models without harming stem cells [49]. Biodegradable designs, including hydrogel helices and acid-labile carriers, further reduce the risk of retention or toxicity [50,51].

3.9. Materials, Biocompatibility, Safety, and Limitations

Material choices shape every safety dimension. Reviews of medical microrobots emphasize the need for biocompatible surfaces, controllable magnetic cores, and imaging visible components to enable closed loop navigation and retrieval [41]. Soft matter robots distribute contact loads and are less likely to gouge dentin, whereas hydrogel bodies and polymeric helices can be formulated to hydrolyze or enzymatically degrade after task completion, reducing retention risk [49,50]. MOF-style carriers provide a built-in exit plan via acid-labile linkages that disassemble in mildly acidic microenvironments, enabling on-site release, while remaining stable near neutral pH as the tissue

returns to baseline [51]. Iron oxide toxicity profiles are dose-, size-, and coating dependent, with oxidative stress and iron overload as the dominant cellular risks, underscoring why clinically vetted formulations and conservative dosing are preferred for dental use [56].

Four failure modes dominate planning. The first is off target lodging or incomplete retrieval. Magnetic designs that enable field reversal extraction and disassemblable capsules mitigate retention, as shown for helical nanobots and microcapsule collectives [29,47]. Second, unintended tissue injury may occur. Soft, hydrogel rich bodies and low frequency magnetic actuation reduce wall stresses and heat, and multi sonic negative pressure irrigation can be paired to minimize apical extrusion during combined procedures [35,42,55]. The third factor is chemical overexposure. High concentration NaOCl is effective yet cytotoxic and can weaken dentin, so replacing part of the oxidant burden with site specific catalytic nanozymes or drug microcarriers can lower the systemic chemical load while preserving efficacy [42,46]. Fourth, there is a loss of control or invisibility. Medical microrobot roadmaps stress real time imaging, localization, and closed loop control as prerequisites for clinical deployment, which dovetail with the magnetic guidance, contrast, and retrieval strategies emphasized for dental microrobots [35,41].

3.10. Evaluation Framework, Models, Metrics, and Reporting Standards

Clinical credibility for intraradicular microrobots will be won or lost on the basis of the strength of their evidence pipeline. This pipeline must begin with models that faithfully recreate the two constraints that defeat conventional disinfection: the microanatomy of the canal system and the physics of biofilms. The classic dentinal tubule infection model established the benchmark for depth resolved outcomes, and it remains essential for showing whether new devices actually sterilize tubules rather than merely thinning surface biomass [57]. Standardized canal phantoms now allow reproducible isthmus and lateral complexity, providing controlled testbeds for comparing navigation, coverage, and biofilm removal under identical geometries [58]. In this context, microrobots must be evaluated with metrics that couple locomotion fidelity to antibiofilm mechanisms. The field's most successful platforms combine mechanical disruption with catalytic or drug payloads, so reporting should separate how completely biomass is physically removed from how completely the surviving cells are killed and then quantify the synergy of both processes [59,60]. The magnetic actuation parameters should be stated in terms of the field, frequency, and gradient, since torque driven rolling and gradient driven pulling demand distinct operating envelopes and decay differently with distance [59,61,62]. Finally, the adoption of endodontic reporting standards ensures that sample size, anatomical matching, and allocation methods are transparent and replicable, which is vital when effects hinge on millimeter scale geometry [63].

A tiered model strategy makes the evaluation both rigorous and clinically meaningful. First, dentin block or root slice tubule models quantify bacteria by depth killing and can reveal whether microrobotic action or delivered agents penetrate beyond the smear layer into tubules [57]. Second, 3D printed canals that embed standardized isthmuses and fins enable head to head navigation tests where coverage, dwell time, and apical reach are mapped against a known ground truth [58]. Third, topography rich substrates such as titanium meshes and stents such as lattices stress the robot's ability to negotiate trenches and crevices, mirroring the challenges of ribbons such as isthmuses and inter canal communications; liquid bodied magnetic robots and multimodal magnetic swarms have already demonstrated crevice access and mesh debridement under controlled magnetic programs [59,64,65]. Metrics should reflect both motion control and antimicrobial effects. For motion, report field amplitude, frequency, and gradients; path tracking error; time to target; wall following fidelity; and contact shear forces, since torque and force dominant modes produce different near wall stresses that govern scrubbing and penetration [59,61,62]. For antibiofilm performance, pair biomass assays with CFU reduction and depth resolved microscopy, then explicitly report whether efficacy arises from mechanical removal, catalysis or drug payloads, or their synergy. Both catalytic antimicrobial robots and switchable viscoelastic magnetic hydrogels synergistically outperform either mechanism alone, and payload identity and loading strongly modulate outcomes [59,60]. To ensure

reproducibility and reduce bias tied to anatomy, PRILE 2021 was adopted. Predefine primary outcomes, justify sample sizes, randomize and conceal allocation where feasible, and anatomically match specimens via pre experimental analysis or imaging [58,63].

3.11. *Clinical Translation and Future Directions*

Bringing microrobotics from the laboratory bench to the dental chair requires a carefully planned journey from concept to clinical reality. The first step on this path is establishing irrefutable evidence through standardized evaluation. To prove that these miniature systems can reliably navigate and disinfect the complex, three-dimensional labyrinth of a root canal, they must be tested in models that faithfully replicate clinical challenges. Advanced 3D-printed phantoms are crucial here, providing reproducible and anatomically accurate environments to test navigation, biofilm removal, and overall efficacy, setting a clear benchmark for performance.

Once validated, the focus shifts to designing a seamless clinical workflow. This process would likely begin with advanced preoperative imaging, allowing the clinician to map the canal anatomy and plan the microrobots' mission. Intraoperatively, the deployment would be a guided procedure, followed by a critical final step: postoperative verification. Clinicians must be able to confirm that the microrobots have been fully retrieved or have safely biodegraded as designed, leaving no unintended residue.

Underpinning this entire process are stringent regulatory and ethical considerations. Translating this technology demands clear regulatory pathways that rigorously assess the safety and biocompatibility of the materials used, as well as foolproof protocols for containment. Ethically, microrobotics offers a compelling advantage in the fight against antimicrobial resistance. By delivering potent, localized therapy directly to the site of infection, it promises to reduce the reliance on broad-spectrum antibiotics and high-concentration chemical irrigants.

3.11. *Clinical Translation, Regulation, and Future Directions*

Translating intraradicular microrobots into the operatory requires a workflow where actuation, imaging, and disinfection are orchestrated as a single procedure. Clinically scaled magnetic systems can generate uniform rotating fields and gradients compatible with image guided operation, and benchtop magnet on robotic arm platforms have demonstrated real time navigation under endoscopic and fluoroscopic guidance in anatomically relevant conduits [59,61]. Within endodontics, microrobotic therapies are positioned to do what irrigants and activation cannot reach, scrub, and sample from confined microspaces and then retrieve or neutralize what they deploy [44,66]. A credible translation plan must therefore align realistic testing environments, clear value propositions in the chairside workflow, and early regulatory pathways that track device performance, safety, and clinical benefit in stepwise studies [41–43,67].

