

Bioactive Restorative Materials in Modern Dentistry: A Comprehensive Review of Remineralization Potential and Clinical Performance

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ABSTRACT

Bioactive restorative materials have become increasingly important in modern minimally invasive dentistry because they are designed not only to replace lost tooth structure but also to interact with the surrounding oral environment. Unlike conventional inert restorative materials, bioactive systems may release fluoride, calcium, phosphate, strontium, silicate, or alkaline ions, thereby promoting remineralization, buffering acidic biofilm conditions, and potentially reducing secondary caries. This narrative review summarizes current knowledge regarding the mechanisms, laboratory evidence, clinical performance, limitations, and future directions of bioactive restorative materials. The review focuses on glass-ionomer cements, resin-modified glass ionomers, giomers, alkasites, bioactive resin composites, calcium silicate-based materials, and bioactive glass-modified systems. The available evidence suggests that ion-releasing materials can support remineralization under controlled in vitro or in situ conditions, particularly when demineralized dentin or enamel is exposed to repeated acidic challenges. Clinical evidence is more heterogeneous. Glass-ionomer and resin-modified glass-ionomer materials show meaningful advantages in high-caries-risk patients and pediatric dentistry, whereas bioactive resin composites and alkasites often demonstrate clinical performance comparable to conventional composites but not consistently superior longevity. Failure patterns are influenced by moisture control, marginal adaptation, mechanical loading, adhesive compatibility, material solubility, and patient-level caries risk. Current evidence supports selective use of bioactive materials as part of comprehensive caries management rather than as stand-alone substitutes for prevention. Future research should standardize definitions of bioactivity, include long-term randomized trials, and integrate biological outcomes with restoration survival.

Keywords

Bioactive materials; remineralization; glass ionomer cement; fluoride release; alkasite; giomer; secondary caries

INTRODUCTION

Dental caries and restoration failure remain major clinical challenges despite substantial progress in adhesive dentistry, preventive strategies, and restorative materials. Contemporary caries science views the disease as a dynamic ecological process in which repeated episodes of acid production shift the balance toward mineral loss, while saliva, fluoride, calcium, phosphate, and plaque control support remineralization [1]. This shift from a purely surgical model to a biological model has encouraged restorative dentistry to move beyond replacement of damaged tissues toward preservation, repair, and prevention of lesion recurrence [2].

The term bioactive restorative material has been used broadly, and sometimes inconsistently, to describe materials that release therapeutic ions, form apatite-like deposits, neutralize acids, inhibit bacterial activity, or interact chemically with dental hard tissues. This definitional uncertainty is one of the central controversies

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in the field. A material may release fluoride or calcium *in vitro*, but the clinical relevance of that ion release depends on magnitude, recharge capacity, diffusion through adhesive layers, biofilm thickness, pH cycling, and patient caries risk [3]. Consequently, laboratory bioactivity should not be equated automatically with superior clinical longevity.

Early discussions of bioactive restorative materials focused heavily on glass-ionomer cements and calcium-containing cements, but the modern category now includes resin-modified glass ionomers, giomers with surface pre-reacted glass-ionomer fillers, alkasites, bioactive resin composites, resin-based materials containing amorphous calcium phosphate or bioactive glass, and calcium silicate-based liners or dentin substitutes [4]. These systems differ substantially in setting chemistry, mechanical properties, ion-release profiles, solubility, bonding approach, and indications. The clinical question is therefore not whether a material is bioactive in a generic sense, but whether its biological benefit is sufficient for a particular lesion, cavity design, tooth type, and patient risk profile.

This review aims to synthesize evidence on the remineralization potential and clinical performance of bioactive restorative materials in modern dentistry. Specific objectives are to describe the biological basis of remineralization, compare major material classes, evaluate laboratory and clinical evidence, analyze common failure patterns, and identify future research directions relevant to clinicians and investigators.

Biological Basis of Remineralization and Material Bioactivity

Remineralization is a physicochemical process in which calcium and phosphate ions are redeposited into partially demineralized enamel or dentin crystals. Fluoride enhances this process by lowering enamel solubility, promoting fluorapatite-like mineral phases, and altering bacterial metabolism when present in the biofilm fluid during acid challenge [1]. Dentin remineralization is more complex than enamel remineralization because dentin contains a collagen-rich matrix, fluid-filled tubules, and deeper lesion zones that are less accessible to mineral ions. Therefore, a bioactive restorative material intended to remineralize dentin must provide ions in a way that permits diffusion into the lesion while maintaining a stable marginal seal.

