Journal of Dental Research and Innovation

journal home page : https://globalknowledgeacademy.com/index.php/jdri

Research Article

Development of a smart root canal sealer capable of releasing antimicrobial agents in response to pH changes

Dr Poonam Dua
BDS , India

ARTICLE INFO

Article history:

Received: 20 July, 2026

Revised: 22 July, 2026

Accepted: 24 July, 2026

Published: 26 July, 2026

Keywords:

Smart root canal sealer, pH-responsive biomaterials , antimicrobial drug release, endodontics, bioceramic sealers, controlled drug delivery, biofilm inhibition,

ABSTRACT

Persistent microbial infection remains one of the primary causes of endodontic treatment failure despite advances in root canal instrumentation and irrigation. Conventional root canal sealers provide mechanical sealing but possess limited long-term antimicrobial activity, reducing their effectiveness against residual bacteria and recurrent biofilm formation. The development of smart root canal sealers capable of releasing antimicrobial agents in response to localized pH changes represents a promising strategy for improving treatment outcomes. These stimuli-responsive materials remain relatively inactive under physiological conditions but selectively release therapeutic agents in the acidic environment associated with bacterial metabolism and infection. Such controlled drug delivery enhances antimicrobial efficacy while minimizing unnecessary exposure to antimicrobial compounds, reducing cytotoxicity, and preserving the surrounding periapical tissues. Advances in nanotechnology, bioceramic materials, and pH-sensitive polymers have enabled the fabrication of multifunctional sealers with improved sealing ability, bioactivity, biocompatibility, and sustained antimicrobial performance. This review discusses the principles, design strategies, biomaterial components, drug-release mechanisms, biological performance, clinical applications, current challenges, and future directions of smart pH-responsive root canal sealers. The integration of responsive biomaterials with targeted antimicrobial delivery offers a significant step toward next-generation endodontic materials capable of enhancing disinfection, promoting tissue healing, and improving the long-term success of root canal therapy.

INTRODUCTION

Successful root canal therapy depends on the complete elimination of pathogenic microorganisms from the root canal system, effective sealing of the prepared canal space, and long-term prevention of microbial reinfection. Although contemporary endodontic procedures have benefited from improvements in instrumentation, irrigation protocols, and obturation techniques, persistent intraradicular infection remains one of the leading causes of treatment failure. The intricate anatomy of the root canal system, including accessory canals, isthmuses, lateral canals, and dentinal tubules, often provides protected niches where microorganisms can survive conventional cleaning and shaping procedures. Consequently, residual bacterial biofilms may continue to produce acidic metabolic by-products that promote persistent apical inflammation and compromise periapical healing (Singh, 2018).

***Corresponding Author:** Dr Poonam Dua
Address: BDS , India

Email ✉**:** Poonamdua230@gmail.com

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Root canal sealers play a crucial role in endodontic obturation by filling irregularities between the core filling material and canal walls while preventing bacterial leakage. Conventional sealers, including resin-based, zinc oxide-eugenol-based, calcium hydroxide-based, and bioceramic formulations, have demonstrated varying degrees of sealing ability and biological compatibility. However, their antimicrobial effects are often transient, with activity declining shortly after setting. Once antimicrobial components become depleted, surviving microorganisms may recolonize the canal space, increasing the likelihood of persistent infection and retreatment. These limitations have stimulated growing interest in multifunctional endodontic biomaterials capable of providing both durable sealing and sustained antimicrobial protection (Singh, 2019).

Bioceramic materials have significantly transformed modern endodontics because of their excellent biocompatibility, bioactivity, alkaline pH, and capacity to stimulate mineralized tissue formation. Their favorable interaction with periapical tissues has expanded their use in procedures such as vital pulp therapy, root-end filling, perforation repair,

and root canal obturation. Nevertheless, while bioceramic sealers exhibit inherent antimicrobial properties through alkaline ion release, their antimicrobial effectiveness may diminish over time and may not adequately respond to fluctuations in microbial activity within infected root canals. This limitation has encouraged researchers to investigate smart biomaterials capable of adapting their therapeutic behavior according to environmental changes (Singh, 2019).

