

Bioactive Restorative Materials Beyond Remineralization: Can Restorations Become Therapeutic Devices?

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Abstract

Bioactive restorative materials mark an important shift in restorative dentistry, moving beyond the replacement of lost tooth structure to materials that actively interact with dental tissues and the oral environment. This narrative review examined evidence published between 2021 and 2026 on ion release, remineralization, antibacterial activity, biofilm modulation, self-healing, and environmental responsiveness, and considered whether contemporary materials perform functions that extend beyond structural replacement. Ion-releasing systems modify the tooth-material interface and support remineralization of caries-affected tissue, while antibacterial formulations limit bacterial colonization and secondary caries. Responsive materials react to stimuli such as pH, whereas smart systems combine responsiveness with additional therapeutic functions. Self-healing composites, based mainly on microcapsule systems, remain largely experimental. Across categories, most supporting data come from laboratory and short-term investigations, and few materials demonstrate sustained clinical biological effects. Long-term randomized trials are required before these materials can be regarded as genuine therapeutic devices for routine restorative practice.

Keywords: Bioactive restorative materials; remineralization; ion release; antibacterial activity; biomimetic dentistry; therapeutic restorations.

INTRODUCTION: THE EVOLUTION OF BIOACTIVE MATERIALS

Bioactive restorative materials are considered among the most significant advances in modern restorative dentistry because of their ability to interact with dental structures and the oral environment [1]. Unlike conventional materials, several bioactive formulations release therapeutic ions and interact with dental tissues, promoting enamel and dentin remineralization while helping to protect the tooth against external insults. The oral cavity is a complex, dynamic environment subject to continuous physiological, chemical, and microbiological change; restorative materials must therefore combine adaptability, durable adhesion, wear resistance, and color stability to perform satisfactorily [2].

The development of these materials has transformed the traditional concept of the dental restoration. Beyond a

purely mechanical function, they participate in biological processes: their remineralizing and reparative properties help preserve enamel and dentin, while antibacterial activity and pulp protection reduce bacterial colonization, lower the risk of secondary caries, and may enhance the longevity of restorations. [3] For these reasons, bioactive materials have attracted increasing interest in restorative dentistry [2]. The progressive escalation of function from inert replacement toward a therapeutic device is illustrated in Figure 1.

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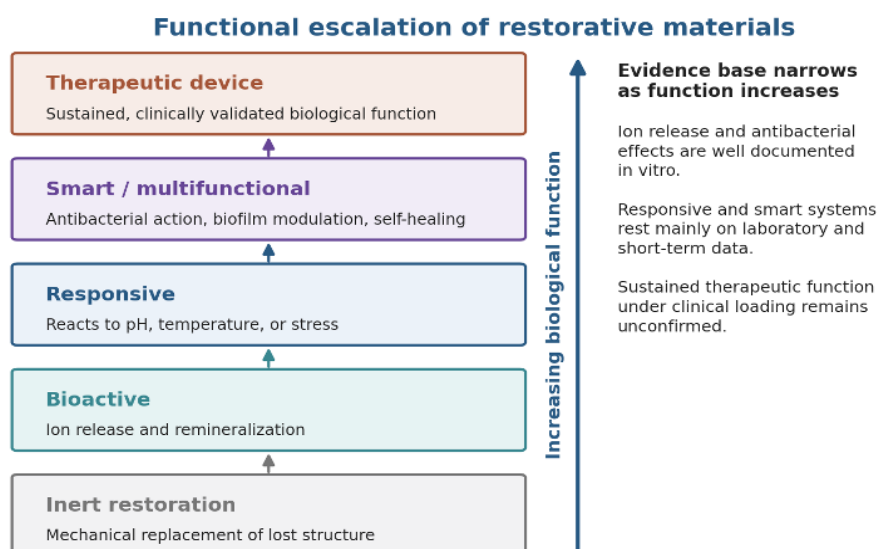


Figure 1. Functional escalation of restorative materials, from inert replacement of lost tissue through bioactive, responsive, and smart formulations toward a validated therapeutic device. The strength of the supporting evidence narrows as biological function increases. REF: [2-4].

