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Bioactive Dental Materials: Improving Adhesion, Remineralization, and Longevity of Restorations

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Abstract

Bioactive dental materials have emerged as a transformative approach in restorative dentistry, addressing the limitations of conventional materials by combining mechanical function with biological activity. Unlike traditional inert restoratives, these materials actively interact with the oral environment through mechanisms such as ion release, hydroxyapatite formation, pH modulation, and antibacterial effects. This review explores the fundamental properties, classification, mechanisms of action, and clinical applications of bioactive dental materials, with a particular focus on their role in improving adhesion, promoting remineralization, and enhancing the longevity of restorations. Various categories, including bioactive glasses, calcium silicate-based materials, resin-based bioactive composites, ion-releasing systems, and emerging smart materials, are discussed in detail. The ability of these materials to release calcium, phosphate, and fluoride ions plays a critical role in reversing early carious lesions and reinforcing tooth structure. Additionally, their antibacterial properties and improved interfacial bonding contribute to reduced microleakage and lower incidence of secondary caries. Despite these advantages, challenges such as mechanical limitations, long-term stability, esthetic concerns, controlled ion release, and cost remain. Continued advancements in nanotechnology and biomimetic material design are expected to overcome these limitations and further enhance their clinical performance. Overall, bioactive dental materials represent a significant step toward minimally invasive, preventive, and regenerative dental care.

Keywords: Bioactive dental materials, Remineralization, Ion release, Adhesion, Antibacterial properties, Biodentine.

1 | Introduction

The field of restorative dentistry has experienced remarkable advancements over the past few decades, driven by the increasing demand for materials that not only restore the structural integrity and aesthetics of teeth but also actively contribute to their biological health. Traditionally, dental restorative materials such as amalgam, conventional resin composites, and ceramics were designed primarily to replace lost tooth structure and provide acceptable mechanical performance [1–5]. While these materials have been successful in many clinical

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applications, they are largely considered biologically inert, lacking the capacity to interact dynamically with the surrounding oral environment. Consequently, persistent challenges such as secondary caries, marginal degradation, postoperative sensitivity, and limited longevity of restorations continue to affect clinical outcomes. In response to these limitations, the concept of bioactivity has emerged as a transformative approach in dental material science [6]. Bioactive dental materials are characterized by their ability to elicit specific biological responses at the interface between the material and the surrounding tissues. Unlike conventional materials, these advanced systems are capable of interacting with saliva, enamel, dentin, and oral microbiota in a way that promotes tissue regeneration and inhibits pathological processes. This interaction is often mediated through the controlled release of biologically relevant ions such as calcium, phosphate, fluoride, and in some cases, strontium or silicate ions. These ions play a crucial role in enhancing remineralization, buffering acidic conditions, and fostering the formation of apatite-like structures that integrate with natural tooth tissues [7–12]. A comparison between conventional and bioactive dental materials highlights significant differences in their biological activity, ion release capability, and clinical performance, as summarized in *Table 1*. One of the most significant advantages of bioactive dental materials lies in their capacity to promote remineralization, a process that is fundamental to maintaining the structural and functional integrity of teeth. Demineralization, caused primarily by acidic by-products of bacterial metabolism, leads to the loss of mineral content in enamel and dentin, ultimately resulting in caries formation. Bioactive materials counteract this process by serving as reservoirs of essential ions that can be released over time, thereby supporting the natural repair mechanisms of the tooth. The formation of hydroxyapatite or fluorapatite crystals within demineralized areas not only restores mineral density but also enhances resistance to future acid attacks. This property is particularly valuable in preventing the progression of early carious lesions and reducing the incidence of recurrent caries at restoration margins [13–15]. Adhesion between restorative materials and tooth structures represents another critical factor influencing the success and durability of dental restorations. Achieving a stable and long-lasting bond is inherently challenging due to the complex composition of dental tissues and the dynamic conditions of the oral environment, including moisture, temperature fluctuations, and mechanical loading. Conventional adhesive systems rely predominantly on micromechanical retention and hybrid layer formation, which are susceptible to degradation over time. In contrast, bioactive materials introduce a chemical dimension to adhesion by facilitating ionic exchange and the formation of a biologically integrated interface. This ion-mediated bonding mechanism enhances interfacial stability, reduces microleakage, and minimizes the risk of bond failure, particularly in dentin where adhesion is more difficult to achieve. In addition to their remineralizing and adhesive properties, many bioactive dental materials exhibit antimicrobial activity, which further contributes to their clinical effectiveness. The presence of pathogenic bacteria in the oral cavity plays a central role in the initiation and progression of dental caries and restoration failure. By releasing ions that disrupt bacterial metabolism or alter local pH conditions, bioactive materials can inhibit biofilm formation and reduce bacterial colonization at the restoration interface [10–13]. This antimicrobial effect, combined with improved sealing ability, significantly lowers the likelihood of secondary caries, which remains one of the primary reasons for restoration replacement. The longevity of dental restorations is a key indicator of clinical success and patient satisfaction. Failures often result from a combination of mechanical, chemical, and biological factors, including material degradation, loss of adhesion, and recurrent decay. Bioactive dental materials address these multifactorial challenges through their multifunctional properties, offering not only mechanical support but also biological protection and self-repair potential. By continuously interacting with the oral environment, these materials provide a dynamic defense mechanism that extends the lifespan of restorations and reduces the need for repeated interventions. Despite their promising advantages, bioactive dental materials are not without limitations. Issues related to mechanical strength, long-term stability, ion release kinetics, and cost-effectiveness remain areas of ongoing research [14]. Furthermore, the complexity of designing materials that achieve an optimal balance between bioactivity and mechanical performance presents a significant challenge for material scientists. Nevertheless, continuous innovations in nanotechnology, material engineering, and biomimetic approaches are paving the way for the development of next-generation restorative materials with enhanced functionality and clinical reliability [15–17]. In light of these considerations, bioactive dental materials represent a paradigm shift in restorative dentistry, moving from passive replacement strategies toward active therapeutic solutions. Their ability to improve adhesion, promote remineralization, and enhance the longevity of restorations underscores their growing importance in modern clinical practice. This study aims to explore the fundamental properties, mechanisms of action, and clinical implications of bioactive dental materials, with particular emphasis on their role in addressing the longstanding challenges associated with dental restorations.