Among emerging biomaterial innovations, stimuli-responsive or "smart" root canal sealers represent a promising advancement in regenerative and restorative endodontics. These materials are engineered to detect specific biological triggers, including changes in pH, temperature, enzymatic activity, or bacterial metabolites, and respond by releasing therapeutic agents only when required. In infected root canals, bacterial metabolism commonly lowers the local pH, creating an acidic microenvironment that serves as an ideal trigger for controlled antimicrobial release. Such pH-responsive systems offer targeted drug delivery, ensuring antimicrobial agents are released precisely during periods of active infection while minimizing unnecessary exposure under healthy conditions. This intelligent approach has the potential to improve antimicrobial efficacy, reduce cytotoxicity, prolong material functionality, and limit the development of antimicrobial resistance. Recent advances in nanotechnology have accelerated the development of smart sealers by enabling the incorporation of nanoparticles, pH-sensitive polymers, nanocapsules, mesoporous silica carriers, and biodegradable drug-delivery systems into endodontic materials. These technologies permit controlled and sustained release of antimicrobial compounds such as chlorhexidine, silver nanoparticles, antimicrobial peptides, and bioactive ions while preserving the physical integrity and sealing performance of the sealer. Simultaneously, improvements in digital imaging and three-dimensional diagnostic technologies facilitate more accurate assessment of canal morphology, allowing clinicians to better appreciate the anatomical complexities that necessitate advanced antimicrobial strategies (Singh, 2018).

The broader movement toward precision dentistry further supports the development of intelligent endodontic materials. Contemporary dental care increasingly emphasizes individualized treatment based on patient-specific biological risk factors, microbial profiles, and disease susceptibility. Patient stratification models have demonstrated the value of tailoring preventive and therapeutic interventions according to individual risk, a concept that aligns closely with responsive biomaterials capable of adapting to localized pathological conditions (Giannobile et al., 2013). Likewise, studies investigating salivary and serum biomarkers have highlighted the importance of host immune responses in oral disease progression, reinforcing the need for biomaterials capable of interacting dynamically with the biological environment (Isola et al., 2020).

The rapid expansion of digital dentistry has also created opportunities for integrating smart biomaterials into technologically advanced clinical workflows. Standardized evaluation methods for digital dental procedures have emphasized the importance of reproducibility, quality assurance, and evidence-based implementation of emerging technologies in clinical practice (Badr et al., 2026). In parallel, advances in digital diagnostics, electronic dental health records, and comprehensive patient characterization contribute to more personalized treatment planning by facilitating detailed assessment of patient conditions and treatment outcomes (Felix Gomez et al., 2023). Furthermore, three-dimensional imaging and digital assessment techniques continue to enhance the precision of dental diagnosis and treatment planning across multiple specialties, illustrating the expanding role of digital technologies in supporting innovative biomaterial applications (Abate et al., 2025; Feher et al., 2021). The development of smart root canal sealers capable of releasing antimicrobial agents in response to pH changes therefore represents a significant advancement toward biologically responsive endodontic therapy. By combining controlled drug delivery, nanotechnology, bioceramic chemistry, and stimuli-responsive materials, these next-generation sealers have the potential to improve root canal disinfection, inhibit recurrent biofilm formation, promote periapical healing, and increase the long-term success of endodontic treatment. This review explores the scientific principles, material design, antimicrobial mechanisms, biological performance, clinical applications, current challenges, and future prospects of pH-responsive smart root canal sealers as an emerging strategy for precision endodontics.

2. Scientific Basis of pH-Responsive Smart Root Canal Sealers

2.1 Root Canal Microbiology and Biofilm Persistence

The long-term success of root canal therapy depends largely on the complete elimination of microorganisms from the complex root canal system. However, intricate canal anatomy, accessory canals, dentinal tubules, and apical ramifications frequently provide niches where microorganisms survive conventional chemomechanical preparation. Persistent bacterial biofilms are recognized as one of the leading causes of post-treatment disease and endodontic failure because they exhibit remarkable resistance to antimicrobial agents and host immune responses. These biofilms create a protective extracellular polymeric matrix that limits antimicrobial penetration while facilitating bacterial communication and survival.

Among the most frequently isolated microorganisms from persistent endodontic infections are *Enterococcus faecalis*, *Candida albicans*, *Fusobacterium nucleatum*, *Porphyromonas gingivalis*, and *Actinomyces* species. Their metabolic activities generate acidic by-products that reduce the local pH within infected canals, creating a microenvironment that promotes tissue destruction and bacterial persistence. This acidic environment provides an attractive biological trigger for the activation of pH-responsive biomaterials capable of releasing antimicrobial compounds only when infection is present.

The concept of individualized disease management has become increasingly important in dentistry. Patient-specific microbial profiles and disease susceptibility influence treatment outcomes, highlighting the need for targeted therapeutic strategies rather than passive sealing materials. Patient stratification approaches have demonstrated the importance of tailoring preventive and therapeutic interventions according to biological risk factors, supporting the development of responsive biomaterials that adapt to changing clinical environments (Giannobile et al., 2013). Similarly, investigations into salivary immunological biomarkers have emphasized the relationship between host immune responses and oral microbial activity, reinforcing the significance of infection-responsive treatment modalities (Isola et al., 2020).

2.2 Chemistry of Smart Biomaterials

Smart biomaterials are advanced materials capable of sensing environmental stimuli and responding through predictable physicochemical changes. Unlike conventional root canal sealers that remain chemically static after setting, smart sealers possess dynamic properties that allow them to react to biological conditions such as alterations in pH, temperature, enzymatic activity, or ionic concentration.