A pragmatic integration sequence starts at diagnosis and proceeds through guided debridement to verification. Pre operatively, micro CT data and 3D printed surrogates can be used to select the actuation mode and plan coverage patterns for known isthmuses or fins [58]. Intra operatively, a torque dominant rolling mode provides efficient wall contact scrubbing, then a gradient dominant mode deforms or pulls collectives into narrow recesses, an approach shown to overcome undulating and trench like topographies in stent mesh analogs [59]. Field programs and distances should be set with the recognition that torque falls with the cube of distance, whereas force falls with the fourth power, which favors torque based locomotion when the magnet or coils cannot be placed very close to the tooth [59,62]. Therapy should couple mechanical disruption with chemical killing. Catalytic platforms and photoactive or antibiotic carried swarms have each shown that combining scrubbing with localized antimicrobial action improves eradication compared with either alone [59,60,64]. Integration with irrigants is natural; standardized canal phantoms already quantify how solution parameters, including temperature, influence biofilm removal in isthmus geometries and can be extended to hybrid microrobot irrigant protocols [58]. Retrieval and verification close the loop:

magnetic recollection of swarms or robots, followed by depth resolved sampling from targeted sites for diagnostics, is a key differentiator envisioned for endodontic microrobotics [44,66].

3.12. Regulatory, Ethical, and Economic Considerations with a Focused Research Roadmap

Early human studies should follow medical device good clinical practice, including prespecified endpoints, monitoring, and risk management under the ISO 14155 framework [68]. Hardware that enters or is used near MRI environments must be labeled via the MR safe, MR conditional, or MR unsafe scheme so that peri procedural imaging is risk assessed and documented consistently [69,70]. Preclinical biocompatibility and toxicity testing should grow from in vitro cytotoxicity and hemocompatibility screens to targeted in vivo assessments with histology and serum chemistry, as recommended in recent technology roadmapping for micro and nanorobots [67]. Ethically, protocols must guarantee containment and retrieval or in situ neutralization of materials, minimize off target exposure, and justify antimicrobial choices that avoid promoting resistance, since microrobot enabled localized therapy can reduce reliance on broad systemic dosing [44,59]. Health economic analyses can then test whether targeted, instrument independent access to microanatomy reduces retreatment drivers, using standardized models and PRILE compliant outcomes that translate cleanly to clinical endpoints [58,63].

A focused agenda emerges from these constraints. First, define a clinic ready actuation stack. Comparative studies should quantify the practical envelopes of coil based clinical systems versus compact magnet on arm devices in dental operatory geometries, using torque and force scaling and real time tracking accuracy as primary outcomes [59,61,62]. Second, decide when to deploy single body helical drills, liquid bodied soft robots, or swarming nanoparticle collectives in canals with distinct anatomies, testing which platform best balances access to narrow recesses with the driving force needed to traverse viscous interfaces [59,64,66]. Third, coverage metrics and depth of kill endpoints can be standardized by uniting 3D printed isthmus models with tubule infection assays so that navigation maps correlate directly with bacteriological success [57,58]. Fourth, the mechano chemical synergy should be optimized. Factorial designs should vary field programs and payloads to identify minima for drug dose and actuation time that still achieve complete biomass removal and CFU suppression, building on catalytic and photoactive exemplars [59,60,64]. Fifth, standards and safety should be codified. Priel checklists should be adopted prospectively in laboratory work, readouts should be mapped to ISO 14155 endpoints, and MR labeling and MRI equipment requirements where imaging is involved [63,68–71]. Finally, the translation is grounded in real physiology. Recent roadmaps emphasize that success hinges on testing in environments that reproduce non Newtonian fluids, tissue interfaces, and patient specific variability, which should guide the selection of ex vivo teeth, organ models, and eventual early feasibility trials [41,44,67]. **Table 2** summarize recent studies that used microrobotics in endodontics.

Table 2. Recent Studies that Used Microrobotics in Endodontics.

Study (Ref)	Type of Microrobotics Used	Aim of the Study	Significance
Dasgupta et al., 2022 [29]	Magnetic helical silica-iron nanorobots	Intratubular navigation and localized	Achieved ~2 mm intratubular navigation and localized

		hyperthermia against <i>E. faecalis</i>	hyperthermia for <i>E. faecalis</i> disinfection.
Hwang et al., 2019 [60]	Catalytic magnetic microrobot swarms	Mechanochemical biofilm eradication on dental substrates	Enabled mechanochemical biofilm eradication and tetherless intracanal disinfection with radiographic tracking.
Babeer et al., 2022 [66]	Iron-oxide-nanoparticle-based catalytic magnetic microswarms and opacifier-infused 3D-molded soft helicoids	Tetherless intracanal biofilm disruption and sample retrieval with controlled magnetic navigation to the apical region, plus radiographic tracking using opacifier-infused helicoids.	Magnetically responsive nanozyme capsules and adaptive assemblies provided targeted, selective biofilm disruption in confined spaces.
[48]Tran et al., 2025	Magnetically responsive nanozyme-shelled microcapsules	Target and disrupt biofilms in confined microgeometries	Provided boundary-following contact and rapid, selective biofilm treatment in narrow channels and confined spaces.
[47] Tran et al., 2025	Adaptive robotic microcapsule assemblies	Treat biofilms in rugged, crevice-rich spaces	Adapted mobility for sustained contact-catalytic disruption in tortuous, crevice-rich anatomy.
Mayorga-Martinez et al., 2022 [64]	Swarming photoactive magnetic microrobots	Eradicate biofilm on complex dental surfaces	Showed mechanochemical synergy of scrubbing with photoactivation on implant substrates, with potential translation to intraradicular biofilms.

Sun et al., 2025 [59]	Liquid-bodied magnetic soft robots	Navigate and clear biofilms on undulating, trench-like surfaces	Overcame complex surface topographies using switchable viscoelastic properties and achieved effective antibiofilm performance on rugged surfaces.
Mayorga-Martinez et al., 2023 [65]	Multimodal magnetic microrobots	Debride biofilms in crevices and meshes	Validated access and debridement in crevice-like features and titanium meshes, analogous to root-canal recesses.
Xing et al., 2025 [34]	3D-printed microrobots integrating magnetic actuation, MPI visibility, and magnetothermal therapy	Combine navigation, imaging, and localized therapy	Platform integrates actuation, magnetic particle imaging visibility, and magnetothermal treatment, aligning with image-guided interventions in constrained anatomy.
[49] Gao et al., 2024	Soft helical magnetic microrobots	Targeted antimicrobial or drug delivery	Demonstrated drug-carrying helical soft microrobots where geometry controls swimming and torque, enabling guided delivery.
Ye et al., 2023 [52]	Ligand-targeted magnetic microrobots	Bind receptor-positive targets for specific payload delivery	Added molecular specificity via folate targeting to enhance guided disinfection or therapy in heterogeneous infections.

Li et al., 2019 [36]	Magnetically actuated microrobots with optical coherence tomography (OCT) feedback	Closed-loop imaging guidance for navigation	Provided high-resolution OCT feedback for closed-loop navigation and tracking in shallow tissues, useful near the chamber and orifice.
Alabay et al., 2024 [37]	Miniature magnetic robots localized by clinical C-arm fluoroscopy	Radiographic localization and steering	Demonstrated real-time localization and steering of miniature robots using clinical C-arm fluoroscopy with VR interface, compatible with procedural settings.
Li et al., 2024 [38]	Magnetic microrobots in clinical-scale fields	Demonstrate human-scale magnetic navigation	Supported feasibility of clinical magnetic navigation systems at human scale, informing translation to dental settings.
Go et al., 2022 [39]	MRI-visible, magnetically driven PLGA-gelatin microbeads with surface Fe ₃ O ₄	Combine vessel embolization and doxorubicin delivery with intra-operative real-time x-ray guidance and postoperative MRI confirmation	Demonstrated magnetic targeting and selective embolization in a rat liver tumor model with drug-loaded beads, real-time x-ray tracking during targeting, and postoperative MRI localization. Provides a complete imaging-actuation-therapy workflow that informs translational imaging stacks for constrained anatomies.