Scientific evidence indicates that bioactive restorative materials can elicit specific biological responses in cells and tissues through several mechanisms that contribute to oral health [4]. Their performance depends on interaction with the oral environment, where salivary pH and temperature directly influence ion release and, consequently, remineralizing capacity, biocompatibility, and long-term behavior [5]. Comparative studies indicate that these factors alter the biological interactions between restorative materials and dental tissues, affecting both the function and durability of bioactive restorations [6].

The evolution of these materials has also encouraged a more therapeutic approach to restorative practice. The aim is no longer solely to replace lost tooth structure but also to prevent future damage, stimulate repair, and promote tissue regeneration through close interaction between material and tooth. In this context, the bioactive proteins present in dentin and their interactions with cellular receptors have become an important area of research in the development of new biomaterials [7]. The biological response can nevertheless vary according to the concentration of bioactive components, cellular activation and differentiation, interactions with the extracellular matrix, and relationships with other bioactive molecules, so further study of these processes is still required [8].

Numerous studies are currently evaluating materials based on bioactive glass and calcium silicates, as well as formulations incorporating ion-releasing fillers and antimicrobial agents [8]. These materials are designed to respond to the acidic conditions produced by cariogenic

microorganisms, promoting remineralization, reducing demineralization, and modifying the bacterial biofilm, thereby enhancing not only the therapeutic function of the restoration but also its restorative and esthetic performance [3]. Important limitations remain, including polymerization shrinkage and the difficulty of maintaining sustained ion release over time, so further laboratory and clinical studies are needed to define their biological and clinical potential [9]. Given these advances, an important question arises: can bioactive restorative materials go beyond remineralization to become true therapeutic devices that actively participate in the prevention, repair, and regeneration of dental tissues?

ION-RELEASING MATERIALS

As restorative dentistry shifts toward a therapeutic approach, restorations are expected not only to repair lost tooth structure but also to prevent further damage, promote healing, and adapt to the oral environment. In this context, bioactive materials that release ions such as calcium, fluoride, and phosphate have gained increasing relevance [9].

Mechanisms and profiles of ion release vary with the material's composition and its interactions with the surrounding environment. Glass-ionomer-based materials, calcium-phosphate systems, calcium-silicate materials, and bioactive glass-containing resins do not release the same ions or in the same amounts. Release generally occurs through interaction of the material with water or saliva, which allows soluble components to

dissolve and diffuse from the restorative matrix, so that pH, temperature, exposure time, filler concentration, and material permeability all affect the process [6,10]. A comparative in vitro study found that both the high-viscosity glass ionomer Equia Forte HT and the alkasite Cention N released fluoride and calcium under different

pH and temperature conditions, although Equia Forte HT showed consistently higher values, a difference attributed to its acid-base glass-ionomer structure compared with the polymeric resin matrix of the alkasite [11]. The main material classes and their release profiles are compared in Table 1.

Table 1. *Principal classes of bioactive restorative materials, their characteristic ion release, and reported mechanisms [6,11-13].*

Material class	Principal ions	Reported mechanism	Clinical considerations
Glass ionomer / high-viscosity GIC	Fluoride, calcium, strontium, aluminium	Acid-base setting reaction; sustained fluoride release and recharge	Highest ion release of the classes compared; lower mechanical strength
Resin-modified glass ionomer	Fluoride, calcium	Combined acid-base and polymerization reaction	Improved handling; intermediate release and strength
Alkasite (for example, Cention N)	Fluoride, calcium, hydroxide	Alkaline filler release buffering acid challenge	Lower release than GIC; polymeric matrix offers different mechanics
Bioactive glass containing resin	Calcium, phosphate, silicon, sodium	Surface apatite formation; release rises with filler load	Higher filler load improves bioactivity but may affect mechanics
Calcium silicate-based	Calcium, hydroxide, silicon	Hydration reaction; high alkalinity; mineral deposition	Strong biological response; mainly liner and base indications
Calcium phosphate systems	Calcium, phosphate	Ion supersaturation supporting mineral precipitation	Supports remineralization of caries-affected dentin