Bioactivity in restorative dentistry generally involves

one or more mechanisms: release of fluoride, calcium, phosphate, strontium, sodium, silicate, or hydroxyl ions; increase in local pH; formation of an apatite-like surface layer; chemical bonding to tooth structure; or antibacterial effects through ionic stress and reduced acid tolerance. Bioactive polymeric composites were developed to combine remineralizing chemistry with acceptable handling and mechanical properties; however, increasing ion release can increase water sorption, reduce strength, or compromise wear resistance if the resin matrix and filler interface are not optimized [5].

The clinical value of remineralization depends on whether mineral gain occurs at a biologically meaningful location. Surface precipitation on a restoration may be visually impressive in scanning electron microscopy but may not repair the subsurface dentin-resin interface or prevent secondary caries. Similarly, fluoride release during the first few days after placement may not be sufficient unless the material can recharge from toothpaste or professional fluoride exposure. Thus, the most relevant materials are those that combine sustained ion release, recharge potential, marginal integrity, mechanical resistance, and biocompatibility.

Glass-Ionomer Cements and Resin-Modified Glass Ionomers

Conventional glass-ionomer cements are the prototypical bioactive restorative materials. Their acid-base setting reaction, chemical adhesion to enamel and dentin, coefficient of thermal expansion close to tooth structure, fluoride release, and fluoride recharge make them biologically attractive for cervical lesions, atraumatic restorative treatment, pediatric restorations, root caries, and high-caries-risk patients [6]. The early low pH and fluoride release of glass ionomers contribute to antibacterial and cariostatic effects, while maturation improves strength over time. Nevertheless, conventional glass ionomers are moisture sensitive during early setting and generally have lower fracture toughness and wear resistance than resin composites.

Resin-modified glass ionomers were introduced to improve handling, early strength, and moisture tolerance while retaining fluoride release. They are especially relevant in primary teeth, class V lesions, and patients in whom isolation is difficult. Network meta-analysis evidence suggests that glass ionomer may be favorable for controlling secondary caries in permanent teeth, while resin-modified glass ionomer may perform well

in deciduous teeth over longer follow-up periods [7]. This does not mean that they universally outperform resin composites; rather, their advantage is most plausible when caries risk, cervical margins, moisture control limitations, or fluoride-recharge opportunities are clinically significant.

A major limitation of the glass-ionomer family is the trade-off between bioactivity and load-bearing performance. Posterior stress-bearing restorations require resistance to wear, fracture, and marginal breakdown. High-viscosity glass ionomers and glass hybrids have improved the mechanical profile, but they are still generally less esthetic and less polishable than resin composites. Therefore, clinical selection requires balancing ion release against mechanical demand and patient expectations.

Giomers, Alkasites, and Bioactive Resin-Based Restoratives

Giomers contain surface pre-reacted glass-ionomer fillers dispersed in a resin matrix. This design aims to provide fluoride release and recharge while preserving composite-like esthetics and handling. Reviews of giomers describe them as hybrid materials at the boundary between glass-ionomer and resin composite technology, but their clinical advantage over conventional composites remains dependent on the indication and study design [8]. Because giomers require adhesive bonding, the diffusion of ions toward dentin may be limited by the adhesive layer. However, ion release into the adjacent biofilm or saliva may still support a cariostatic environment, particularly around restoration margins.

Alkasites, such as Cention N, release fluoride, calcium, and hydroxyl ions and are promoted as bulk-fill, tooth-colored, ion-releasing materials. In a randomized clinical trial of Class II restorations, an alkasite-based restorative showed 12-month performance comparable to a resin composite when both were placed under controlled clinical conditions [9]. This supports short-term acceptability but does not establish superiority in long-term secondary caries prevention. The performance of alkasites may depend strongly on adhesive strategy, cavity design, and occlusal loading.

Bioactive resin composites and ionic resin-based materials attempt to bridge the gap between mechanical performance and ion release. In vitro characterization of commercial bioactive composites has demonstrated

release of fluoride, calcium, phosphate, or silicate ions and potential formation of mineral deposits under selected conditions [10]. However, laboratory immersion media often differ from saliva, plaque fluid, and pH-cycling environments. Consequently, clinicians should interpret claims of apatite formation cautiously unless supported by clinical data.