4. 3D Printing & Bioprinting

Three-dimensional (3D) printing is an additive manufacturing process in which objects are fabricated layer by layer from computer-aided design (CAD) models. Technologies such as stereolithography (SLA), fused deposition modeling (FDM), and selective laser sintering (SLS) allow the creation of complex, high-precision structures, making 3D printing highly valuable in dentistry for both clinicians and patients [72]. In endodontics, it represents a paradigm shift, enabling treatment

to be tailored to individual patients in ways that conventional two-dimensional imaging cannot achieve [73,74]. The ability to produce highly detailed replicas of root canal systems supports more accurate treatment planning, while patient-specific models and navigation guides are particularly useful in managing calcified or atypical canals, reducing complications and improving outcomes [75,76]. Beyond clinical applications, 3D printing enhances education by allowing practitioners to simulate complex cases and serves as a valuable tool for patient communication, improving understanding of treatment procedures [77].

One important educational application is the fabrication of practice teeth. 3D-printed teeth can be produced cost-effectively and reproducibly from micro-CT scans of natural teeth, providing standardized conditions and ensuring comparable difficulty across students [78]. They also eliminate hygienic and ethical concerns associated with extracted teeth. Student evaluations of realism were favorable, with reported scores of 65.5% (± 16.8) for overall appearance, 64.7% (± 20.8) during root canal preparation, 74.4% (± 15.9) during filling, 73.9% (± 19.4) for canal anatomy, and 71.6% (± 20.0) for pulp chamber representation. Suitability for practice was rated significantly higher for 3D-printed teeth (84.0% ± 15.4) compared with acrylic blocks (49.1% ± 25.0 , $p < 0.001$), and handling was comparable to natural teeth (70.3% ± 21.4 vs. 70.9% ± 19.3). Students further noted advantages such as reduced preparation time and better opportunities for simulating patient treatment. In addition to cost-effectiveness, these models allow replication of complex canal anatomies, improving the learning environment and generating strong student acceptance. Techniques such as SLA and PolyJet printing are particularly valued for their precision in replicating fine details [79].

3D printing has also enabled the development of novel biomaterials with antimicrobial potential. Hydrogel scaffolds incorporating benzylidimethyldodecylammonium chloride (BDMDAC) demonstrated strong activity against pathogens including *Enterococcus faecalis*, *Porphyromonas gingivalis*, and *Streptococcus mutans* [80]. Concentrations of 125 $\mu\text{g/mL}$ and 250 $\mu\text{g/mL}$ maintained over 70% viability of human dental pulp stem cells, indicating low cytotoxicity. Freeze-dried scaffolds retained stability for at least six months with sustained antimicrobial function, while BDMDAC release was controlled over 60 hours and correlated with initial concentration. Importantly, 3D printing allows patient-specific customization of scaffold geometry, meeting the need for individualized endodontic applications.

In guided endodontics, 3D-printed surgical guides improve precision in procedures such as apicoectomy and guided access cavity preparation. These guides minimize tissue damage, reduce operative time, and enhance accuracy in locating canal entrances and establishing access pathways, thereby reducing procedural errors. Guided access cavity preparation employs stents, guide sleeves, or dynamic navigation systems to facilitate conservative and accurate cavity formation [81,82]. This approach shortens chair time, preserves tooth structure, and lowers the risk of iatrogenic complications, aligning with minimally invasive endodontic principles [83–85]. Clinical case reports have demonstrated the effectiveness of these guides in canal localization and access preparation, particularly in calcified or anatomically complex cases [86–88]. Representative studies highlighting the impact of guided endodontics and 3D-printed applications are summarized in **Table 3**, providing comparative insights across ex vivo, in vitro, and clinical contexts.

Despite these advances, several challenges remain. The high purchase cost of 3D printers, along with ongoing expenses for maintenance and materials, poses a barrier to widespread adoption in dental practice [89–91]. The quality of printed products also depends heavily on the materials and techniques used, leading to variability in outcomes [92,93]. Furthermore, student evaluations revealed that the suitability and handling of printed teeth were rated slightly lower compared to natural models, reflecting the difficulty of replicating enamel, the hardest tissue in the human body [78].

Future improvements could address these limitations. Student suggestions include enhancing tooth retention in models ($n=30$), optimizing material hardness ($n=7$), integrating access cavity preparation by closing the pre-provided cavity ($n=5$), and generating variations of canal anatomies ($n=3$) [78]. Advances in material science and printing precision may help overcome current barriers,

enabling 3D printing to further expand its role in endodontic education, research, and clinical practice.

Recent research has highlighted the significant potential of 3D printing in advancing endodontic education and clinical practice. In a 2025 study, *Plascencia et al.* [94] reported high trainee acceptance of 3D-printed models, with a 96.6% approval rate on the Academic Satisfaction Scale and 70.79% favorable responses on the Open-Apex Model Questionnaire. These models enabled residents to perform procedures with an overall accuracy rate of 86.14%, comparable to that achieved with natural teeth. However, inferential analysis revealed notable shortcomings. Errors were significantly more frequent in determining the working length ($p = 0.045$) and in producing a homogeneous apical barrier without voids ($p = 0.034$). These limitations were attributed to the material properties of the 3D-printed models, particularly their tactile sensation and radiographic characteristics, which differed from natural teeth.

Beyond training applications, 3D printing has also demonstrated clinical value [95]. *described* a complex case involving the autotransplantation of a third molar to replace a non-restorable maxillary first molar associated with odontogenic sinusitis. A 3D-printed replica of the donor tooth was used to prepare the recipient socket in advance, reducing the donor tooth's extraoral time to less than one minute and minimizing the risk of damage. At the 3-year follow-up, the patient exhibited complete bone formation, a healthy periodontal ligament, and full resolution of the sinus infection without further intervention. This case supports the use of autotransplantation as a cost-effective and biologically sound alternative to implants and prostheses, with outcomes significantly enhanced by 3D planning and replication technologies.

Alamri et al. [96] conducted a cross-sectional study assessing the knowledge and awareness of 3D design and printing among dental students in Saudi Arabia. The findings indicated a generally satisfactory understanding of the technology's applications, benefits, and challenges. A large proportion of students (82.4%) expressed strong interest in further exploring 3D printing, underscoring the demand for specialized education. However, the high cost of equipment, reported by 40.4% of participants, emerged as the most significant barrier to adoption. Knowledge levels varied notably across academic years and regions, with fifth-year students and those in the Eastern region demonstrating greater proficiency. The study emphasized the need for integrating 3D printing into dental curricula and offering practical workshops to capitalize on student interest and better prepare future dental professionals for clinical implementation. Details of these limitations, together with proposed solutions, are further contextualized by the studies listed in **Table 3**.

