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Recent Advancements in Bioactive Restorative Materials: A Review of Clinical Performance

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Abstract

The evolution of restorative dentistry has progressed from the use of inert materials toward biologically interactive systems capable of modulating the oral environment and supporting tooth tissue repair. Bioactive restorative materials have emerged as a promising class of materials designed to release therapeutic ions, promote remineralization, inhibit bacterial activity, and potentially improve the longevity of restorations. This review aims to comprehensively analyze recent advancements in bioactive restorative materials and critically evaluate their clinical performance based on available in vitro and in vivo evidence. A systematic search of major electronic databases was conducted for studies published between 2019 and 2025. Glass ionomer cements, resin-modified glass ionomers, giomers, alkasite materials, and bioactive resin composites were included. Clinical performance parameters such as marginal integrity, retention, wear resistance, postoperative sensitivity, and secondary caries prevention were assessed. Current evidence indicates that bioactive restorative materials particularly glass ionomer–based systems exhibit favorable clinical outcomes in caries-prone patients, mainly due to sustained ion release and chemical bonding to tooth structure. However, limitations related to mechanical strength, material heterogeneity, and the paucity of long-term randomized clinical trials persist. Standardized evaluation methods and further clinical validation are required before widespread adoption of newer bioactive materials can be fully justified.

Keywords
Bioactive restorative materials; glass ionomer cement; ion-releasing restorations; secondary caries; remineralization; clinical performance.

Introduction

Dental caries remains one of the most prevalent chronic diseases globally, affecting individuals across all age groups despite advances in preventive dentistry and increased oral health awareness. Restoration of carious lesions continues to be a cornerstone of dental practice; however, the long-term success of restorative procedures is frequently compromised by secondary caries, marginal breakdown, material degradation, and biological incompatibility. Secondary caries is consistently reported as the primary reason for restoration replacement, contributing significantly to the restorative cycle and cumulative loss of tooth structure [1].

Conventional restorative materials such as dental amalgam, resin composites, ceramics, and gold alloys were primarily designed to restore form, function, and esthetics. These materials are largely inert and do not actively participate in the biological processes occurring at the tooth–restoration interface. Although resin com-posites offer excellent esthetics and satisfactory mechanical properties, they are susceptible to polymerization shrinkage, microleakage, and biofilm accumulation, which predispose restorations to recurrent caries [2].

The concept of bioactivity has introduced a paradigm shift in restorative dentistry. Originating from orthopedic biomaterials, bioactivity was initially defined as the ability of a material to form a direct chemical bond with living tissue through the formation of a hydroxyapatite layer. In dentistry, this concept has expanded to include materials capable of releasing biologically beneficial ions, promoting enamel and dentin remineralization, buffering acidic environments, and exerting antibacterial effects [3]. However, the absence of a universally accepted definition has resulted in considerable variability in how materials are classified and marketed as bioactive [4].

Glass ionomer cements (GICs) were among the first restorative materials to demonstrate inherent bioactive properties through sustained fluoride release and chemical bonding to tooth structure. Subsequent developments, including resin-modified glass ionomers, giomers, alkasite materials, and bioactive resin composites, aimed to combine improved mechanical properties with therapeutic benefits. These innovations align closely with the principles of minimally invasive dentistry, which emphasize preservation of tooth structure and control of disease progression rather than aggressive mechanical intervention.

Despite promising laboratory data demonstrating ion release, pH modulation, and apatite formation, the clinical relevance of these properties remains under scrutiny. Clinical performance measured in terms of retention, marginal adaptation, wear resistance, postoperative sensitivity, and secondary caries prevention ultimately determines the success of any restorative material. This review therefore integrates laboratory findings with clinical evidence to provide a comprehensive and balanced evaluation of bioactive restorative materials in contemporary dentistry.

Aim

The aim of this review is to critically evaluate recent advancements in bioactive restorative materials with particular emphasis on their mechanisms of bioactivity and clinical performance, including longevity, resistance to secondary caries, and functional durability in restorative dentistry.

Materials and Methods

Search Strategy

A comprehensive electronic search was conducted using PubMed, Scopus, Web of Science, Embase, ScienceDirect, and the Cochrane Library. Articles published between January 2019 and November 2025 were included. The search strategy combined MeSH terms and keywords such as “bioactive restorative materials,” “glass ionomer cement,” “ion-releasing composites,” “giomers,” “alkasite materials,” “secondary caries,” “remineralization,” and “clinical performance.” Boolean operators (AND, OR) were used to refine the search.