Recent in vitro evidence indicates that ions are rapidly released in environments below pH 4.0 [14]. In resin-based materials containing 45S5 bioactive glass, increasing the concentration of glass filler produced greater calcium and phosphate release and promoted apatite formation; once released, these ions may increase mineral supersaturation and support precipitation of calcium-phosphate phases at the material surface [12-13]. Fluoride, calcium, and phosphate-releasing materials have also been shown to induce apatite-like deposition and to increase the microhardness of mineral-deficient dentin, particularly when combined with a biomimetic primer, with simulated chewing favoring ion diffusion into affected dentin [1,15]. Release from Equia Forte HT and Cention N increased over time, with measurable changes at 1, 7, and 28 days, confirming that release profiles depend on both formulation and duration of environmental exposure [11].

These findings are clinically relevant because ion-releasing restorations and cements may modify the environment at the tooth-material interface. The released ions can limit mineral loss, support remineralization, and improve protection of caries-affected dentin after selective caries removal, which may be particularly useful in patients at high caries risk or at sites where recurrent demineralization is likely. Laboratory evidence of ion release and apatite

formation does not, however, automatically confirm long-term clinical effectiveness [11]. The comparison between the glass ionomer and the alkasite also indicates that the amount of ion release should not be the only criterion for material selection: although the glass ionomer released more ions, the polymeric matrix of the alkasite may offer different mechanical characteristics, which highlights the need to balance bioactivity against strength, stability, and suitability for definitive restorations [16].

Overall, ion-releasing materials make restorations more than passive replacements by enabling chemical interactions with surrounding dental tissues. Their therapeutic effect nevertheless depends on sustained ionic availability and on satisfactory clinical performance; while these materials can condition the local environment and support tissue repair, they cannot by themselves restore damaged tooth structure [2].

SELF-HEALING MATERIALS

Self-healing restorative materials represent an emerging approach aimed at one of the main limitations of conventional restorations, namely progressive structural degradation over time. Resin-based composites may develop microcracks as a result of polymerization shrinkage, repetitive occlusal stress, thermal variation, and chemical challenge in the oral environment. These

defects can compromise marginal integrity, facilitate bacterial infiltration, and contribute to restoration failure, so materials capable of detecting and repairing internal damage represent an important step toward restorative systems with therapeutic potential [17].

The concept is inspired by biological systems in which tissues respond to injury through repair mechanisms. In dentistry, the most investigated strategy involves resin composites containing microcapsules loaded with healing agents. When mechanical stress induces cracks in the material, the microcapsules rupture and release their contents into the damaged area, where polymerization or other chemical reactions can partially restore the material's structure, potentially delaying crack propagation and improving longevity [17].

Studies of microcapsule-based composites show that healing efficiency depends on capsule size, concentration, distribution within the resin matrix, and compatibility between the healing agent and restorative material. Ning and colleagues demonstrated that microcapsule parameters and initiator concentration significantly influence self-healing capacity, underscoring the need to optimize composition to achieve repair capacity without compromising mechanical properties [17]. More recent work has focused on improving stability and efficiency through functionalized and reinforced microcapsules, modifications intended to enhance mechanical resistance, improve release of healing agents, and increase compatibility with dental resin matrices; current evidence suggests these advanced designs may deliver more predictable self-repair while maintaining the strength required for restorative use [18-19].

Beyond structural repair, self-healing materials may contribute to bioactive restorative systems when combined with additional therapeutic properties. Incorporating

ion-releasing components, antimicrobial agents, or remineralizing fillers could allow future materials not only to repair mechanical damage but also to regulate the surrounding environment, reduce bacterial activity, and support preservation of dental tissues, a multifunctional approach that reinforces the transition from passive restorations toward materials that interact actively with the oral environment [5,20].