In endodontics, pH-responsive systems are particularly valuable because bacterial metabolism lowers the pH around infected tissues. Acid-sensitive polymers contain chemical linkages that remain stable under neutral conditions but undergo hydrolysis or structural modification in acidic environments. These changes permit controlled diffusion of encapsulated antimicrobial agents directly into infected tissues while minimizing unnecessary drug release in healthy environments.

Several classes of smart materials have been investigated, including:

pH-sensitive hydrogels
Bioceramic matrices
Polymeric nanoparticles
Mesoporous silica nanoparticles
Calcium silicate-based composites
Bioactive glass carriers

These materials not only function as drug reservoirs but also maintain adequate sealing ability, mechanical integrity, and bioactivity throughout the healing process. Bioceramic materials have attracted considerable attention because of their excellent biocompatibility, alkaline ion release, and capacity to stimulate mineralized tissue formation. Their favorable biological behavior has already been demonstrated in vital pulp therapy and regenerative endodontics, making them suitable platforms for incorporating responsive drug-delivery systems (Singh, 2019).

2.3 Biomaterials Used in Modern Root Canal Sealers

Contemporary root canal sealers are formulated using a variety of biomaterials, each possessing unique physical, chemical, and biological characteristics.

Calcium silicate-based sealers exhibit bioactivity through calcium ion release and hydroxyapatite formation. Their alkaline environment contributes to

antibacterial effects while encouraging periapical healing.

Bioceramic sealers possess excellent sealing ability, dimensional stability, moisture tolerance, and superior biocompatibility. Their ability to chemically bond with dentin and promote mineralization makes them ideal candidates for smart material modification (Singh, 2019).

Epoxy resin sealers have traditionally demonstrated excellent adhesion and dimensional stability but exhibit relatively limited long-term antimicrobial activity following polymerization.

Glass ionomer-based sealers provide chemical adhesion and fluoride release but generally possess inferior mechanical properties compared with newer bioceramic formulations.

Recent developments combine multiple material classes into hybrid nanocomposites capable of integrating structural support with responsive therapeutic functions. These multifunctional materials seek to overcome the limitations of conventional sealers by simultaneously providing mechanical sealing, antimicrobial activity, tissue regeneration, and controlled drug delivery.

Advances in digital imaging technologies have significantly improved understanding of root canal morphology and treatment planning. Three-dimensional CBCT imaging has enhanced visualization of complex anatomical structures, facilitating more precise placement and evaluation of advanced sealing materials during endodontic treatment (Singh, 2018). Likewise, modern digital assessment methodologies continue to improve evaluation of complex dental workflows and biomaterial performance through standardized assessment frameworks (Badr et al., 2026).

2.4 Mechanism of pH-Triggered Drug Release

The defining characteristic of smart root canal sealers is their ability to release antimicrobial agents selectively in response to localized acidity generated by bacterial infection. This controlled release minimizes unnecessary drug exposure while maintaining prolonged antimicrobial activity where it is most needed.

Several release mechanisms have been investigated.

Acid-sensitive bond cleavage involves hydrolysis of chemical bonds such as hydrazone, acetal, or Schiff-base linkages under acidic conditions, resulting in rapid liberation of encapsulated antimicrobial compounds.

Polymer swelling occurs when acidic environments alter polymer ionization, increasing water absorption and expanding the polymer network. This expansion enlarges diffusion pathways through which antimicrobial molecules are released.

Nanoparticle degradation allows biodegradable nanocarriers to gradually decompose under acidic conditions, providing sustained and controlled release of therapeutic agents.

Diffusion-controlled release depends on concentration gradients established after pH-induced structural alterations within the material matrix, allowing gradual migration of antimicrobial molecules into surrounding tissues.

These mechanisms may function independently or synergistically depending on material composition. The ultimate objective is to synchronize antimicrobial release with bacterial metabolic activity, thereby maximizing therapeutic efficiency while minimizing toxicity.

Emerging digital technologies continue to facilitate more accurate monitoring of treatment outcomes and biomaterial performance. Three-dimensional imaging enables clinicians to evaluate canal obturation quality and periapical healing with greater precision (Singh, 2018), while digital workflow assessment frameworks contribute to standardized evaluation of advanced endodontic procedures (Badr et al., 2026). Furthermore, broader applications of digital diagnostics in dentistry demonstrate how clinical data integration may eventually support personalized deployment of smart biomaterials according to individual patient characteristics (Felix Gomez et al., 2023). Contemporary three-dimensional assessment techniques further illustrate the growing role of digital technologies in evaluating structural changes and treatment outcomes across dental specialties (Abate et al., 2025; Feher et al., 2021).