Ref	Title	Conclusion
[97]	Guided Endodontics: Volume of Dental Tissue Removed by Guided Access Cavity Preparation-An Ex Vivo Study	Guided endodontic access GEA preserved a greater volume of dental tissue in extracted upper human molars than conventional endodontic access CEA; however, there was no significant difference between CEA and GEA in the volume of dental tissue removed from mandibular incisors.

[98]	Guided Endodontics for a Tooth with Root Fracture: A Case Report	The obtained results suggest that the use of guided endodontics can improve outcomes in cases with pulp canal obliteration and complex fractures, offering a minimally invasive and predictable approach.
[99]	Targeted Endodontic Microsurgery of a Mandibular First Molar with a Separated Instrument Using the 3D-printed Guide and Trephine Bur: A Case Report with a 2-year Follow-up	This case report describes the use of the 3D-printed guide and the trephine bur to accurately perform Endodontic microsurgery of a mandibular first molar with a separated instrument and periapical lesions.
[100]	Effective Management of Calcified Root Canals Using Static-guided Access: A Case Series	The cases demonstrated that static-guided endodontics is a safe accurate treatment approach to access calcified canals, reducing working time, minimizing removal of tooth structure, and decreasing the risk of iatrogenic damage.
[101]	Guided endodontics a pathbreaking approach to the management of calcified canals: A case report	For conservative, precise, and predictable outcomes, a digital workflow that makes use of CBCT imaging, planning software, and a 3D-printed endodontic guide may be taken into consideration when managing extensively calcified canals.
[102]	Minimization of Tooth Substance Removal in Normally Calcified Teeth	The use of guided endodontics in normally calcified teeth enables the

	Using Guided Endodontics: An In Vitro Pilot Study	preservation of a significant amount of tooth substance. However, this advantage must be carefully balanced against a greater radiation burden and risk of perforation, higher costs, and more difficult debridement and visualization of the pulp chamber and root canals.
[103]	Real-Time Guided Endodontics with a Miniaturized Dynamic Navigation System Versus Conventional Freehand Endodontic Access Cavity Preparation: Substance Loss and Procedure Time	real-time guided endodontics is a practicable, substance-sparing method performed in comparable time as the conventional freehand method. Moreover, real-time guided endodontics seems to be independent of operator experience.
[95]	Case Report: Dental autotransplantation for the resolution of odontogenic sinusitis using 3D replication	This case demonstrates that, when properly planned and executed, dental autotransplantation can be an effective and biological alternative for dental rehabilitation, especially with the use of advanced technologies, such as cone beam computed tomography and 3D-printed replicas of donor teeth.
[104]	Guided endodontics versus conventional access cavity preparation: an ex vivo comparative study of substance loss	For access cavity preparation in teeth with pulp canal calcification, both conventional access cavity preparation by a specialist and guided endodontics by a general dentist produce good

		results in terms of substance loss and time requirements.
[87]	Influence of Calcified Canals Localization on the Accuracy of Guided Endodontic Therapy: A Case Series Study	In any of the analyzed cases, the guided endodontic technique applied to pulp canal obliteration did not determine the presence of iatrogenic errors, such as perforations. However, the apical localization of the obliteration increases the probability of being off-center with the drill during the instrumentation phase by about 15 times.
[105]	Comparing accuracy in guided endodontics: dynamic real-time navigation, static guides, and manual approaches for access cavity preparation - an in vitro study using 3D printed teeth	Although guided endodontic access preparation may require more time compared to the freehand technique, the guided navigation is more accurate and saves tooth structure.

5. Regenerative Endodontic

Conventional root canal therapy (RCT) has long been regarded as the gold standard for treating irreversible pulpitis and apical periodontitis. The procedure involves complete debridement of infected pulp tissue followed by mechanical instrumentation and obturation. While the overall success rate of RCT ranges from 86–98%, failures are not uncommon due to microbial persistence, complex canal anatomy, procedural errors, and structural weakening of the tooth after instrumentation. Moreover, RCT renders the tooth non-vital, eliminating its immunological defense and regenerative potential [106,107].

To overcome these limitations, attention has shifted toward regenerative endodontics (RE), an interdisciplinary field that combines endodontics, stem cell biology, tissue engineering, and material science. The objective of regenerative endodontic therapy (RET) is not only to disinfect the canal system but also to restore pulp vitality, promote dentinogenesis, revascularization, and establish functional pulp–dentin complex regeneration. RET thereby aims to provide a biologically based alternative to conventional RCT [108].

5.1. Strategies in Regenerative Endodontics

Cell-based transplantation and cell homing represent two available strategies to achieve pulp-dentin complex regeneration. Transplantation relies on introducing exogenous stem cells into the empty root canal. In contrast, cell homing influences the recruitment of endogenous cells inside the host root canal system, facilitating pulp tissue regeneration. Owing to its feasibility and reduced clinical complexity, cell homing appears to hold greater clinical practice potential compared to transplantation [106].

5.2. Cell Transplantation Strategy

This approach relies on the transplantation of exogenous stem/progenitor cells into the root canal system. Dental pulp stem cells (DPSCs), stem cells from the apical papilla (SCAPs), and periodontal ligament stem cells (PDLSCs) are most frequently investigated [109,110]. Cells are delivered within a suitable scaffold and supported by signaling molecules. The primary advantage of the cell transplantation strategy lies in its ability to provide predictable cell populations with a high potential for true tissue regeneration. However, this approach is not without limitations, as it carries the risk of immune rejection, requires complex ex vivo cell expansion procedures, and is further constrained by ethical and regulatory challenges [111].

Although cell transplantation has not yet become part of routine clinical endodontic practice, several pioneering clinical trials have demonstrated its safety, feasibility, and preliminary efficacy in both immature and mature permanent teeth [112–114]. Despite encouraging progress, significant obstacles hinder clinical translation. These challenges include complex in vitro procedures for cell isolation, expansion, storage, and transport ; unpredictable in vivo performance in terms of cell survival, proliferation, and differentiation ; and biosafety concerns related to abnormal differentiation, pathogen transmission, and tumorigenic risk [115–119]. Furthermore, growing evidence indicates that transplanted stem cells primarily exert their therapeutic benefits via paracrine signaling mechanisms, which remodel the local microenvironment and stimulate endogenous regeneration, rather than directly differentiating into new tissue [120,121].

In light of these limitations, considerable debate remains as to whether cell transplantation can serve as a true substitute for conventional root canal treatment. At present, neither the European Society of Endodontology nor the American Association of Endodontists recommends stem cell transplantation for regenerative endodontic procedures in clinical settings. Nonetheless, once predictable and reproducible regeneration of the pulp dentin complex is achieved by cell transplantation, this approach is expected to play a role in regenerative endodontic procedure [121].

5.3. Cell Homing Strategy

Cell homing exploits the body's endogenous regenerative potential by recruiting resident stem/progenitor cells to the site of injury via chemotactic cues [122]. Bioactive molecules released from dentin (e.g., TGF- β , BMPs, VEGF, FGF) or incorporated into scaffolds act as attractants to guide migration and differentiation [123,124]. This strategy circumvents the limitations of exogenous cell transplantation and is considered more clinically feasible.