Despite these promising characteristics, self-healing restorative materials remain largely experimental. Most available evidence comes from laboratory studies of crack repair, mechanical recovery, and material characterization. Important challenges include achieving repeated healing capacity, maintaining mechanical properties, ensuring long-term biocompatibility, and demonstrating predictable performance under clinical conditions involving saliva, thermal change, bacterial biofilms, and continuous loading [1,20]. Future research should improve healing efficiency, optimize stability, and validate these systems in long-term clinical studies; integration of self-healing mechanisms with other bioactive functions may allow restorations to evolve from passive replacements into devices capable of protecting, adapting to, and maintaining dental tissues.

ANTIBACTERIAL RESTORATIVE MATERIALS

Antibacterial restorative materials have gained relevance because they limit bacterial growth, reduce biofilm formation, and lower the risk of secondary caries, one of the most frequent causes of restoration failure according to the revised FDI clinical criteria [21]. Their development reflects the shift toward biologically oriented dentistry, in which restorative materials are expected not only to replace lost tooth structure but also to contribute actively to maintaining oral health [2]. The principal antibacterial strategies and their mechanisms of action are compared in Table 2.

Table 2. Antibacterial strategies incorporated into restorative materials, their mechanisms, and current limitations REF: [11,14,22-23].

Strategy	Mechanism of action	Durability	Principal limitation
Ion-releasing fillers	pH modulation and inhibition of bacterial metabolism	Depends on sustained release	The effect diminishes as the release declines
Quaternary ammonium compounds	Contact killing; membrane disruption; reduced adhesion	Immobilized in the polymer network	Efficacy limited to the material surface
Silver nanoparticles	Broad-spectrum ion release; enzymatic interference	Long-lasting while ions are released	Discoloration and cytotoxicity concerns
Zinc and copper oxide nanoparticles	Reactive oxygen species; membrane disruption	Moderate	Effect on mechanical properties at higher loading
Fluoride from GIC and RMGIC	Inhibition of bacterial metabolism and acid production	Sustained, rechargeable	Weaker than dedicated antimicrobial agents
Nanostructured hybrid systems	Combined antibacterial and remineralizing action	Under investigation	Predominantly in vitro evidence

Bioactive resin composites containing ion-releasing fillers show measurable antibacterial effects. These materials release calcium, phosphate, fluoride, and other ions that can modulate local pH and inhibit the metabolic activity of *Streptococcus mutans* and *Lactobacilli*, microorganisms strongly associated with secondary caries [1]. The effect is linked to both ion release and the alkalizing response generated under acidic conditions, which disrupts bacterial homeostasis and reduces acid production; this dual mechanism supports the idea that restorations act as therapeutic devices and complements the remineralizing properties described above [13].

Another strategy incorporates quaternary ammonium compounds into resin matrices. These molecules act through contact-killing mechanisms, damaging bacterial membranes and reducing adhesion and viability; because they are immobilized within the polymer network rather than leached, their activity can remain stable over time, making them suitable for restorations placed at high-risk sites or in patients with elevated caries activity [22].

Metallic and metal-oxide nanoparticles, particularly silver, zinc oxide, and copper, have also been added to restorative materials. Silver nanoparticles exhibit broad antimicrobial activity and reduce biofilm formation on composite surfaces, while zinc-based systems provide antibacterial effects alongside mineral-forming potential, making them useful in hybrid bioactive formulations [22-23]. These particles interfere with bacterial enzymatic systems, generate reactive oxygen species, and disrupt membrane integrity, producing a multifactorial antibacterial response [14].

Glass ionomer cements and resin-modified glass ionomers retain an important role due to their fluoride release, which inhibits bacterial metabolism and reduces acid production. Although their antibacterial effect is generally weaker than that of materials containing dedicated antimicrobial

agents, sustained fluoride release contributes to long-term caries prevention, and high-viscosity formulations have shown improved resistance to biofilm formation, making them suitable for atraumatic restorative treatment and pediatric dentistry [11,15].