Newer bioactive resin research has focused on multifunctional systems incorporating amorphous calcium phosphate nanoparticles, quaternary ammonium monomers, antibacterial fillers, bioactive glass, or protein-repellent surfaces. These approaches are scientifically promising because they address both sides of the secondary caries problem: mineral loss and cariogenic biofilm activity [11]. Yet incorporation of multiple functional agents can create formulation challenges, including reduced degree of conversion, color instability, water sorption, filler agglomeration, and reduced mechanical durability.

Evidence for Remineralization Potential

Remineralization evidence is strongest in laboratory studies using microhardness testing, transverse microradiography, energy-dispersive X-ray spectroscopy, surface microanalysis, micro-computed tomography, and pH-cycling models. In an in vitro demineralized dentin model, ACTIVA BioActive-Restorative and Beautifil II demonstrated mineral recovery, with ACTIVA showing greater changes in calcium-phosphate ratio and hardness than comparator groups [12]. Such findings support the biological plausibility of ion-releasing restorative materials, particularly in demineralized dentin left after selective caries removal.

Bioactive glass-modified materials can release calcium, phosphate, sodium, and silicate ions and may promote apatite-like precipitation. Addition of bioactive glass to glass-ionomer cements has been investigated to improve remineralization and biological response, but modifications can alter setting time, mechanical strength, and handling [13]. This highlights a recurring theme: the most bioactive formulation is not necessarily the best clinical restorative material if it compromises placement or durability.

Antibacterial activity is another relevant, although indirect, mechanism supporting remineralization. In vitro work comparing ACTIVA BioActive-Restorative and a silver-containing glass ionomer

against *Streptococcus mutans* found significant growth inhibition by both materials, with no statistically significant difference between them [14]. More recent direct-contact tests and S-PRG filler studies further suggest that ion release can alter biofilm growth, glucan synthesis, pH, and acid tolerance. Nevertheless, mono-species models using *S. mutans* cannot fully represent multispecies plaque biofilms, saliva buffering, dietary sugars, or mechanical cleaning.

The strongest interpretation of the remineralization literature is therefore moderate rather than absolute. Bioactive materials can produce measurable mineral changes in controlled environments, especially when the substrate is demineralized and pH conditions favor ion exchange. However, evidence that these changes translate into consistent long-term clinical superiority is still evolving.

Clinical Performance and Longevity

Clinical performance is best evaluated by restoration retention, marginal adaptation, marginal staining, postoperative sensitivity, secondary caries, wear, fracture, surface roughness, esthetics, and radiographic outcomes. The available clinical literature is heterogeneous because studies differ in lesion type, dentition, isolation, operator skill, caries risk, follow-up duration, and evaluation criteria. Many trials have short follow-up periods of 6 to 24 months, which may be insufficient to capture biologically meaningful differences in secondary caries and restoration survival.

A systematic review and network meta-analysis on secondary caries found differences among bioactive and conventional materials, with glass ionomer performing favorably in permanent teeth and resin-modified glass ionomer in deciduous teeth at longer follow-up intervals [7]. This finding aligns with the concept that high fluoride-releasing materials are most useful where caries control is clinically relevant. In contrast, a later systematic review of bioactive resin materials for posterior restorations concluded that these materials showed similar performance to conventional composites for preventing secondary caries and retention loss, without clear evidence of added longevity benefit [15]. The contrast between these conclusions reflects differences in material classes: fluoride-rich glass-ionomer systems may behave differently from resin-based bioactive composites.

Clinical trials in primary molars have also provided

useful evidence. A two-year split-mouth randomized trial comparing ACTIVA BioACTIVE with compomer in Class II cavities of primary molars reported non-inferior clinical and radiographic performance [16]. This supports ACTIVA as a clinically acceptable option in pediatric restorations, but non-inferiority does not prove superior remineralization or caries prevention. Similarly, short-term trials of alkasite restoratives suggest acceptable clinical behavior, but longer follow-up is needed to determine whether ion release reduces secondary caries beyond the first year [9].

Failure Patterns and Clinical Determinants

Failure of bioactive restorations is multifactorial. Marginal breakdown and secondary caries occur when the interface permits plaque retention, acid penetration, or microleakage. In resin-based bioactive materials, polymerization shrinkage, adhesive degradation, water sorption, and incomplete conversion may compromise the marginal seal. In glass-ionomer materials, early moisture contamination, desiccation, insufficient maturation, and wear can reduce marginal integrity. Thus, bioactivity cannot compensate for poor isolation, improper material thickness, inadequate curing, or occlusal overload.