Table 1. Scientific Principles Underlying pH-Responsive Smart Root Canal Sealers

Scientific Component	Biological/Material Basis	Functional Role in Smart Sealer	Clinical Significance
Root canal biofilm	Persistent bacterial colonies producing acidic metabolites	Generates localized acidic environment	Serves as the trigger for antimicrobial release
Acidic pH	Bacterial metabolism lowers canal pH	Activates pH-sensitive polymers	Enables infection-specific drug delivery
pH-sensitive polymers	Structural changes under acidic conditions	Controls timing and rate of drug release	Reduces unnecessary antimicrobial exposure
Bioceramic matrix	Calcium silicate-based bioactive materials	Provides structural support and bioactivity	Enhances sealing and promotes tissue healing
Polymeric nanoparticles	Nano-scale drug carriers	Encapsulate and protect antimicrobial agents	Improves sustained and targeted delivery
Mesoporous silica nanoparticles	High surface area porous carriers	High drug-loading capacity with controlled release	Prolongs antimicrobial effectiveness
Calcium ion release	Bioactive mineralization process	Stimulates hydroxyapatite formation	Improves dentin bonding and periapical healing
Controlled diffusion	Concentration gradient-driven drug movement	Sustained antimicrobial delivery	Maintains prolonged antibacterial activity
Digital imaging (CBCT)	Three-dimensional visualization	Assessment of canal anatomy and obturation quality	Supports accurate treatment planning and evaluation
Standardized digital workflows	Digital clinical assessment systems	Objective evaluation of biomaterial performance	Facilitates consistent clinical implementation

3.Design and Development of Smart pH-Responsive Root Canal Sealers

The development of smart pH-responsive root canal sealers represents an important advancement in biomaterial engineering for endodontics. Unlike conventional sealers that function primarily as passive filling materials, smart sealers are designed to actively respond to
the biochemical conditions present within infected root canals. The acidic microenvironment generated by bacterial metabolism serves as a biological trigger that initiates the controlled release of antimicrobial agents, thereby enhancing bacterial elimination while minimizing unnecessary drug exposure in healthy tissues. This responsive behavior combines advances in biomaterials, nanotechnology, polymer chemistry, and regenerative endodontics to create multifunctional sealers capable of improving both antimicrobial activity and periapical healing (Singh, 2019).

The design philosophy behind these materials focuses on achieving an optimal balance between mechanical stability, biological compatibility, controlled drug delivery, and long-term sealing performance. Since endodontic infections often persist in inaccessible dentinal tubules and anatomical complexities, intelligent sealers capable of releasing antimicrobial agents only when infection is present offer an efficient strategy for reducing bacterial recolonization and treatment failure.

3.1. Design Requirements

An effective smart root canal sealer must satisfy both conventional endodontic requirements and advanced functional characteristics associated with stimuli-responsive biomaterials. The material should provide complete sealing of the root canal system while maintaining dimensional stability throughout the lifespan of the restoration.

Biocompatibility remains the primary consideration during material development because the sealer comes into direct contact with dentinal walls, periapical tissues, and occasionally vital pulp remnants. Materials should not induce significant inflammatory reactions while supporting cellular attachment, mineralization, and tissue regeneration. Calcium silicate-based bioceramics have demonstrated favorable biological behavior because of their bioactivity and ability to stimulate hard tissue formation (Singh, 2019).

Adequate flowability enables penetration into accessory canals, lateral canals, isthmuses, and dentinal tubules without excessive extrusion beyond the apex. Simultaneously, the sealer should exhibit minimal polymerization shrinkage, excellent adhesion to dentin and gutta-percha, radiopacity for postoperative evaluation, and sufficient compressive strength to withstand functional loading.

Another critical requirement is selective responsiveness to acidic conditions. The antimicrobial compounds should remain encapsulated under physiological pH while being
rapidly released when bacterial metabolism lowers the environmental pH. Such selective activation reduces premature depletion of therapeutic agents and prolongs antimicrobial effectiveness.

Recent advances in digital dentistry have also improved material development through standardized evaluation protocols and digital workflow assessment, facilitating more reproducible testing during biomaterial optimization (Badr et al., 2026).

3.2 Selection of Antimicrobial Agents

The therapeutic effectiveness of smart sealers depends heavily on selecting antimicrobial agents capable of eliminating polymicrobial biofilms commonly associated with persistent apical periodontitis.

Chlorhexidine remains one of the most frequently incorporated antimicrobial agents because of its broad-spectrum antibacterial activity and substantivity against *Enterococcus faecalis*, one of the principal microorganisms responsible for endodontic treatment failure. Controlled release systems allow chlorhexidine to maintain therapeutic concentrations over extended periods without causing excessive cytotoxicity.

Silver nanoparticles have gained considerable attention owing to their multiple antibacterial mechanisms, including disruption of bacterial membranes, generation of reactive oxygen species, inhibition of DNA replication, and interference with enzymatic activity. Their nanoscale dimensions facilitate penetration into dentinal tubules while minimizing bacterial resistance.