Nanostructured materials represent a promising direction, combining antimicrobial agents with remineralizing nanofillers such as nanohydroxyapatite and bioactive glass. Their dual action promotes mineral deposition at the tooth-material interface while limiting bacterial colonization, which aligns with minimally invasive dentistry by providing active protection against caries progression [13-14]. Despite these advances, most antibacterial effects have been demonstrated in vitro, and clinical evidence is still developing; the long-term stability of antibacterial agents, potential cytotoxicity, and interactions with the oral microbiome require further study, and balancing antibacterial efficacy against mechanical performance remains essential for predictable outcomes [2,4].

RESPONSIVE VERSUS SMART RESTORATIVE MATERIALS

Responsive and smart restorative materials represent different levels of interaction between restorative systems and the oral environment. Responsive materials are designed to detect specific environmental changes, such as variations in pH, and to modify their behavior accordingly. Studies have shown that pH-responsive systems can release therapeutic ions under the acidic conditions associated with cariogenic activity, providing a targeted response that may contribute to antibacterial effects and protection of dental tissues [23]. The distinction between the two categories is summarized in Table 3.

Recent evidence indicates that smart restorative materials incorporate broader multifunctional properties than traditional responsive systems, combining environmental

Table 3. Distinction between responsive and smart restorative materials, with the corresponding maturity of the supporting evidence. REF [23-26].

Feature	Responsive materials	Smart materials
Core principle	Detect and react to a single environmental stimulus	Combine responsiveness with additional biological functions
Typical trigger	pH fall associated with cariogenic activity	pH, temperature, or mechanical stress
Functions	Targeted ion release on demand	Ion release, antibacterial action, biofilm modulation, remineralization
Therapeutic intent	Protection during acid challenge	Prevention, adaptation, and tissue preservation
Evidence maturity	In vitro and early laboratory studies	Predominantly laboratory; clinical validation pending
Principal challenge	Sustaining response over time	Retaining mechanical properties while adding function

responsiveness with additional biological functions, including antibacterial activity, remineralization potential, and biofilm regulation. This development has expanded the concept of restorative materials from passive replacement toward active participation in maintaining oral health [24].

Compared with conventional materials, smart systems interact more dynamically with the oral environment. Their capacity to respond to changes such as pH fluctuation

allows controlled release of therapeutic components only when required, which may improve effectiveness against the processes involved in caries development and represents an important step toward more personalized and preventive restorative approaches [25]. The relationship between the underlying mechanisms and the clinical outcomes proposed for these materials is outlined in Figure 2.

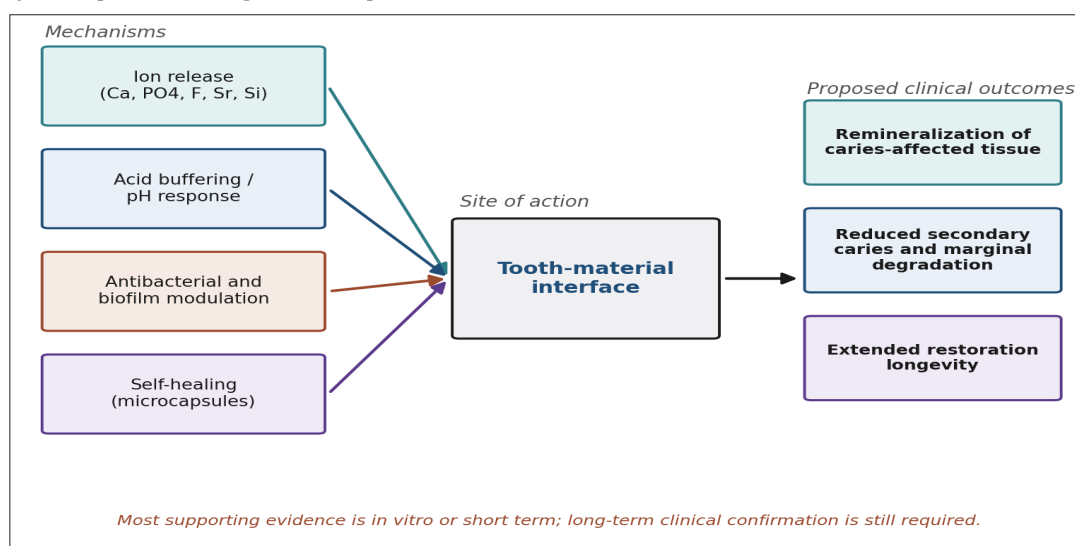


Figure 2. Relationship between the principal mechanisms of bioactive restorative materials, their site of action at the tooth-material interface, and the clinical outcomes proposed for them REF. [1-2,24].