Table 1. Comparison of conventional vs bioactive dental materials.

Feature	Conventional Materials	Bioactive Dental Materials
Biological interaction	Inert (no interaction)	Active interaction with tissues
Ion release	None	Releases Ca, PO_4, F ions
Remineralization	Not supported	Promotes remineralization
Adhesion mechanism	Micromechanical bonding	Chemical + micromechanical bonding
Antibacterial effect	Limited	Present in many materials
Marginal integrity	Susceptible to leakage	Improved sealing ability
Longevity	Moderate	Enhanced durability
Secondary caries prevention	Weak	Strong

2 | Materials and Classification of Bioactive Dental Materials

Bioactive dental materials represent a highly advanced and rapidly evolving class of restorative and regenerative biomaterials designed to interact dynamically with the oral biological environment. Unlike conventional inert restorative materials, which primarily serve structural and aesthetic roles, bioactive systems actively participate in biological processes at the material tissue interface, including ion exchange, apatite formation, stimulation of cellular activity, antibacterial effects, and enhanced adhesion to dental hard tissues. As a result, these materials contribute not only to restoration but also to the preservation and regeneration of tooth structure. A comprehensive overview of bioactive dental materials, including their composition, mechanisms of action, and clinical applications, is summarized in *Table 2*. Based on their chemical composition, structural characteristics, and biological mechanisms, bioactive dental materials can be broadly classified into five major categories: 1) bioactive glasses, 2) calcium silicate-based materials, 3) resin-based bioactive composites, 4) ion-releasing restorative systems, and 5) emerging hybrid smart materials [18–20].

2.1 | Bioactive Glasses

Bioactive glasses are among the earliest and most extensively investigated bioactive materials, originally developed by Hench [21] in the form of the 45S5 Bioglass system. These materials typically consist of silica (SiO_2), sodium oxide (Na_2O), calcium oxide (CaO), and phosphorus pentoxide (P_2O_5). Their unique property lies in their surface reactivity when exposed to physiological fluids such as saliva. Upon implantation or clinical application, a series of surface reactions occurs, including ion exchange, silica gel layer formation, and subsequent precipitation of a Hydroxycarbonate Apatite (HCA) layer. This layer closely resembles the mineral phase of natural enamel and dentin, which enables strong interfacial bonding and promotes remineralization. Additionally, the release of calcium and phosphate ions contributes to the regeneration of demineralized tooth structure and helps buffer acidic environments, thereby reducing caries progression [22].

2.2 | Calcium Silicate-Based Materials

Calcium silicate-based materials, including Mineral Trioxide Aggregate (MTA), Biodentine, and other hydraulic cements, are widely used in endodontic and restorative dentistry. Their bioactivity is primarily derived from hydration reactions that produce calcium hydroxide, resulting in a highly alkaline environment (pH ~ 12). This alkaline condition provides strong antibacterial effects and stimulates the differentiation of odontoblast-like cells, promoting the formation of reparative dentin. These materials are particularly effective in procedures such as pulp capping, pulpotomy, apexification, perforation repair, and root-end filling. Their excellent sealing ability, biocompatibility, and ability to induce hard tissue formation make them essential in regenerative endodontics [16].

2.3 | Resin-Based Bioactive Composites

Resin-based bioactive composites combine the mechanical strength, polishability, and aesthetic properties of conventional resin composites with the biological functionality of bioactive fillers. These fillers may include bioactive glass particles, Amorphous Calcium Phosphates (ACPs), nanohydroxyapatite, or fluoride-releasing compounds embedded within a polymeric resin matrix. Unlike traditional composites, these materials are capable of sustained ion release over time, particularly calcium, phosphate, and fluoride ions. This enables them to actively participate in remineralization processes at the restoration margins. Moreover, they maintain acceptable wear resistance and mechanical stability, making them suitable for both anterior and posterior restorative applications [12].

2.4 | Ion-Releasing Restorative Materials

Ion-releasing materials, particularly Glass Ionomer Cements (GICs) and Resin-Modified Glass Ionomers (RMGIs), play a crucial role in preventive and minimally invasive dentistry. These materials are characterized by their ability to release fluoride ions continuously over time. Fluoride release enhances enamel resistance to acid attacks, inhibits demineralization, and promotes remineralization of early carious lesions. In addition, these materials chemically bond to tooth structure through ionic interaction between carboxyl groups and calcium in hydroxyapatite, eliminating the need for extensive adhesive systems. This makes them particularly useful in pediatric dentistry, cervical lesions, and high caries-risk patients [12–16].