Cell homing involves the endogenous recruitment of stem / progenitor cells to the injured pulp, governed by dynamic interactions among signaling molecules, extracellular matrix (ECM) components, and the surrounding microenvironment [123,124]. This mechanism is a hallmark of regeneration across multiple tissues and is crucial for achieving functional pulp regeneration. The primary processes include (i) chemotactic migration of stem/progenitor cells originating from periapical tissues, and (ii) the deployment of biomaterial scaffolds enriched with bioactive signaling factors. Together, these elements not only ensure cell recruitment and retention but also facilitate their differentiation and integration into functional dentin pulp complex [125].

Numerous signaling molecules orchestrate chemotactic migration and lineage specific differentiation of stem cells (**Table 4**).

Table 4. represents role of Signaling Molecules in Chemotaxis.

Signaling Molecules	Role	Ref
SDF-1	central regulator that drives mesenchymal stem cell (MSC) mobilization through its receptor CXCR4	[126–128].
PDGF	Platelet derived growth factor is equally vital, supporting both angiogenesis and mesenchymal stem cells (MSC) recruitment processes indispensable for pulp dentin complex regeneration	[125,129].
FGF	Fibroblast growth factor (FGF) contributes by enhancing cell migration and differentiation, thereby accelerating reparative events	[125,130,131].
TGF- β	transforming growth factor beta regulates cell movement and stimulates odontoblastic differentiation, playing a pivotal role in orchestrating tissue regeneration	[125,132,133].

5.4. Stem/Progenitor Cell Sources

The effectiveness of regenerative therapies is closely tied to the type of stem/progenitor cell employed (Table 5).

Table 5. Stem/Progenitor Cell Sources.

Stem cells	Role	Ref
SCAPs	Stem cells from apical papilla exhibit high proliferative potential and resistance to inflammation, rendering them particularly advantageous for pulp dentin regeneration.	[125,134].
iPAPCs	Inflammatory periapical progenitor cells identified in inflamed periapical lesions, display differentiation, making them important contributors to reparative pathways.	[135].
BMMSCs	Bone marrow-derived mesenchymal stem cells are adaptable to diverse environments and support both bone and pulp repair.	[136,137].

PDLSCs	periodontal ligament stem cells possess immunomodulatory activity alongside odontogenic potential.	[138–140].
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5.5. Scaffolds in Regenerative Endodontics

Traditional tissue engineering strategies incorporate and balance 3 major ingredients, e.g., stem cells, scaffold materials, and bioactive molecules (generally growth factors)[5]. Scaffolds play a central role in regenerative endodontics by providing a three-dimensional framework that mimics the natural extracellular matrix (ECM). This microenvironment supports cell adhesion, proliferation, differentiation, and vascular ingrowth, all of which are essential for the regeneration of the pulp-dentin complex [141]. An ideal scaffold should be biocompatible, biodegradable, mechanically stable, and capable of delivering bioactive signals that guide tissue development [142]. Based on their origin and composition, scaffolds are broadly categorized into natural, synthetic, bioceramic, and advanced smart scaffolds [7].

5.6. Natural Scaffolds

Natural Scaffolds can be divided into four main categories: bioceramic, synthetic polymers, natural polymers, and composite scaffolds [7] and smart scaffolds, Natural polymers includes collagen, collagen-mineral combinations, gelatin, fibrin, and polysaccharides, such as hyaluronic acid and chitosan are considered to provide better biocompatibility [143], they are nevertheless valuable despite their advantages because they are biocompatible and closely resemble the extracellular matrix, which provides vital biological cues that improve cellular responses [8,9].

Collagen, the most abundant ECM protein, is widely employed due to its excellent biocompatibility and ability to promote odontoblastic differentiation [11]. Gelatin, a denatured form of collagen, is less immunogenic and has proven effective for the delivery of growth factors and drugs [14]. Fibrin, often utilized in the form of platelet-rich plasma (PRP) or platelet-rich fibrin (PRF) [14], is particularly valuable as it is autologous, inherently angiogenic, and supports cellular proliferation and migration.

Other promising natural scaffolds include silk fibroin[16], which provides high tensile strength and slow degradation, alginate [1] and chitosan [19], which offer antimicrobial and bioactive properties, and decellularized extracellular matrix (dECM) [22], which retains native bioactive cues and closely mimics the pulp microenvironment. Hyaluronic acid (HA) has also been explored for its hydrophilic nature and ability to modulate inflammation and wound healing [24]. In addition, host-derived scaffolds such as blood clot, concentrated growth factor (CGF), and platelet derivatives represent clinically practical and cost-effective options that are enriched with signaling molecules and growth factors [26].

5.7. Synthetic Polymer Scaffolds

Synthetic scaffolds, particularly those fabricated from FDA-approved polymers such as polylactic acid (PLA), polyglycolic acid (PGA), and their copolymer poly (lactic-co-glycolic acid) (PLGA) [1], have been extensively studied in regenerative endodontics [27]. These materials offer distinct advantages including controlled biodegradation rates, scalable manufacturing, and favorable mechanical properties that provide structural support within the root canal [8,9]. However, their limitations lie in the lack of inherent bioactivity and the potential generation of acidic degradation byproducts, which may interfere with tissue healing and regeneration. Recent innovations include hybrid scaffolds that combine the biological properties of natural materials with the mechanical strength of synthetic ones. These scaffolds optimize the balance between biocompatibility and structural support, further enhancing their regenerative potential [10].

5.8. Bioceramic and Composite Scaffolds

Bioceramic Scaffolds made from calcium phosphate, bioactive glass, and other bioceramics promote regeneration by mimicking the mineralized components of dental tissue [28]. These materials enhance osteoconductivity and encourage DPSCs to differentiate into odontoblast-like cells. Bioceramic scaffolds provide robust structural integrity while releasing bioactive ions, such as calcium and phosphate, to stimulate tissue growth and repair. Their ability to integrate with natural dental structures makes them particularly effective for restoring pulp vitality in necrotic teeth [10].

5.9. Smart and Advanced Scaffolds

Recent developments in material science have introduced a new generation of advanced scaffolds designed to more closely replicate the dynamic conditions of the pulp microenvironment [29]. By integrating stimulus-responsive functionality, these advanced materials achieve targeted antibiofilm action without compromising biocompatibility, offering a sustainable solution to infection control in oral rehabilitation [3]. Injectable hydrogels enable minimally invasive clinical application and can deliver bioactive molecules in situ [13]. Electrospun nanofibers provide a biomimetic architecture that closely resembles natural ECM, supporting cell alignment and differentiation. The advent of three-dimensional (3D) printing has further revolutionized scaffold fabrication by allowing precise customization of scaffold geometry to match patient-specific root canal anatomy. Furthermore, smart scaffolds responsive to environmental stimuli such as light [30], pH [13], temperature [32], or enzymatic activity [34] are being engineered to provide controlled, on-demand release of growth factors, thereby enhancing the predictability and efficacy of regenerative endodontic procedures. Table 6 provides a comprehensive comparison of commonly used biomaterials, including collagen, chitosan, alginate, hyaluronic acid, and host-derived scaffolds, highlighting their significance, limitations, and scaffold designs. Stimuli-responsive hydrogels for regenerative endodontics: types of stimuli, advantages, and limitations are presented in Table 7.

Table 6. Biomaterials investigated for regenerative endodontics: significance, limitations, and scaffold designs.