The incorporation of bioactive fillers, nanoparticles, and functional components has enhanced the biological performance of materials, and current studies report promising results for ion release, remineralization capacity, antimicrobial activity, and interactions with dental tissues. Most of the available evidence, however, comes from laboratory studies, so further clinical investigation is required to confirm long-term effectiveness [26]. Computational approaches, such as materials informatics, may accelerate this development by guiding formulation design prior to laboratory testing [27].

Although smart restorative materials show significant potential, several challenges remain, including maintenance of mechanical properties, achievement of controlled and sustained therapeutic responses, and predictable behavior in the complex oral environment. Future research should focus on improving material stability and clinical translation before these systems enter routine use [3]. Overall, current evidence suggests that responsive materials represent an important step in the evolution of bioactive restorations, while smart materials offer a more advanced approach by integrating adaptation, prevention, and tissue preservation, supporting a transition toward

materials that contribute not only to the restoration of lost structure but also to prevention and maintenance of dental health [25-26].

CONCLUSION: TOWARD LIVING RESTORATIONS

The development of bioactive restorative materials represents one of the most significant shifts in modern restorative dentistry. Evaluation has traditionally focused on survival, structural integrity, marginal adaptation, and mechanical performance, criteria that do not always capture materials offering additional biological benefits. More comprehensive evaluation methods, addressing interaction with dental tissues and behavior in clinical settings, are therefore increasingly used, and this shift is essential for advancing practice and improving patient outcomes [21].

Research shows that bioactive materials are designed to interact with dental tissues and the oral cavity through controlled ion release, remineralization, and antibacterial activity, with the aim of improving the management of dental caries [2]. Advances in particle design have optimized particle size and ion release, and these materials represent a valuable resource when used correctly and on

the basis of scientific evidence, which requires clinicians to understand their mechanisms of action in order to select an appropriate material for each case and to deliver minimally invasive, durable restorations [28].

The future of bioactive restorations lies in the move toward living restorations with therapeutic functions, since mechanisms of action and emerging clinical evidence demonstrate genuine biological interaction. For these materials to enter daily practice, however, long-term clinical studies confirming safety, stability, and efficacy under clinical conditions are essential, and a solid scientific foundation would enable the establishment of clinical protocols to evaluate their benefits without compromising outcome quality [5]. Experimental work on scaffolds and hydrogel systems that regulate odontogenic differentiation indicates the direction such regenerative strategies may take [29].

Advances in bioactive restorative materials have begun to transform practice by replacing lost tissue while helping to protect and repair the tooth. These properties support a more conservative and preventive approach that prioritizes preservation of healthy tissue. Routine use nevertheless requires protocols that appropriately guide clinicians, and their incorporation into practice requires evaluation that accounts for the stability of caries remineralization over time, so that these materials can be integrated safely and effectively [1,4].

Returning to the question posed at the outset, can restorations become therapeutic devices? The evidence supports a qualified yes. Contemporary bioactive materials demonstrably release ions in a controlled manner, buffer pH fluctuations, and modulate bacterial activity at the tooth-material interface, and these functions extend beyond simple structural replacement [1]. What remains unproven is durability: most supporting data are in vitro or short-term, and few studies confirm that these effects persist under function long enough to alter clinical outcomes [2,4]. Bioactive materials are therefore best regarded at present as restorations with therapeutic potential rather than established therapeutic devices, and long-term randomized clinical trials are the decisive step needed to close that gap [28].

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