2.5 | Hybrid and Smart Bioactive Systems

Recent advances in biomaterials science have led to the development of hybrid and "smart" bioactive systems. These materials integrate multiple functional components, enabling simultaneous ion release, antibacterial activity, and mechanical reinforcement. Some of these systems are pH-responsive, meaning they release therapeutic ions preferentially under acidic conditions associated with demineralization. This targeted response enhances their preventive and therapeutic efficiency. The integration of nanotechnology and biomimetic approaches has further improved their performance, making them promising candidates for next-generation restorative dentistry [18].

Table 2. Comprehensive classification of bioactive dental materials.

Category	Examples	Main Composition	Bioactivity Mechanism	Ion Release	Clinical Applications	Key Advantages
Bioactive glasses	Bioglass	SiO_2, CaO, Na_2O_5 P_2O_5	Formation of Hydroxycarbonate Apatite (HCA) layer	Ca^{2+} PO_4^{3-} Na^{+}	Remineralization, coating materials	Strong bonding, high bioactivity
Calcium Silicate-based	MTA, Biodentine	Calcium silicate hydrates	Calcium hydroxide formation, high pH environment	Ca^{2+} OH^{-}	Endodontics, pulp capping, root repair	High biocompatibility, dentin formation
Resin-based Bioactive Composites	Bioactive composites	Resin matrix + bioactive fillers	Ion diffusion from filler phase	Ca^{2+} PO_4^{3-} F^{-}	Restorative dentistry (anterior/posterior)	Aesthetic + functional properties
Ion-releasing materials	GIC, RMGI	Fluoroaluminosilicate glass	Acid-base reaction + ionic bonding	F^{-} Al^{3+} Ca^{2+}	Pediatric dentistry, cervical lesions	Fluoride release, chemical bonding
Hybrid smart materials	Experimental bioactive systems	Multi-phase nanocomposites	pH-responsive ion release + antibacterial effect	Multiple ions	High-risk patients, advanced restorations	Multifunctionality, adaptive response

3 | Mechanism of Action of Bioactive Dental Materials

The clinical success of bioactive dental materials is fundamentally attributed to their dynamic interaction with the oral environment through a series of physicochemical and biological processes. These mechanisms collectively contribute to remineralization, antibacterial activity, improved adhesion, and long-term stability of restorations. The primary processes involved include ion release, hydroxyapatite formation, pH modulation, antimicrobial effects, and interfacial bonding [20].

3.1 | Ion Release Mechanism

One of the defining characteristics of bioactive dental materials is their ability to release therapeutic ions in a controlled and sustained manner. This process is typically initiated upon contact with saliva or dentinal fluid, which acts as a medium for ion exchange. In materials such as bioactive glasses and calcium silicate-based cements, the mechanism begins with the exchange of alkali or alkaline earth ions (e.g., Na^+, Ca^{2+}) with hydrogen ions (H^+) from the surrounding environment. This ion exchange leads to the dissolution of the material surface and the subsequent release of calcium (Ca^{2+}), phosphate (PO_4^{3-}), hydroxyl (OH^-), and fluoride (F^-) ions. The rate and extent of ion release depend on several factors, including material composition, particle size, porosity, and environmental pH. Importantly, many modern bioactive materials are designed to exhibit smart ion release, where ion liberation is enhanced under acidic conditions, such as those present during cariogenic attacks. This ensures that therapeutic effects are activated precisely when needed [16], [22], [23].

3.2 | Hydroxyapatite Formation Process

The formation of Hydroxyapatite (HA) or Hydroxycarbonate Apatite (HCA) represents a fundamental mechanism underlying the remineralization capability of bioactive dental materials. This process occurs through a well-defined sequence of physicochemical reactions initiated by the release of calcium and phosphate ions from the material into the surrounding environment. As the concentration of these ions increases, a supersaturated state is established relative to apatite, which facilitates the precipitation of ACP on the material surface or within demineralized regions of enamel and dentin. Subsequently, this amorphous phase gradually undergoes transformation into a more stable crystalline hydroxyapatite structure through a process of crystal growth and maturation. The newly formed apatite layer then integrates with the natural hydroxyapatite of the tooth structure via chemical bonding, resulting in a continuous and stable mineral interface. This regenerated mineral layer not only restores the lost mineral content of dental tissues but also serves as a protective barrier against future acid attacks, thereby significantly enhancing the overall resistance of the tooth [20].

3.3 | pH Modulation and Buffering Effect

Bioactive dental materials play a crucial role in regulating the local pH of the oral environment. Many of these materials, particularly calcium silicate-based systems, release hydroxyl ions (OH^-), resulting in the establishment of an alkaline environment, often with pH values exceeding 10–12. This alkaline shift exerts multiple beneficial effects, including the neutralization of acids produced by cariogenic bacteria, inhibition of demineralization processes, and promotion of remineralization. Furthermore, certain bioactive materials exhibit pH-responsive behavior, in which ion release is enhanced under acidic conditions typically associated with cariogenic challenges. This adaptive buffering capacity allows these materials to respond dynamically to environmental changes, thereby maintaining a favorable biochemical environment for mineral deposition and facilitating tissue repair [19].