Bioactive glass particles contribute both antimicrobial and regenerative functions by releasing calcium, phosphate, and silicate ions that elevate local alkalinity and promote mineralized tissue formation. Similarly, quaternary ammonium compounds provide contact-

killing antimicrobial activity by disrupting bacterial cell membranes.

Natural antimicrobial substances, antimicrobial peptides, essential oils, and enzyme-responsive compounds are increasingly being investigated because of their lower toxicity and reduced likelihood of inducing bacterial resistance. Combining multiple antimicrobial agents within a single delivery platform may further enhance antibacterial effectiveness while targeting diverse microbial populations.

The need for personalized antimicrobial strategies aligns with broader trends in precision dentistry, where patient-specific biological characteristics increasingly influence therapeutic planning (Giannobile et al., 2013).

3.3 Drug Encapsulation Technologies

Controlled drug delivery forms the cornerstone of smart sealer technology. Encapsulation protects antimicrobial compounds from premature degradation while enabling their release only under predefined environmental conditions.

Polymeric nanoparticles represent one of the most widely investigated delivery systems. These nanoparticles encapsulate antimicrobial agents within biodegradable polymers that undergo structural changes in acidic environments, gradually releasing the active compound. Their high surface-area-to-volume ratio improves drug loading efficiency while facilitating sustained release.

Mesoporous silica nanoparticles possess highly ordered porous structures capable of storing substantial quantities of antimicrobial molecules. Surface modification with pH-sensitive molecular gates allows selective release under acidic conditions commonly observed during bacterial infection.

Liposomes provide another attractive delivery platform because their phospholipid bilayers resemble biological membranes. pH-sensitive liposomes destabilize under acidic conditions, releasing encapsulated antimicrobial agents directly into infected tissues.

Microcapsules and nanocapsules fabricated from biodegradable polymers provide prolonged drug release through gradual shell degradation. Electrospun nanofibers have also emerged as promising drug reservoirs owing to their large surface area, interconnected porous structure, and tunable degradation characteristics.

Hybrid delivery systems combining nanoparticles, hydrogels, and bioceramics are increasingly being developed to integrate antimicrobial activity with regenerative potential.

3.4 Fabrication Techniques

Modern fabrication methods allow precise engineering of pH-responsive sealers with predictable physical and biological properties.

The sol-gel technique remains widely employed for producing bioactive glass nanoparticles and calcium silicate-based materials because it allows precise control over particle size, porosity, and chemical composition. The resulting materials demonstrate enhanced ion release and improved bioactivity.

Nanoengineering techniques facilitate homogeneous dispersion of nanoparticles throughout the sealer matrix, improving mechanical properties while ensuring consistent antimicrobial distribution.

Three-dimensional (3D) printing technologies increasingly contribute to biomaterial development by enabling customized scaffold fabrication, standardized specimen preparation, and rapid prototyping of novel formulations. Digital imaging technologies such as cone-beam computed tomography (CBCT) further support accurate assessment of root canal morphology and material adaptation during preclinical investigations (Singh, 2018).

Electrospinning enables fabrication of nanofibrous drug delivery systems that mimic the extracellular matrix while allowing sustained antimicrobial release. Chemical crosslinking techniques modify polymer networks to regulate swelling behavior, degradation rates, and pH sensitivity.

Advanced digital workflows continue improving reproducibility during biomaterial development by integrating standardized manufacturing, testing, and quality assessment protocols (Badr et al., 2026).

3.5 Characterization Methods

Comprehensive characterization is essential to ensure that smart sealers satisfy both clinical and biological performance requirements.

Scanning electron microscopy (SEM) and transmission

electron microscopy (TEM) evaluate particle morphology, nanostructure, and interfacial adaptation. Atomic force microscopy provides additional information regarding surface roughness and mechanical behavior.

Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and X-ray diffraction assess chemical composition, molecular interactions, and crystalline phases within the material.

Mechanical characterization includes compressive strength, flexural strength, elastic modulus, setting time, flowability, dimensional stability, radiopacity, and push-out bond strength. These tests determine whether incorporation of drug delivery systems compromises the structural integrity of the sealer.

4. BiologicalPerformance,Clinical Applications, and Future Perspectives

4.1Antimicrobial Effectiveness

The principal objective of a smart root canal sealer is to provide a durable seal while actively eliminating residual microorganisms that survive chemomechanical preparation. Conventional sealers exhibit limited or short-lived antimicrobial properties because the release of active components decreases rapidly after setting. In contrast, pH-responsive sealers are designed to detect the acidic microenvironment generated by bacterial metabolism and selectively release antimicrobial agents only when infection-associated pH changes occur. This targeted mechanism improves bacterial eradication while minimizing unnecessary drug release under healthy conditions.