Inclusion Criteria

- Randomized controlled trials, clinical trials, systematic reviews, and meta-analyses
- In vitro studies with direct clinical relevance
- Studies evaluating restorative materials with claimed bioactive properties
- English-language publications

Exclusion Criteria

- Case reports and narrative opinions
- Studies unrelated to restorative dentistry
- Endodontic or liner materials without restorative application

Discussion

The emergence of bioactive restorative materials represents a fundamental shift in restorative dentistry, reflecting a broader transition from a mechanically driven discipline toward one that integrates biological principles into material selection and treatment planning. Traditional restorative approaches have historically emphasized strength, esthetics, and durability, often overlooking the biological processes at the tooth–material interface. Bioactive restorative materials challenge this paradigm by introducing therapeutic functions intended to modulate the oral environment, reduce disease recurrence, and support tissue preservation. This discussion provides a detailed evaluation of the conceptual framework, material-specific evidence, biological mechanisms, clinical performance, and existing limitations of bioactive restorative materials, while contextualizing their role within contemporary dental practice.

Conceptual Complexity and Terminology of Bioactivity

A critical issue in evaluating bioactive restorative materials is the lack of a clear and universally accepted definition of bioactivity. In classical biomaterials science, bioactivity implies the capacity of a material to elicit a specific biological response, such as the formation of a chemical bond with hard tissues through apatite deposition. In restorative dentistry, however, the term has been expanded to include a wide spectrum of properties, including ion release, pH buffering, antibacterial activity, and remineralization potential [3,4]. While this broader interpretation has facilitated innovation, it has also led to ambiguity and inconsistency in material classification.

Many commercially available restorative materials are labeled as bioactive based primarily on their ability to release fluoride or calcium ions, even when evidence of direct biological interaction with dental tissues is limited. This raises important questions regarding whether ion release alone constitutes bioactivity or whether measurable biological outcomes such as inhibition of lesion progression or enhancement of dentin mineral density should be required. The absence of standardized criteria complicates comparisons across studies and may lead to unrealistic clinical expectations.

Glass Ionomer Cements as the Biological Gold Standard

Glass ionomer cements (GICs) remain the most extensively researched and clinically validated bioactive restorative materials. Their bioactivity is intrinsically linked to their acid–base setting reaction, which facilitates sustained fluoride release and chemical bonding to enamel and dentin [5]. This chemical adhesion minimizes interfacial gaps and microleakage, which are key contributors to secondary caries development.

Extensive clinical evidence supports the superior performance of GICs in preventing secondary caries, particularly in high-caries-risk patients, pediatric populations, and geriatric patients with exposed root surfaces [6,7]. The fluoride reservoir effect of GICs, combined with their ability to recharge fluoride from external sources, contributes to long-term anticariogenic activity. Moreover, GICs demonstrate favorable biocompatibility and minimal postoperative sensitivity, further enhancing their clinical appeal.

Despite these advantages, conventional GICs are limited by relatively poor mechanical properties, including low fracture toughness, inferior wear resistance, and susceptibility to early moisture imbalance. These limitations restrict their use in high-stress posterior restorations and underscore the importance of appropriate case selection.

Resin-Modified Glass Ionomers: Bridging Biology and Mechanics

Resin-modified glass ionomer cements (RMGICs) were developed to address the mechanical deficiencies of conventional GICs while preserving their bioactive char-

-acteristics. The incorporation of hydrophilic resin monomers improves handling properties, early strength development, and resistance to moisture contamination [8]. Although resin modification partially reduces long-term ion diffusion, RMGICs retain clinically significant fluoride release and chemical bonding to tooth structure.

Clinical studies suggest that RMGICs provide a favorable compromise between bioactivity and durability, making them suitable for cervical lesions, non–stress-bearing posterior restorations, and minimally invasive techniques. Their ability to reduce secondary caries incidence while offering improved mechanical performance compared to conventional GICs has been consistently reported [9]. Nevertheless, RMGICs remain inferior to resin composites in terms of wear resistance and long-term esthetic stability, limiting their universal application.

Giomers and Hybrid Bioactive Systems

Giomers represent a hybrid approach that seeks to combine the esthetic and mechanical advantages of resin composites with the ion-releasing potential of glass ionomer technology. The inclusion of surface pre-reacted glass (S-PRG) fillers enables the release of fluoride, strontium, sodium, and borate ions while maintaining a resin-based matrix [10]. Laboratory studies demonstrate that giomers possess fluoride release and recharge capabilities, although these are generally lower in magnitude and duration compared to GICs.