3.4 | Antibacterial Mechanisms

The antibacterial properties of bioactive dental materials are mediated through a combination of direct and indirect mechanisms that collectively inhibit bacterial growth and biofilm formation. One of the primary mechanisms involves the elevation of local pH, which disrupts bacterial cell membranes, denatures proteins, and interferes with essential enzymatic activities required for bacterial survival. In addition, the release of biologically active ions such as fluoride (F^-), calcium (Ca^{2+}), and, in some formulations, silver or zinc ions contributes to antibacterial efficacy by inhibiting bacterial metabolism and reducing biofilm development. Ion release may also induce osmotic stress, creating an unfavorable environment for microbial viability. Among these, fluoride ions play a particularly significant role by inhibiting key enzymes involved in bacterial glycolysis, thereby reducing acid production. This antimicrobial activity is especially critical at the tooth–restoration interface, where bacterial colonization is a major contributing factor to the development of secondary caries [17–20], [22].

3.5 | Interfacial Bonding and Adhesion Enhancement

Bioactive dental materials differ from conventional restorative materials in that they establish a biofunctional interface through a combination of chemical and mechanical interactions, rather than relying predominantly on micromechanical retention. As shown in *Fig. 1*, the bonding mechanism involves ionic interactions between released calcium ions and the tooth structure, along with the formation of an apatite interfacial layer that bridges the restorative material and dentin. Additionally, the infiltration of material components into dentinal tubules enhances micromechanical retention. These combined mechanisms result in reduced microleakage, increased bond durability, and greater resistance to hydrolytic degradation over time. In certain systems, the hybrid layer formed between resin and dentin is further reinforced by mineral deposition, which stabilizes the collagen matrix and protects it from enzymatic degradation, thereby contributing to the long-term integrity of the adhesive interface [17–20].

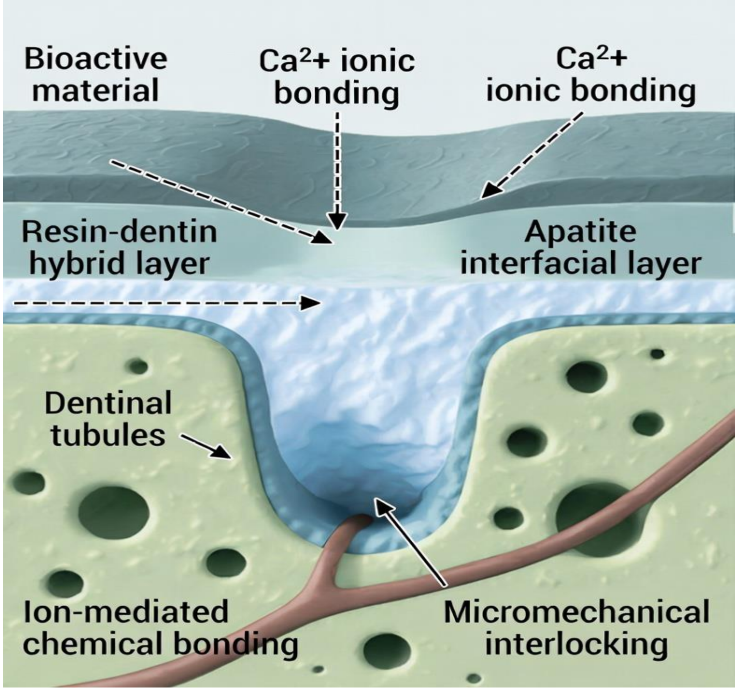

Fig. 1. Bonding mechanism of bioactive restorative materials to dentin.

3.6 | Adhesion Mechanisms

Adhesion in bioactive dental materials is achieved through a complex interplay of chemical and micromechanical bonding mechanisms, both of which contribute to the stability and longevity of the tooth restoration interface *(Fig. 2)*. Unlike conventional adhesive systems that rely primarily on micromechanical interlocking through the formation of a hybrid layer, bioactive materials introduce an additional chemical bonding component via ionic interactions. Specifically, released calcium and phosphate ions can interact with the mineral phase of enamel and dentin, facilitating the formation of a chemically integrated interface, often mediated by the deposition of an apatite layer. This dual bonding mechanism enhances both the immediate bond strength and its long-term stability. The smear layer, a byproduct of tooth preparation, plays a critical role in adhesion and can either hinder or facilitate bonding depending on the material and adhesive strategy employed. In traditional etch-and-rinse systems, the smear layer is removed to allow deeper resin penetration into the underlying dentin. In contrast, self-etch and certain bioactive systems modify or partially dissolve the smear layer, incorporating it into the bonding interface. This approach reduces technique sensitivity and preserves the underlying dentinal structure while still allowing effective adhesion. Resin infiltration into the demineralized collagen network of dentin is another key factor influencing bond quality. Effective infiltration results in the formation of a stable hybrid layer, where resin monomers polymerize within the collagen matrix, providing micromechanical retention. In bioactive systems, this process may be further enhanced by concurrent mineral deposition, which reinforces the hybrid layer and protects exposed collagen fibrils from hydrolytic and enzymatic degradation. The durability of the adhesive bond remains a major concern in restorative dentistry, as degradation over time can lead to microleakage, secondary caries, and restoration failure. Bioactive dental materials address this challenge by promoting ongoing remineralization at the interface, stabilizing the hybrid layer, and reducing the susceptibility of collagen to breakdown. Additionally, their ability to release ions and maintain a favorable chemical environment contributes to long-term bond preservation, making them a promising alternative to conventional adhesive systems [20].