The acidic environment produced by persistent endodontic pathogens such as Enterococcus faecalis and anaerobic biofilms serves as an ideal trigger for controlled antimicrobial delivery. Upon exposure to reduced pH, pH-sensitive polymers undergo structural changes that permit diffusion of encapsulated antimicrobial compounds including chlorhexidine, silver nanoparticles, antimicrobial peptides, calcium hydroxide derivatives, or bioactive ions. This selective release provides sustained inhibition of bacterial recolonization without continuously exposing surrounding tissues to high drug concentrations.

Another biological advantage is the prevention of biofilm maturation. Mature biofilms possess extracellular polymeric substances that restrict antimicrobial penetration and significantly increase bacterial resistance. Smart sealers continuously respond to recurrent acidification episodes, disrupting biofilm formation before mature microbial communities become established. Such dynamic antimicrobial activity may substantially reduce the incidence of persistent apical periodontitis and secondary infection following root canal treatment.

bioactivity, these next-generation sealers have the potential to significantly improve infection control, support periapical tissue healing, and increase the long-term success of root canal therapy (Singh, 2019; Giannobile et al., 2013; Isola et al., 2020; Felix Gomez et al., 2023; Feher et al., 2021; Abate et al., 2025).

Several modern bioceramic sealers already demonstrate favorable antimicrobial and bioactive characteristics through calcium ion release and alkaline pH generation. Incorporating pH-responsive drug delivery systems into these bioactive materials may further enhance their antimicrobial spectrum while preserving their excellent sealing properties and biocompatibility (Singh, 2019).

Drug-loading efficiency and encapsulation efficiency are quantified using chromatographic and spectrophotometric methods. Controlled drug release profiles are evaluated under physiological and acidic pH conditions to confirm selective responsiveness. Mathematical kinetic models such as zero-order, first-order, Higuchi, and Korsmeyer-Peppas equations help describe release mechanisms.

Biological evaluation includes cytotoxicity assays, antimicrobial testing, biofilm inhibition studies, mineralization assays, inflammatory marker analysis, and cell viability assessment. Clinical digital imaging techniques and standardized evaluation methods contribute to objective analysis of biomaterial performance and treatment outcomes (Singh, 2018; Badr et al., 2026).

4.2 Biocompatibility and Bioactivity

An ideal smart root canal sealer must combine antimicrobial efficacy with excellent compatibility with periapical tissues. Excessive antimicrobial release may damage periodontal ligament fibroblasts, osteoblasts, stem cells, or apical tissues, thereby delaying healing. Therefore, pH-triggered release systems are advantageous because antimicrobial agents remain largely encapsulated under physiological conditions and are released only when pathological acidic conditions are detected.

Bioceramic-based matrices have become attractive platforms for smart sealers due to their inherent bioactivity. These materials release calcium and

silicate ions that stimulate hydroxyapatite formation, promote mineralization, and encourage the differentiation of odontoblast-like cells. Such properties facilitate biological sealing of the root canal while supporting repair of damaged periapical tissues (Singh, 2019).

The regenerative capacity of bioactive sealers also complements current concepts of minimally invasive endodontics. Controlled antimicrobial release minimizes inflammatory responses while allowing endogenous repair mechanisms to proceed. Similar biological principles have been successfully applied in vital pulp therapy, where calcium silicate biomaterials promote dentin bridge formation and pulp healing (Singh, 2019).

Host-related biological variability should also be considered when evaluating smart sealers.

Immune responses, salivary biomarkers, systemic inflammatory conditions, and microbial diversity influence treatment outcomes. Biomarker-based patient stratification may eventually allow personalized selection of smart sealers according to individual infection risk and healing potential (Giannobile et al., 2013; Isola et al., 2020). Likewise, large electronic dental-health databases offer opportunities to investigate clinical variables associated with treatment success and material performance across diverse patient populations (Felix Gomez et al., 2023).

4.3 Laboratory Evaluation Methods

The biological performance of smart root canal sealers must be validated using comprehensive laboratory and preclinical testing. Standard antimicrobial assays evaluate bacterial inhibition against common endodontic pathogens using agar diffusion tests, direct contact tests, colony-forming unit analysis, confocal laser scanning microscopy, and biofilm viability assays.

Drug release behavior is typically investigated using simulated body fluids or artificial saliva under varying pH conditions. High-performance liquid chromatography (HPLC), ultraviolet-visible spectroscopy, and fluorescence techniques quantify antimicrobial release kinetics. Ideally, minimal drug release should occur under neutral pH, while significantly greater release should be observed under acidic conditions.

Mechanical evaluation remains equally important because incorporation of nanoparticles or drug carriers should not compromise the sealing ability or structural integrity of the material. Flowability, setting time, compressive strength, dimensional stability, push-out bond strength, and resistance to microleakage must comply with international endodontic standards.