Biomaterial	Significance	Limitations	Scaffolds Used	References
Collagen	Highly biocompatible and bioactive; key component of pulp–dentin ECM; supports mineralization and differentiation.	Pure collagen lacks mechanical strength and regenerative capacity without additives.	Collagen–hydroxyapatite composites, collagen–hyaluronic acid, and AceCol scaffolds.	[7,35–37]
Alginate	Biocompatible, low immunogenicity, and versatile in scaffold formation.	Weak mechanics and uncontrolled biodegradation.	Alginate/acemannan beads, PVA/alginate composites, and silk fibroin–alginate hydrogels.	[38,39] [40]

Hyaluronic acid	Excellent biocompatibility, supports cell environment, non-cytotoxic.	Limited adhesion, proliferation, and differentiation enhancement.	Photocross-linked silk fibroin/HA hydrogels with hDPSCs.	[25,41]
Cellulose	Abundant, cost-effective, supports adhesion and odontogenic differentiation.	Weak mechanical strength and low intrinsic bioactivity.	Carboxymethyl cellulose–Laponite nanocomposite hydrogels.	[41]
Chitosan	Antibacterial, bioactive, supports pulp-like tissue formation, versatile for drug delivery.	Poor mechanical strength; properties vary by source/deacetylation.	Chitosan–gelatin–alginate, calcium silicate–chitosan, and phosphorylated pullulan–chitosan scaffolds.	[42,43], [20]
Decellularized ECM (dECM)	Preserves ECM proteins, enhances cell proliferation, supports vital pulp regeneration.	Preparation is complex and variable.	dECM–silk fibroin hybrids	[44,45]
Fibrin	Injectable, biocompatible, reduces infection, supports pulp regeneration.	Mechanical strength and degradation rate depend on scaffold design.	Dentin ECM–bioactive glass/GelMA and fibrin-based hydrogels.	[15,41,45]
Gelatin	Derived from collagen, biocompatible, low immunogenicity, supports controlled release of growth factors.	Rapid degradation and weak mechanical properties unless reinforced.	Gelatin–chitosan–alginate scaffolds.	[14,39]

Silk	Robust, stable under environmental stress, highly compatible with stem cells.	Requires precise degumming to remove immunogenic sericin.	Silk fibroin/HA hydrogels and silk-hydroxyapatite composites.	[16] [46] [47]
Host-derived scaffolds	Autologous, immune-safe, rich in growth factors, promotes stem cell recruitment.	Variable effectiveness and lack of preparation standardization.	Platelet-rich plasma scaffolds.	[26] [1] [52]

Table 7. Stimuli-responsive hydrogels for regenerative endodontics: types of stimuli, advantages, limitations, and key references.

Type of stimuli		Advantages	Limitations	References
Physical Stimuli	Light Responsive Hydrogel	Offer precise spatiotemporal control (e.g., stiffness modulation, drug release) and rapid responsiveness (≈ 260 ms). NIR light allows deep tissue penetration (e.g., inside root canals).	Risk of cytotoxic byproducts and unintended heat damage.	[30] [13] [31]
	Thermo-responsive hydrogels	Convenient (liquid at room temp, gel at body temp), versatile (LCST/UCST systems), widely explored in tissue engineering and drug delivery.	Cytotoxicity from crosslinkers, complex tuning of LCST, and risk of burst drug release.	[30] [32] [13] [21] [33]
	Magnetic-responsive hydrogels	Enable non-invasive, localized therapy with external magnetic control.	Dependence on magnetic nanoparticles' safety and limited field penetration depth.	[26] [13]

Chemical Stimuli	pH-responsive hydrogels	Swell, shrink, or degrade with pH changes, allowing targeted drug delivery in inflamed or acidic tissues.	Small pH differences in vivo reduce targeting specificity; buffering weakens response.	[13] [34]
	Redox-responsive hydrogels	React to oxidative stress (ROS), protecting cells and modulating drug release profiles.	Variable ROS levels across patients and slow reaction kinetics can limit efficacy.	[13] [34]
Biochemical Stimuli	Enzyme-responsive hydrogels	Use enzyme-cleavable motifs for personalized, biologically triggered responses; enable in-situ degradation and dynamic scaffold remodeling.	Enzyme variability across patients/disease states may cause unpredictable outcomes.	[34] [13]
	Glucose-responsive hydrogels	Widely studied for diabetes; release therapeutic agents (e.g., insulin) in response to high glucose levels.	Require direct contact with body fluids and often have lag times in drug release.	[34] [51]

5.10. Clinical Trials

Regenerative endodontics represents a transformative approach to dental care, revitalizing necrotic teeth. These studies evaluated the role of platelet aggregates compared to the traditional blood clot method in regenerative endodontics. A previous Systematic Review and Meta-Analysis demonstrated that No statistically significant difference was observed for different outcome parameters such as apical root closure, positive pulp vitality, healing response, and overall clinical success when blood clot was compared to PRP and PRF. Therefore a conclusion can be drawn that BC serves as an effective primary scaffold in RET for non-vital immature teeth, reserving PRP and PRF for cases where difficulty to induce intracanal blood is encountered [144]. Other studies in **Table 8**.

Table 8. represents studies evaluated platelet aggregates compared to the traditional blood clot method.

Study	Outcome
[145]	Overall success rate was 76.5%. Sensitivity recovery varied (29.4% A-PRF, 41.2% S-PRF, 17.6% BC).

[146]	Favorable clinical outcomes with reduced symptoms and restored vitality. Radiographs and CBCT showed periapical healing, root lengthening, canal wall thickening, and dentin formation.
[147]	Most teeth survived up to 3 years post-REP. Flare-ups occurred in some cases. Periapical healing was high on PR evaluation (~90%) but lower on CBCT (~50%). Root development was limited.
[148]	Pulp sensibility responses were inconsistent; PRF showed best response at 12 months (66.6%). All groups showed good periapical healing, but radiographic differences in root development were not evident.
[149]	Significant improvement in sensibility and periradicular healing at 6 and 12 months, with no difference between groups at 12 months.
[150]	High overall success (91.7%) in children. Success was greater in developmental anomalies (98.4%) than trauma (84.3%). Radiographs showed improved root characteristics, with no significant difference between CGF and BC scaffolds.
[151]	No groups regained vitality. PRP showed increased root–root area (RRA), though not statistically significant.

5.11. Challenges and Limitations

Although regenerative endodontic therapy has shown promising outcomes in both laboratory and clinical studies, several challenges continue to limit its predictability and widespread adoption. One of the primary concerns is the variability of clinical results, as some cases show complete regeneration with continued root development, while others result in repair with cementum- or bone-like tissues rather than true pulp–dentin complex regeneration. This inconsistency highlights the need for more refined and standardized treatment protocols.

Another significant limitation is the difficulty of achieving complete disinfection of the root canal system. Persistent microorganisms or residual biofilm can interfere with cell recruitment, scaffold integration, and tissue regeneration, ultimately leading to treatment failure. Moreover, the lack of universally accepted protocols for scaffold preparation, growth factor delivery, and canal conditioning has further contributed to variability in treatment outcomes.

From a biological standpoint, the limited vascular supply and confined anatomy of the root canal present additional barriers to predictable regeneration. Immune rejection is also a potential risk when exogenous stem cells are used, and the requirement for ex vivo expansion of these cells increases both technical complexity and financial cost. Ethical and regulatory restrictions surrounding the clinical use of stem cells further hinder the translation of laboratory findings into everyday practice.