Clinical studies evaluating giomers report satisfactory retention rates, marginal adaptation, and surface integrity comparable to conventional resin composites. However, evidence supporting a significant reduction in secondary caries remains limited. The lower ion release may not provide sufficient therapeutic benefit in high-caries-risk patients, suggesting that giomers may be best suited for patients with moderate caries risk who require improved esthetics and mechanical performance.

Alkasite Materials and pH-Responsive Bioactivity

Alkasite materials represent a novel class of restorative materials designed to respond dynamically to changes in the oral environment. These materials release calcium, fluoride, and hydroxide ions under acidic conditions, thereby neutralizing local pH and promoting remineralization [11]. This pH-responsive behavior aligns closely with the episodic nature of cariogenic challenges and represents a promising advancement in bioactive material design.

Laboratory studies have demonstrated effective buffering capacity and ion release from alkasite materials during acidic challenges. However, clinical data remain limited, and long-term performance under functional loading conditions has yet to be conclusively established. Furthermore, the extent to which pH-responsive ion release translates into clinically meaningful reductions in secondary caries requires further investigation.

Bioactive Resin Composites: Balancing Innovation and Risk

Bioactive resin composites incorporating bioactive glass, calcium phosphate, or nanohydroxyapatite fillers have generated considerable interest due to their potential to combine high mechanical strength with therapeutic functionality. In vitro studies consistently demonstrate ion release, apatite formation, and dentin remineralization potential [10]. These findings suggest that bioactive resin composites may address the long-standing limitations of conventional composites, particularly their inability to counteract demineralization at restoration margins.

However, clinical translation of these materials remains challenging. Ion release is often associated with increased water sorption, which can compromise mechanical integrity through hydrolytic degradation. Aging studies have reported reductions in flexural strength, increased wear, and surface roughening over time [12]. While short-term clinical studies report acceptable performance, the absence of long-term randomized controlled trials limits confidence in their durability and reliability.

Biological Mechanisms Underpinning Clinical Outcomes

The clinical performance of bioactive restorative materials is mediated by multiple interrelated biological mechanisms. Fluoride ions inhibit enamel demineralization, enhance remineralization, and disrupt bacterial metabolism by inhibiting key enzymatic pathways [13]. Calcium and phosphate ions contribute to hydroxyapatite nucleation and growth, reinforcing demineralized tooth structure and stabilizing the tooth–material interface.

pH modulation plays a critical role in controlling cariogenic activity. By buffering acidic environments, bioactive materials reduce bacterial virulence and slow lesion progression. Additionally, the formation of an apatite-like layer at the tooth–restoration interface may improve marginal sealing and reduce microleakage. However, whether this phenomenon occurs consistently under the complex conditions of the oral environment remains a subject of debate [14].

Secondary Caries Prevention: Strength of Evidence

Secondary caries remains the most common cause of restoration failure, highlighting the clinical importance of bioactive restorative materials. Robust evidence supports the superior performance of glass ionomer-based materials in reducing secondary caries incidence, particularly in high-risk populations [15]. This benefit appears to be primarily attributable to sustained fluoride release and chemical bonding rather than enhanced mechanical properties.

In contrast, evidence supporting secondary caries prevention by newer bioactive resin-based materials is less conclusive. Many studies rely on surrogate laboratory outcomes rather than direct clinical endpoints, and variability in diagnostic criteria further complicates interpretation.

Limitations of Current Research

Several limitations affect the current body of evidence. Many clinical trials have relatively short follow-up periods, often limited to 12–24 months, which may not accurately reflect long-term restoration survival. The heterogeneity of materials labeled as bioactive and the lack of standardized testing protocols further limit comparability [16]. Additionally, in vitro studies often fail to replicate the complex mechanical, chemical, and biological challenges encountered in vivo.

Conclusion

From a clinical standpoint, bioactive restorative materials should be viewed as adjuncts rather than replacements for conventional restorative materials. Glass ionomer and resin-modified glass ionomer cements remain the most reliable options for caries-prone patients, pediatric dentistry, and minimally invasive approaches. Resin-based bioactive materials may offer advantages in selected cases but should be used judiciously until long-term clinical evidence becomes available.

Future Perspectives

Future research should emphasize long-term randomized clinical trials, standardized bioactivity assessment protocols, optimization of material formulations to balance bioactivity and strength, development of smart pH-responsive systems, and inclusion of patient-centered and cost-effectiveness outcomes.

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