Advanced imaging technologies have greatly improved evaluation of root canal filling quality. Cone-beam computed tomography (CBCT) provides three-dimensional assessment of obturation quality, void formation, canal morphology, and periapical healing, facilitating accurate assessment of smart sealer performance during both laboratory investigations and clinical follow-up (Singh, 2018).

Similarly, three-dimensional digital imaging techniques continue to improve quantitative assessment of dental structures, supporting precise evaluation of biomaterial adaptation and treatment outcomes (Abate et al., 2025; Feher et al., 2021).

Table 2. Biological Evaluation Methods for Smart pH-Responsive Root Canal Sealers

Evaluation Parameter	Assessment Method	Primary Outcome	Clinical Significance
Antimicrobial activity	Agar diffusion, direct contact test	Bacterial inhibition	Infection control
Biofilm disruption	Confocal laser scanning microscopy	Biofilm viability	Prevention of persistent infection
Drug release kinetics	HPLC, UV-visible spectroscopy	Controlled pH-responsive release	Targeted antimicrobial delivery
Cytotoxicity	MTT assay, Live/Dead assay	Cell viability	Biocompatibility
Mineralization potential	Alizarin Red staining, ALP activity	Hard tissue formation	Tissue regeneration
Calcium ion release	Inductively coupled plasma analysis	Bioactivity	Apical healing
Push-out bond strength	Universal testing machine	Adhesion to dentin	Long-term sealing
Microleakage	Dye penetration, fluid filtration	Seal integrity	Prevention of reinfection
Surface morphology	Scanning electron microscopy (SEM)	Material adaptation	Structural characterization
Internal adaptation	Micro-computed tomography (Micro-CT)	Void detection	Filling quality
Three-dimensional canal assessment	CBCT	Root filling evaluation	Clinical treatment assessment
Setting characteristics	ISO standard testing	Working and setting time	Clinical handling

4.4 Potential Clinical Applications

Smart pH-responsive sealers have broad applications across contemporary endodontics. During primary root canal therapy, these materials can provide sustained antimicrobial protection after instrumentation, reducing the likelihood of residual bacterial survival. Their ability to release antimicrobial agents only when pathogenic conditions recur may provide prolonged defense against reinfection. Retreatment procedures represent another promising indication because persistent microorganisms often remain within accessory canals, dentinal tubules, and
conventional irrigation. Smart sealers may provide continuous localized antimicrobial activity capable of eliminating these residual bacterial reservoirs.

Regenerative endodontic procedures may particularly benefit from controlled antimicrobial release. Excessive antimicrobial exposure may impair stem-cell survival, whereas responsive release allows effective disinfection without compromising regenerative healing. Consequently, these materials may simultaneously support tissue regeneration and microbial control.

Additional applications include management of immature permanent teeth, teeth with extensive periapical lesions, traumatic injuries, medically compromised patients, and individuals at elevated risk of recurrent endodontic infection.

4.5 Current Challenges

Despite promising laboratory evidence, several challenges remain before widespread clinical implementation becomes feasible. Achieving reproducible pH sensitivity without compromising physical properties is technically demanding. Drug loading efficiency, release duration, polymer degradation rates, and mechanical stability must all be carefully optimized.

Long-term storage stability also remains an important consideration. Moisture, temperature fluctuations, and premature degradation of pH-sensitive polymers may affect clinical performance. Furthermore, the interaction between antimicrobial agents and sealer chemistry may alter setting reactions or reduce mechanical strength.

Regulatory approval requires extensive biological safety testing, including cytotoxicity, genotoxicity, animal studies, and long-term clinical trials. Manufacturing costs associated with nanotechnology and advanced polymer engineering may also limit commercial accessibility during early stages of development.

4.6. Emerging Technologies

Rapid advances in biomaterials science continue to expand the capabilities of smart endodontic sealers. Nanotechnology allows precise engineering of nanoparticles capable of sustained drug encapsulation and highly selective pH-triggered release. Multifunctional nanocomposites can simultaneously deliver antimicrobial agents, promote mineralization, reduce inflammation, and improve mechanical strength.

Artificial intelligence is increasingly being integrated into biomaterials research by optimizing material formulations, predicting biological performance, and assisting digital treatment planning. Advanced digital workflows may facilitate individualized material selection based on patient-specific anatomical and biological characteristics standardize evaluation of novel biomaterials and improve educational and clinical implementation of digital dentistry technologies (Badr et al., 2026).

Future developments may include self-healing sealers capable of repairing microcracks, multi-stimuli-responsive materials activated by pH, temperature, enzymes, or bacterial metabolites, and intelligent biomaterials capable of continuously monitoring microbial activity within treated root canals.