Patient-level factors are equally important. High sugar exposure, xerostomia, poor plaque control, orthodontic appliances, root exposure, and limited fluoride exposure can overwhelm the protective capacity of restorative materials. Conversely, in low-risk patients who brush with fluoride toothpaste and maintain plaque control, differences among materials may be small because the oral environment itself supports remineralization. This explains why some clinical studies fail to detect superiority of bioactive materials even when laboratory ion release is evident.

Preventive and Therapeutic Strategies

Bioactive restorative materials should be integrated into a broader preventive philosophy rather than used as isolated therapeutic agents. Caries risk assessment, dietary counseling, plaque control, topical fluoride, saliva management, and recall scheduling remain essential. In minimally invasive dentistry, selective caries removal can leave affected dentin capable of remineralization if the restoration seals the lesion and the material supports a favorable ionic environment. Biomimetic approaches emphasize conservation of tooth structure, bonding to remaining tissues, and

regeneration or reinforcement where possible [17].

Preventive benefit is also influenced by fluoride recharge. Materials that can absorb fluoride from toothpaste, mouth rinse, or varnish and rerelease it during acid challenge may function as local reservoirs. This behavior is strongest in glass-ionomer systems and more limited in many resin-based materials. Clinically, the recharge concept reinforces the need for continued fluoride exposure even after placement of a bioactive restoration.

Future Directions

Future development should focus on materials that preserve mechanical durability while delivering site-specific, responsive ion release. Ideal systems would release ions when pH drops, recharge efficiently, resist biofilm colonization, maintain color and polish, bond reliably to enamel and dentin, and avoid excessive solubility. Advanced bioactive restorative adhesive materials have been proposed as a future direction because the adhesive interface is often the weakest link in restoration longevity [18]. If adhesives themselves can remineralize collagen, inhibit matrix metalloproteinases, resist hydrolysis, and release ions without compromising bond strength, the biological benefit may reach the location where many failures begin.

DISCUSSION

The reviewed evidence indicates that bioactive restorative materials occupy a meaningful but carefully defined role in modern dentistry. Their greatest strength lies in their capacity to support the biological management of caries, especially when fluoride, calcium, phosphate, or alkaline ions are released in response to acidic conditions. However, the clinical literature does not uniformly support the idea that all materials marketed as bioactive provide superior longevity. Instead, the benefit appears material-specific, indication-specific, and patient-specific.

Glass-ionomer and resin-modified glass-ionomer materials have the most established biological rationale because their fluoride release, chemical adhesion, and recharge potential are clinically relevant in high-caries-risk settings. Their limitations are primarily mechanical and esthetic. Resin-based bioactive materials, giomers, and alkasites improve esthetics

and handling, but their ion release may be lower, less sustained, or less accessible to the tooth-restoration interface. Consequently, their clinical performance is often comparable to conventional composites rather than clearly superior. [19-21]

A key gap is the lack of long-term trials that simultaneously measure mineral changes, biofilm behavior, and restoration survival. Many studies examine either laboratory remineralization or clinical retention, but few link the two. Another gap is the inconsistent definition of bioactivity. Without agreed thresholds for ion release, apatite formation, pH buffering, or biological effect, comparisons among materials remain difficult. Future work should determine not simply whether a material releases ions, but whether this release reduces lesion progression or restoration replacement in defined clinical populations.

For clinicians, the implication is that bioactive materials should be selected deliberately. In high-risk patients, children, root caries, cervical lesions, and situations where moisture control is compromised, ion-releasing materials may offer meaningful advantages. In low-risk patients with excellent isolation and high esthetic demand, conventional adhesive composites may perform similarly. Bioactive materials should therefore complement, not replace, sound operative technique and preventive care.

CONCLUSION

Bioactive restorative materials represent an important evolution from passive replacement toward biologically interactive restorative care. Their remineralization potential is supported by substantial laboratory evidence, particularly for ion-releasing glass-ionomer systems, bioactive composites, alkasites, and materials containing calcium-phosphate or bioactive glass phases. Clinical evidence is more nuanced: glass ionomer and resin-modified glass ionomer remain especially valuable for caries-prone patients and pediatric dentistry, whereas bioactive resin composites and alkasites currently demonstrate acceptable but not consistently superior long-term outcomes compared with conventional composites. The future of bioactive restorative dentistry depends on standardized definitions, interface-focused material design, and long-term clinical trials that integrate biological, mechanical, and patient-centered outcomes.



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