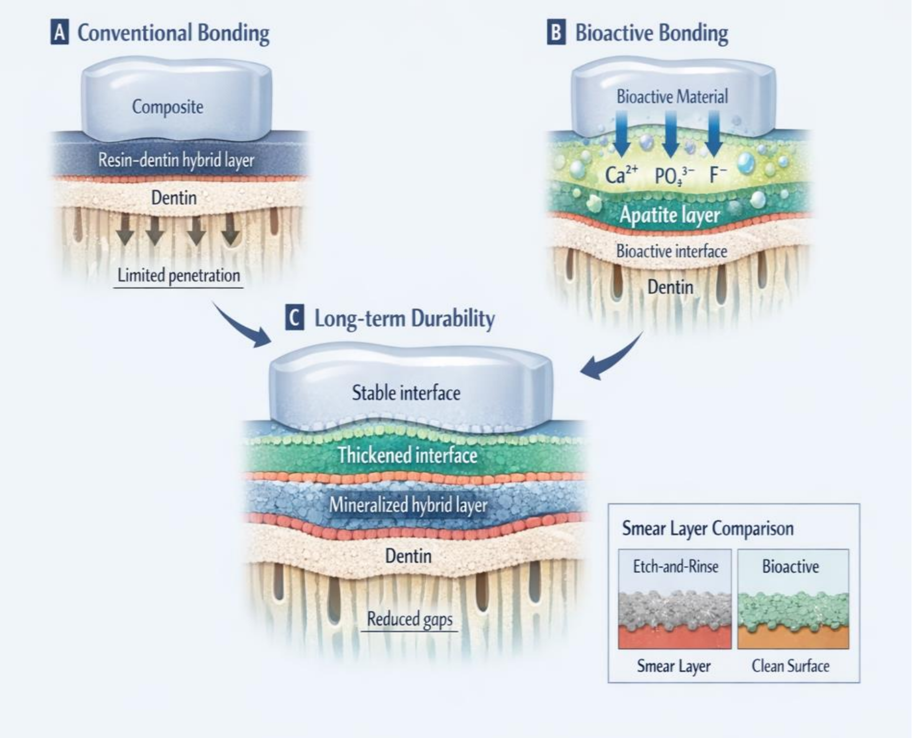

Fig. 2. Adhesion mechanisms of bioactive dental materials.

4 | Remineralization Process

The remineralization process is a fundamental biological and physicochemical mechanism through which bioactive dental materials contribute to the repair and stabilization of demineralized dental hard tissues, particularly enamel and dentin, which differ significantly in structure and mineral composition. Enamel, being highly mineralized (~96% inorganic content), exhibits a well-organized crystalline hydroxyapatite structure and is primarily affected by surface and subsurface mineral loss during early carious attacks, whereas dentin, with a lower mineral content and higher organic matrix (notably collagen), is more susceptible to rapid lesion progression but also presents a greater capacity for diffusion-mediated remineralization within its tubular structure. Bioactive materials facilitate remineralization by releasing key ions such as calcium (Ca^{2+}), phosphate (PO_4^{3-}), and fluoride (F^-), which collectively drive the reprecipitation of apatite minerals within demineralized zones *(Fig. 3)*. Calcium and phosphate ions serve as essential building blocks for hydroxyapatite formation, while fluoride enhances this process by promoting the formation of fluorapatite, a more acid-resistant mineral phase that improves the structural resilience of enamel and dentin. In early carious lesions, this ion-mediated process enables lesion arrest and even partial or complete caries reversal by restoring mineral density before cavitation occurs, particularly in non-cavitated enamel lesions where the collagen scaffold remains intact. The efficiency of remineralization is strongly influenced by pH cycling dynamics in the oral environment, where alternating periods of demineralization (under acidic conditions caused by bacterial metabolism) and remineralization (during neutral or alkaline pH phases stimulated by saliva or bioactive ion release) determine the net mineral balance. Bioactive materials enhance this natural repair cycle by acting as ion reservoirs that continuously supply remineralizing agents, especially during acidic challenges, thereby shifting the equilibrium toward net mineral gain and supporting the long-term preservation of tooth structure [16], [20], [22], [23].