5.12. Future Perspectives

Future directions in regenerative endodontics focus on developing more reliable, standardized, and clinically feasible approaches. One promising avenue is the design of hybrid scaffolds that integrate the bioactivity of natural polymers with the mechanical stability of synthetic materials or

bioceramics, thereby creating multifunctional platforms capable of supporting true pulp–dentin regeneration. The use of three-dimensional (3D) printing technology allows for the fabrication of patient-specific scaffolds that match the internal morphology of the root canal, ensuring better adaptation and biological outcomes.

Advances in nanotechnology are also opening new opportunities, particularly through the incorporation of nanomaterials that can enhance antibacterial effects, improve mechanical properties, and provide sustained release of growth factors or signaling molecules. Smart, stimuli-responsive scaffolds capable of delivering bioactive factors in response to changes in pH, temperature, or enzymatic activity represent another innovative direction that may significantly improve treatment predictability.

In addition, continued research into the molecular mechanisms governing pulp regeneration will help identify novel growth factors and chemotactic signals that can be harnessed for improved cell homing and differentiation. Well-designed randomized clinical trials with larger sample sizes are urgently needed to validate preclinical findings and establish evidence-based clinical guidelines. Ultimately, the goal is to transition regenerative endodontic therapy from an experimental procedure into a routine clinical option that reliably restores tooth vitality, function, and long-term survival.

6. Imaging in Endodontic Practice

Oral diagnostics and treatment planning are traditionally based on clinical examination and radiographic evaluation. Imaging techniques contribute significantly to all aspects of oral health, from detecting and monitoring disease progression to guiding treatment planning [152]. Historically, endodontic procedures relied heavily on operator skill, two-dimensional (2D) radiographs, and tactile feedback.

Conventional X-ray techniques produce a 2D representation of a three-dimensional (3D) structure, visualizing only apical–coronal and buccal–lingual planes, while the bucco–lingual dimension cannot be adequately defined. This limitation can lead to procedural errors, particularly in complex cases such as calcified canals and curved roots [153].

The introduction of 3D imaging modalities, including computed tomography (CT), cone-beam computed tomography (CBCT), ultrasound imaging (USI), and magnetic resonance imaging (MRI), has markedly improved the understanding of anatomical structures and pathological conditions [154].

The aim of this narrative review is to highlight the most reliable and advanced imaging techniques available in endodontics for early disease detection, precise measurement of lesions in both 2D and 3D, and improved assessment and follow-up.

6.1. Cone-Beam Computed Tomography (CBCT)

CBCT is a three-dimensional radiographic modality designed to overcome the inherent limitations of conventional radiographs, such as anatomical superimposition and geometric distortion [155]. Widely adopted in endodontics over the past two decades, CBCT evolved from the conventional CT scan and employs a cone- or pyramid-shaped X-ray beam. The X-ray source and detector rotate around the object in a single revolution, capturing multiple 2D images that are reconstructed into 3D views using a modified cone-beam algorithm [156].

CBCT provides higher specificity and sensitivity than traditional imaging, enabling accurate diagnosis and more predictable treatment planning [152]. Studies have validated CBCT's reliability for working length determination in comparison to the electronic apex locator. While the electronic apex locator remains the gold standard, CBCT is particularly valuable in complex cases where apex locator accuracy may be compromised, such as in root perforations [157].

CBCT is the only imaging system that allows predictable evaluation of complex root morphologies and sex-related anatomical differences, thereby facilitating the diagnosis and management of root canal anomalies [152,158]. Furthermore, CBCT enables quantitative assessment of periodontal healing in combined endodontic–periodontal lesions over time [158,159].

Another advantage is its ability to detect periapical pathology more accurately than conventional radiography, which requires 30–50% bone loss before lesions become visible [160,161]. Its applications extend to assessing obturation quality in primary teeth [162], evaluating retreatment techniques by quantifying residual filling material [163], and detecting vertical root fractures without overlapping [164]. **Table 9** shows recent studies that utilized CBCT in different applications in endodontics.

However, CBCT has limitations that may affect diagnostic accuracy. Patient movement, artifacts from radiopaque restorations or root fillings, and scattering can obscure image interpretation [165]. The most significant drawback is exposure to ionizing radiation, which restricts repeated use within short intervals. Accordingly, clinicians must apply the ALARA principle (“as low as reasonably achievable”) when considering CBCT for individual patients [166].

Although CBCT demonstrates statistically significant advantages in detecting periapical lesions compared to conventional radiographs, the clinical impact of this difference may be modest [156]. Recent advances, including limited field of view (FOV) scans, high-resolution imaging, and reduced radiation doses, are expected to further increase the clinical applicability of CBCT [159].

Table 9. Summary of recent studies utilizing CBCT in endodontics.

Study (Ref)	Title	Year	Applications
[152]	Present status and future directions: Imaging techniques for the detection of periapical lesions	2022	Detection of periapical lesions throughout the jaws with minimal risk of false positives
[167]	The importance of cone-beam computed tomography in endodontic therapy	2023	Evaluation of root canal anomalies, complex morphologies, and sex differences for accurate diagnosis and treatment planning
[159,164]	“Combined endo-perio lesions” – what is the best treatment? Surgical endodontics	2021, 2022	Quantitative evaluation of combined endo-perio lesions and periodontal healing
[165]	Surgical endodontics	2022	Precise healing assessment through identification of missed canals and root resorption

[159,161]	Diagnostic accuracy of CBCT in identifying periapical lesions; Assessment of endodontic treatment and apical periodontitis prevalence using CBCT	2025, 2024	Accurate diagnosis of periapical pathology underestimated by conventional radiographs
[162]	Evaluation of obturation techniques in primary molars using CBCT	2025	Demonstrated CBCT's utility in 3D assessment of obturation in primary teeth
[163]	Evaluation of canal configuration in maxillary first molars with CBCT	2024	Accurate follow-up of retreatment and residual filling material quantification

6.2. Micro-Computed Tomography (micro-CT)

Micro-computed tomography (micro-CT) is a non-destructive imaging modality that provides high-resolution three-dimensional (3D) reconstructions of dental structures. With a voxel size ranging from 5–50 μm —approximately one million times smaller in volumetric resolution than conventional CT—micro-CT enables detailed multiplanar visualization of the entire tooth [168]. Developed in the early 1980s, the technique is based on convergence of X-ray beams onto the specimen, which are subsequently digitized to generate volumetric datasets [169]. Compared with CBCT, micro-CT offers superior resolution, making it particularly valuable in endodontic research [170].

The advantages of micro-CT include minimal sample preparation, preservation of specimens, and reproducible evaluation without destructive sectioning. It has been extensively used to investigate dentinal cracks, root canal morphology, and material adaptation. Dentinal microcrack detection is influenced by voxel size and specimen hydration; excessive moisture can obscure cracks, whereas dehydration may induce artifacts, highlighting the need for careful specimen handling [171].

Micro-CT has also provided important insights into material performance and treatment outcomes. Applications include evaluation of sealing ability and marginal adaptation in furcation perforation repair, with assessment of porosity and gap formation that cannot be achieved through conventional microleakage tests [172]. It has been employed to quantify residual obturation material following retreatment [173], assess irrigant penetration using radiopaque contrast media (though this approach lacks the biological activity of NaOCl [174], and evaluate porosity distribution in orthograde mineral trioxide aggregate (MTA) obturations in curved canals, which may influence leakage risk [175].