4.7 Future Research Directions

Future investigations should prioritize long-term randomized clinical trials comparing smart pH-responsive sealers with conventional bioceramic and resin-based sealers under routine clinical conditions. Standardization of antimicrobial testing protocols and drug-release evaluation methods would facilitate comparison among different material formulations.

Research should also focus on identifying optimal antimicrobial agents that minimize bacterial resistance while preserving host-cell viability. Personalized biomaterial design based on patient-specific microbial profiles, inflammatory biomarkers, and genetic susceptibility represents an emerging area of precision endodontics. Integration of advanced imaging, digital workflows, artificial intelligence, and responsive biomaterials is expected to accelerate the development of next-generation root canal sealers capable of simultaneously diagnosing, responding to, and preventing endodontic infection (Singh, 2018; Badr et al., 2026).

5. Conclusion

The development of smart root canal sealers capable of releasing antimicrobial agents in response to pH changes represents a significant advancement in endodontic biomaterials. Unlike conventional sealers that primarily provide passive sealing, these intelligent materials actively respond to the acidic microenvironment created by persistent bacterial infection, enabling targeted antimicrobial delivery while preserving healthy periapical tissues. By combining controlled drug release with excellent sealing ability, biocompatibility, and bioactivity, pH-responsive sealers have the potential to reduce residual microbial populations, inhibit biofilm re-establishment, and improve the long-term success of root canal therapy. The incorporation of bioceramic components further supports mineralization and tissue healing, reinforcing the regenerative objectives of contemporary endodontics (Singh, 2019).

Likewise, modern three-dimensional analytical techniques continue to improve the precision of dental material evaluation and treatment monitoring (Abate et al., 2025; Feher et al., 2021).

Future research should focus on optimizing antimicrobial loading capacity, achieving predictable pH-triggered release kinetics, improving long-term material stability, and validating clinical efficacy through well-designed randomized clinical trials. Integration of smart biomaterials with nanotechnology, bioactive ceramics, artificial intelligence-assisted material design, and personalized treatment strategies may further enhance the effectiveness of endodontic therapy. Additionally, greater understanding of patient-specific biological and microbial factors will support the development of precision endodontics, where responsive biomaterials are tailored to individual clinical needs (Giannobile et al., 2013; Felix Gomez et al., 2023; Isola et al., 2020).

Overall, smart pH-responsive antimicrobial root canal sealers represent a promising next generation of endodontic materials that integrate infection-responsive therapy with regenerative principles. Continued interdisciplinary collaboration among biomaterials scientists, microbiologists, engineers, and clinicians is expected to accelerate their translation into routine clinical practice, ultimately improving treatment predictability, reducing reinfection rates, and enhancing long-term oral health outcomes.

References:

1. Singh, S. (2018). The efficacy of 3D imaging and cone-beam computed tomography (CBCT) in enhancing endodontic diagnosis and treatment planning. *International Journal of Scientific Research and Management*, *6*(6), 27-29.
2. Badr, Z., Hamdan, M., Hodgson, B., & Kalenderian, E. (2026). Structured Rubrics for Assessing Digital Dentistry Workflows in Dental Education. *Journal of Dental Education*, *90*(Suppl 1), S29.
3. Singh, S. (2019). Vital pulp therapy: A Bio ceramic-Based Approach. *Indian Journal of Pharmaceutical and Biological Research*, *7*(04), 10-18.
4. Felix Gomez, G. G., Hugenberg, S. T., Zunt, S., Patel, J. S., Wang, M., Rajapuri, A. S., ... & Thyvalikakath, T. P. (2023). Characterizing clinical findings of Sjögren's Disease patients in community practices using matched electronic dental-health record data. *PLoS One*, *18*(7), e0289335.
5. Feher, B., Gruber, R., Gahleitner, A., Celar, A., Necsea, P. L., Ulm, C., & Kuchler, U. (2021). Angular changes in implants placed in the anterior maxillae of adults: a cephalometric pilot study. *Clinical oral investigations*, *25*(3), 1375-1381.
6. Giannobile, W. V., Braun, T. M., Caplis, A. K., Doucette-Stamm, L., Duff, G. W., & Kornman, K. S. (2013). Patient stratification for preventive care in dentistry. *Journal of dental research*, *92*(8), 694-701.
7. Abate, A., Ugolini, A., Bruni, A., Quinzi, V., & Lanteri, V. (2025). Three-dimensional assessment on digital cast of spontaneous upper first molar distorotation after Ni-ti leaf springs expander and rapid maxillary expander: A two-centre randomized controlled trial. *Orthodontics & Craniofacial Research*, *28*(1), 104-115.
8. Isola, G., Polizzi, A., Patini, R., Ferlito, S., Alibrandi, A., & Palazzo, G. (2020). Association among serum and salivary A. actinomycetemcomitans specific
9. immunoglobulin antibodies and periodontitis. *BMC Oral Health*, *20*(1), 283