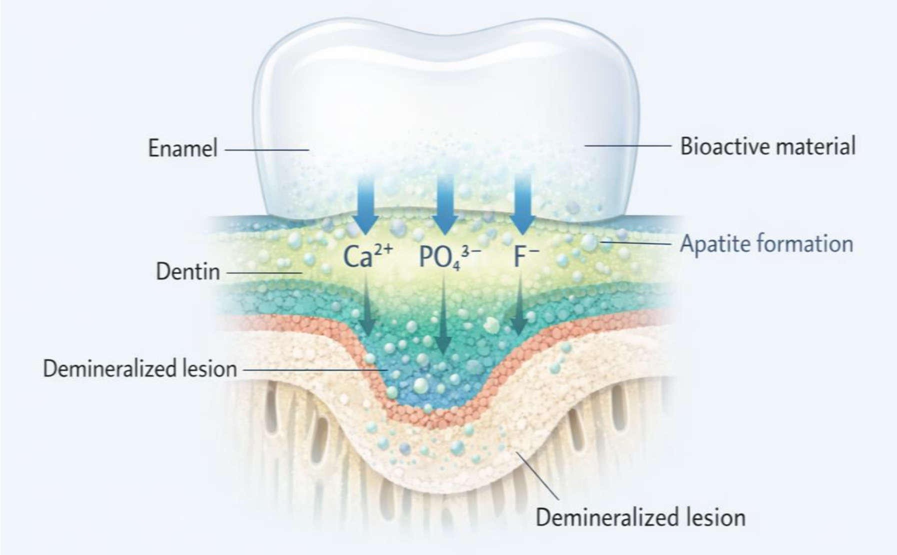

Fig. 3. Remineralization process in bioactive dental materials.

5 | Antibacterial Properties

The antibacterial properties of bioactive dental materials play a crucial role in preventing secondary caries, maintaining marginal integrity, and enhancing the long-term survival of restorations by directly targeting bacterial viability and disrupting biofilm formation at the tooth–restoration interface. One of the most important antibacterial mechanisms is the increase in local pH induced by materials such as calcium silicate-based cements and bioactive glasses, which release hydroxyl ions (OH^-) and create an alkaline environment that is unfavorable for the growth and survival of cariogenic bacteria, particularly Streptococcus mutans and Lactobacillus species. Elevated pH values (often exceeding 9–12 in certain systems) lead to bacterial cell membrane disruption, protein denaturation, and inhibition of essential enzymatic activities involved in glycolysis and energy metabolism, ultimately resulting in reduced acid production and bacterial death. In addition to alkalinity, ion release plays a significant role in antibacterial action, where ions such as calcium (Ca^{2+}), fluoride (F^-), zinc (Zn^{2+}), and occasionally silver (Ag^+) exert direct or indirect toxic effects on bacterial cells. These ions interfere with membrane permeability, disrupt proton gradients, inhibit DNA replication and enzymatic systems, and induce osmotic stress, which collectively compromise bacterial homeostasis. Fluoride ions are particularly important as they inhibit key metabolic enzymes such as enolase, thereby reducing bacterial acidogenicity and weakening the overall cariogenic potential of dental biofilms. Furthermore, calcium and phosphate ion release contributes indirectly by promoting remineralization, which reduces surface roughness and limits bacterial adhesion sites. Another key mechanism is biofilm inhibition, which involves the prevention of bacterial colonization and the disruption of mature biofilm architecture. Bioactive materials interfere with the initial adhesion of bacteria to tooth surfaces by modifying surface energy, reducing pellicle formation, and altering the physicochemical properties of the interface. As biofilms develop, released ions and alkaline conditions penetrate the Extracellular Polymeric Substance (EPS) matrix, weakening its structural integrity and increasing its permeability. This disruption facilitates bacterial detachment and enhances the effectiveness of saliva-mediated clearance. Additionally, some advanced bioactive systems exhibit quorum-sensing interference, reducing bacterial communication and virulence factor expression, which further limits biofilm maturation and pathogenicity [18]. The combined effect of elevated pH, ion toxicity, and biofilm destabilization results in a multifactorial antibacterial defense system that not only reduces bacterial load but also shifts the ecological balance of the oral microbiome toward a less cariogenic state, thereby significantly contributing to the prevention of secondary caries and the long-term success of restorative treatments. A summary of the antibacterial mechanisms of bioactive dental materials is presented in *Fig. 4* and *Table 3*.