Additional studies have investigated dentin bridge formation in pulp capping [176] and cleaning protocols aimed at enhancing post bond strength in canals filled with bioceramic sealers [173]. Despite these advantages, clinical translation of micro-CT remains limited due to high cost, significant radiation exposure, and long acquisition times, restricting its role primarily to research rather than routine practice [176]. A summary of recent studies utilizing micro-CT across different endodontic applications is presented in **Table 10**.

Table 10. Summary of recent studies utilizing Micro-CT in endodontics.

Study (Ref)	Title	Year	Significance
[177]	Brushing motion caused no microcracks: a micro-computed tomography study. Clin Oral Investig	2025	Demonstrated that brushing motion did not induce dentinal microcracks, using high-resolution micro-CT to visualize crack details, location, and extension.
[178]	Marginal adaptation and porosity of calcium silicate-based cements in furcation perforations: a micro-CT comparative study	2025	Evaluated sealing ability of different cements, quantifying marginal adaptation, porosity, and gap formation in furcation perforation repair.
[172]	Evaluation of Root Canal Cleaning and Irrigant Penetration Using Different Irrigation Protocols: A Combined SEM and Single-Tooth Micro-CT Study	2025	Assessed irrigant penetration depth and root canal cleanliness, highlighting differences between activation methods; required radiopaque contrast medium.
[174]	Mineral trioxide aggregate obturation quality with two obturation techniques in severe curved root canals – a micro-CT study	2024	Compared obturation quality of different MTA techniques, assessing porosity distribution in curved canals with implications for leakage risk.
[175]	Comparative Evaluation of Three Calcium Silicate-Based Materials for Direct Pulp Capping: An In Vivo Study in Mice	2025	Used micro-CT to evaluate dentin bridge formation, total volume, and internal voids to compare sealing ability of pulp capping materials.
[176]	Cleaning protocols to enhance bond strength of fiberglass posts on root	2025	Investigated cleaning efficiency and its impact on bond strength of fiber posts,

	canals filled with bioceramic sealer: an in vitro comparative study		with micro-CT providing 3D analysis of sealer removal.
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Magnetic resonance imaging (MRI) is a radiation-free modality that offers superior soft tissue visualization compared with X-ray-based techniques such as CT and CBCT. Unlike conventional radiographic methods that primarily capture hard tissues, MRI enables detailed evaluation of the dental pulp and periapical soft tissues [179].

MRI works by applying magnetic fields and radiofrequency pulses to excite hydrogen nuclei in tissues, which emit signals that are reconstructed into images. This allows accurate and non-invasive visualization of pulpal vitality, inflammation, and necrosis, making MRI a valuable adjunct to sensibility testing [177,180].

Although MRI provides excellent contrast resolution, its use is constrained by high cost, limited availability, and longer scan times compared with CBCT. Additional limitations include artifacts from metallic restorations, and challenges in patients with orthodontic appliances, implants, or claustrophobia [152,156,181]. Nevertheless, advances such as magnetic resonance microscopy have improved voxel resolution ($<100 \mu\text{m}^3$), enabling microscopic-level visualization of root canal anatomy [180].

In endodontics, MRI has shown potential for monitoring regenerative procedures, where it can non-invasively assess pulp vascularization and tissue responses without radiation exposure [177,182]. Furthermore, studies have reported its ability to detect periapical pathologies, distinguish cysts from granulomas, and characterize odontogenic versus non-odontogenic lesions. When combined with CBCT, MRI may provide complementary diagnostic information, particularly for lesions involving both hard and soft tissues [156,181].

A summary of recent studies utilizing MRI in endodontic applications is presented in **Table 11**.

Table 11. Summary of recent studies utilizing MRI in endodontics.

Study (Ref)	Title	Year	Significance
[179,180]	An update of the possible applications of magnetic resonance imaging (MRI) in dentistry: A literature review; Correlation between pulp sensibility and magnetic resonance signal intensity following regenerative endodontic procedures in mature necrotic teeth	2021, 2024	Explored dental MRI applications; demonstrated correlation between MRI signal intensity and pulp sensibility tests in regenerative endodontic procedures.
[157]	Endodontic working length measurements of premolars and molars in high-resolution dental MRI: a clinical pilot	2022	Confirmed MRI's ability to provide reliable working length

	study for assessment of reliability and accuracy		measurements comparable to CBCT.
[177]	Magnetic resonance imaging in the diagnosis of periodontal and periapical disease	2023	Demonstrated MRI's potential to characterize radicular cysts and granulomas with slight overestimation of lesion dimensions, showing reliability comparable to histopathology.

6.3. Ultrasound

Ultrasound (US) is a non-invasive, radiation-free modality widely used in the dento-facial region for assessing soft tissue structures such as salivary glands, tongue, and periapical lesions [153,183]. Echography, or ultrasonography, relies on the transmission of high-frequency sound waves, which are reflected by tissues and processed into real-time images [152].

In endodontics, US has shown high sensitivity and specificity in differentiating periapical cysts from granulomas. The use of color-power Doppler (CPD) enhances diagnostic capability by assessing lesion vascularity: cysts typically appear as well-contoured, anechoic cavities without vascularity, whereas granulomas show echogenicity and detectable blood flow on CPD [152].

Key advantages include the extraoral application of probes, which avoids the need for intraoral radiographic films. This is particularly beneficial in cases with limited mouth opening, severe infection, or posterior lesions [183]. However, limitations include difficulties in linking images to specific teeth, acoustic shadowing at bony borders, inability to assess intrabony lesions, and reliance on operator skill [184]. Conventional US probes are relatively large and suited for extraoral use, while smaller intraoral "hockey stick" probes allow improved lesion orientation but remain restricted in cases of shallow vestibules, thick cortical bone, or palatal defects [153].

Although not yet a routine diagnostic tool, systematic reviews support the potential of ultrasound as a valuable adjunct for differentiating periapical pathologies, complementing conventional radiography and CBCT [183].

7. Conclusion and Future Perspectives

Endodontics is undergoing a paradigm shift from traditional root canal treatment toward biologically regenerative and digitally integrated therapies. Emerging technologies—including nanotechnology, microrobotics, 3D printing, artificial intelligence, and smart stimuli-responsive biomaterials—are redefining how clinicians approach disinfection, regeneration, and long-term tooth preservation. These innovations have demonstrated promising results in experimental and preclinical settings, but significant translational barriers remain.

Future research should prioritize standardization of evaluation frameworks to ensure reproducibility across *in vitro*, *ex vivo*, and *in vivo* studies. Integration of multimodal imaging and navigation systems for real-time clinical translation of microrobotics. Development of hybrid biomaterials that combine mechanical resilience with tailored bioactivity for pulp-dentin regeneration. Ethical and regulatory alignment, particularly for AI-driven diagnostics and microrobotic interventions. Long-term clinical trials that incorporate patient-centered outcomes, including vitality restoration, quality of life, and cost-effectiveness. By bridging cutting-edge

biomaterials with digital and robotic platforms, regenerative endodontics can serve as a model discipline within advanced healthcare materials, illustrating how interdisciplinary science translates into precision, sustainable, and patient-centered care.

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