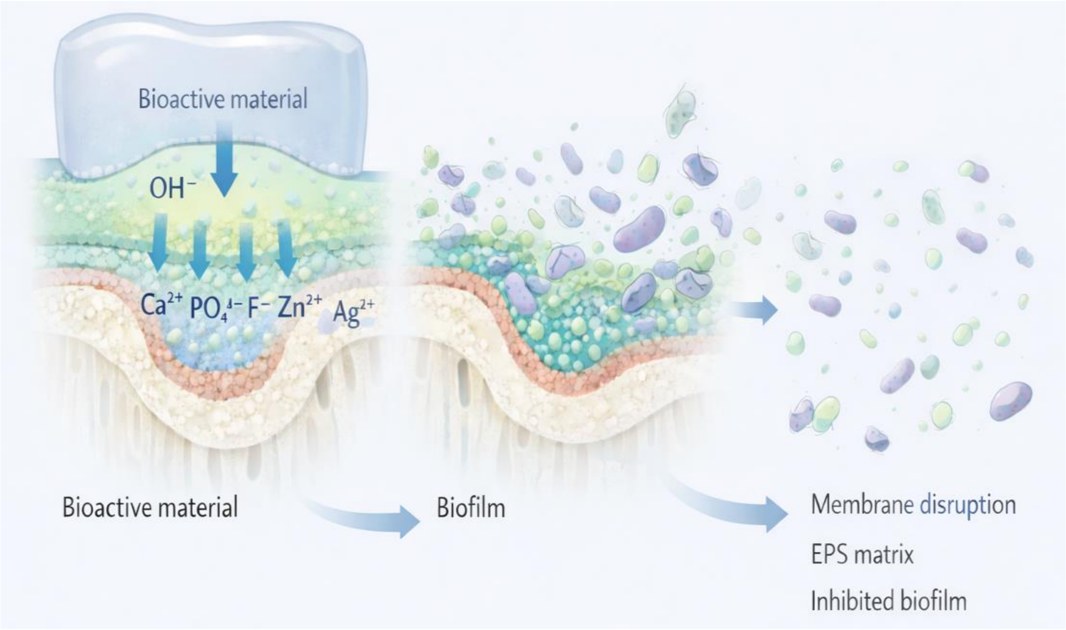

Fig. 4. Antibacterial mechanisms of bioactive dental materials.

Table 3. Antibacterial mechanisms of bioactive dental materials.

Mechanism	Description	Effect on Bacteria	Clinical Outcome
pH Increase	Release of OH^- ions raises local pH (alkaline environment).	Membrane damage, enzyme inhibition, reduced metabolism.	Lower bacterial survival and acid production.
Ion Release (Ca^{2+}, F^-, Zn^{2+}, Ag^+)	Continuous release of bioactive ions.	Toxic effects on cells, enzymes, and DNA inhibition.	Reduced bacterial viability.
Fluoride Action	Fluoride inhibits key bacterial enzymes.	Suppresses glycolysis and acid production.	Reduced cariogenic activity.
Biofilm Inhibition	Interference with bacterial adhesion and EPS matrix.	Disrupted biofilm formation and structure.	Less plaque accumulation.
Quorum Sensing Interference	Disruption of bacterial communication signals.	Reduced virulence and biofilm maturation.	Lower pathogenicity.
Surface Effects	Changes in surface energy and chemistry.	Reduced bacterial attachment.	Improved marginal seal.

6 | Clinical Applications of Bioactive Dental Materials

Bioactive dental materials have transformed modern clinical dentistry by shifting the focus from passive restoration to active biological interaction with dental tissues. Their ability to release therapeutic ions, promote remineralization, enhance adhesion, and exhibit antibacterial effects has led to their widespread use across multiple dental disciplines [16], [18], [23]. A summary of the clinical applications of bioactive dental materials across different fields of dentistry is presented in *Table 4*.

6.1 | Endodontics

In endodontic therapy, bioactive materials such as MTA and Biodentine are considered gold-standard materials for vital pulp therapy and regenerative procedures. These calcium silicate-based materials are extensively used in direct pulp capping, indirect pulp capping, pulpotomy, apexification, and perforation repair. Their high alkalinity (pH ≈ 12) provides strong antibacterial effects while simultaneously stimulating the differentiation of odontoblast-like cells. This leads to the formation of a mineralized dentin bridge, which is essential for maintaining pulp vitality. Additionally, their excellent sealing ability minimizes microleakage, reducing the risk of reinfection and improving long-term treatment success in endodontic applications [20].

6.2 | Restorative Dentistry

In restorative dentistry, bioactive materials are widely used in both direct and indirect restorations. Bioactive resin composites incorporate calcium phosphate, bioactive glass, or fluoride-releasing fillers, enabling them to actively participate in remineralization at restoration margins. These materials combine aesthetic properties with biological functionality, making them suitable for anterior and posterior restorations. GICs and RMGIs are particularly important due to their chemical bonding to tooth structure and sustained fluoride release. They are commonly used in cervical lesions, root caries, sandwich techniques, and Atraumatic Restorative Treatment (ART). Their ability to continuously release ions helps reduce secondary caries and enhances marginal integrity over time [22].

6.3 | Pediatric Dentistry

Bioactive dental materials play a critical role in pediatric dentistry due to their ease of use, minimal technique sensitivity, and preventive benefits. In primary teeth, materials such as GICs and RMGIs are widely used because they bond chemically to enamel and dentin without requiring complex adhesive procedures. Their fluoride-releasing capability is particularly beneficial in children with high caries risk, as it helps prevent demineralization and promotes remineralization of early lesions. Additionally, calcium silicate-based materials such as MTA and Biodentine are used in vital pulp therapy procedures in primary teeth, supporting pulp healing and maintaining tooth function until natural exfoliation. These properties make bioactive materials highly suitable for minimally invasive and child-friendly dental care [23].

6.4 | Preventive Dentistry and Early Caries Management

In preventive dentistry, bioactive materials are increasingly used as part of non-invasive and minimally invasive caries management strategies. They are particularly effective in the treatment of initial non-cavitated enamel lesions, where remineralization is still possible. Through continuous ion release (Ca^{2+}, PO_4^{3-}, and F^-), these materials help restore mineral balance and reverse early demineralization processes. Their ability to maintain a favorable pH environment further inhibits cariogenic bacterial activity and supports natural repair mechanisms. In addition, bioactive coatings and sealants are used to protect pits and fissures, reducing the risk of caries development in high-risk patients. Overall, these materials contribute significantly to shifting dentistry toward a preventive, disease-control-oriented approach rather than purely restorative intervention [16], [18], [20], [22–25].

Table 4. Clinical applications of bioactive dental materials.

Field of Dentistry	Common Materials	Main Clinical Uses	Key Bioactive Functions	Clinical Benefits
Endodontics	MTA, Biodentine, calcium silicate cements	Direct/indirect pulp capping, pulpotomy, apexification, perforation repair	Alkaline pH, ion release (Ca^{2+}), stimulation of dentin bridge formation	Pulp healing, antibacterial effect, improved sealing, long-term success
Restorative dentistry	Bioactive composites, GIC, RMGI	Class I–V restorations, cervical lesions, sandwich technique	Ion release (F^-, Ca^{2+}, PO_4^{3-}), chemical bonding, remineralization	Reduced secondary caries, improved marginal integrity, aesthetic restoration
Pediatric dentistry	GIC, RMGI, Biodentine, MTA	Primary tooth restorations, pulp therapy, ART	Fluoride release, chemical adhesion, pulp protection	High caries prevention, minimal technique sensitivity, pulp preservation
Preventive dentistry	GIC, sealants, bioactive coatings, bioactive varnishes	Early caries management, fissure sealing, non-cavitated lesions	Remineralization, pH buffering, antibacterial ion release	Caries reversal, enamel protection, reduced disease progression

7 | Limitations and Challenges

Despite their significant advantages, bioactive dental materials face several limitations that must be addressed to optimize their clinical performance and broader adoption. One of the primary concerns is their relatively lower mechanical strength compared to conventional restorative materials, particularly in high load-bearing areas, which may limit their use in stress-bearing posterior restorations. Additionally, long-term stability remains a challenge, as continuous ion release and interaction with the oral environment can lead to material degradation, reduced mechanical integrity, and changes in surface properties over time. Achieving controlled and sustained ion release is another critical issue, as excessive or rapid ion release may compromise structural stability, while insufficient release may reduce bioactivity and therapeutic effectiveness. Esthetic limitations are also notable in certain bioactive materials, especially glass ionomer-based systems and some calcium silicate cements, which may exhibit inferior translucency, color stability, and polishability compared to resin composites, thereby restricting their application in highly esthetic zones. Furthermore, the cost of advanced bioactive materials can be higher than that of traditional restorative options, which may limit their accessibility and routine use in some clinical settings. Collectively, these challenges highlight the need for continued research and material optimization to achieve an ideal balance between bioactivity, mechanical performance, esthetics, and economic feasibility [16], [18], [22–24].

8 | Conclusion

Bioactive dental materials represent a significant paradigm shift in restorative dentistry, moving beyond the traditional concept of passive tissue replacement toward a more dynamic, biologically driven approach to oral health management. As discussed throughout this study, these materials are uniquely designed to interact with the oral environment through mechanisms such as controlled ion release, hydroxyapatite formation, pH modulation, and antibacterial activity. This multifunctional behavior enables them not only to restore lost tooth structure but also to actively contribute to tissue regeneration, inhibition of cariogenic processes, and long-term preservation of dental tissues. Their ability to promote remineralization, particularly through the release of calcium, phosphate, and fluoride ions, plays a crucial role in reversing early carious lesions and reinforcing the structural integrity of enamel and dentin. In addition to their remineralizing potential, bioactive dental materials significantly enhance adhesion at the tooth restoration interface. By combining micromechanical retention with chemical bonding mechanisms, these materials form a more stable and durable interface that is less susceptible to degradation over time. The formation of an apatite interfacial layer further strengthens this bond and reduces microleakage, which is a key factor in preventing secondary caries. Moreover, their inherent antibacterial properties mediated through alkaline pH, ion toxicity, and biofilm disruption provide an additional layer of protection against bacterial colonization and acid production, thereby addressing one of the primary causes of restoration failure. The clinical applicability of bioactive materials across various dental disciplines, including endodontics, restorative dentistry, pediatric dentistry, and preventive care, highlights their versatility and growing importance in modern practice. Materials such as MTA, Biodentine, bioactive composites, and GICs have demonstrated considerable success in both therapeutic and preventive applications. Their use in minimally invasive and regenerative procedures aligns with contemporary trends in dentistry that emphasize tissue preservation and disease prevention rather than extensive mechanical intervention. However, despite these promising advantages, several limitations remain. Challenges related to mechanical strength, long-term stability, controlled ion release, esthetic properties, and cost continue to restrict their widespread clinical adoption in certain scenarios. These limitations underscore the need for ongoing research aimed at optimizing material composition, enhancing durability, and achieving a better balance between bioactivity and mechanical performance. Advances in nanotechnology, biomimetic design, and smart material systems are expected to play a pivotal role in overcoming these challenges and improving the clinical reliability of future bioactive materials. Bioactive dental materials offer a comprehensive and innovative solution to many of the longstanding challenges in restorative dentistry. Their ability to integrate biological functionality with restorative performance positions them as key components of next-generation dental care. As research and technology continue to evolve, these materials are expected to become increasingly refined and widely adopted, ultimately leading to improved clinical outcomes, extended restoration longevity, and enhanced patient care.

Authors' Contributions

The author solely conducted the research and prepared the manuscript and has approved its final version.

Data Availability

The data are available from the corresponding author upon reasonable request.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The author confirms consent for the publication of this work

Ethics Approval and Consent to Participate

This article does not include experiments involving humans or animals

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