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Bioactive Restorative Materials in Modern Dentistry: Principles, Clinical Applications, and Future Perspectives

Dr. Mariam Muneer[1], Dr Urmi Reshamdalal[2,*], Dr. Vikram Shad[3], Dr. Ekta Patel[4], Dr. Zulekha Yasin[5], Dr. Ayesha Aijaz[6], Dr. Sandeep Singh[7]

[1]BDS, Master of Philosophy (MPhil Biochemistry), Jinnah Medical and Dental College JMDC (University of Karachi), Karachi, Sindh, Pakistan
[2]BDS, Vaidik Dental College and Research Center, Daman, Gujarat, India
[3]DMD, MPH, BDS, University of Pennsylvania School of Dental Medicine, Philadelphia, PA, USA
[4]BDS, CRDH, S.J.M Dental College and Hospital, Chuttradurga, Karnataka India
[5]BDS, Ziauddin College of Dentistry, Ziauddin University, Karachi, Pakistan
[6]BDS, Jinnah Sindh Medical University, V22W+F2H Rafiqui H.J., Iqbal Shaheed Rd, Karachi, Pakistan
[7]BDS, MDS, Army College of Dental Sciences, Secunderabad, India
*Corresponding author: urmireshamdalal24@gmail.com

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Abstract Bioactive restorative materials have transformed restorative dentistry by combining structural restoration with therapeutic functions that promote tissue repair and oral health. Unlike conventional restorative materials, these materials actively interact with the surrounding dental tissues through ion release, remineralization, antibacterial activity, and stimulation of dentin–pulp regeneration. This review provides a comprehensive overview of the principles of bioactivity, classification of bioactive restorative materials, including glass ionomer cements, calcium silicate-based materials, bioactive composite resins, and bioactive ceramics, their mechanisms of action, clinical applications, advantages, limitations, and future developments. Current evidence suggests that bioactive restorative materials improve restoration longevity, reduce the risk of secondary caries, and support minimally invasive and regenerative treatment approaches. However, challenges related to long-term clinical evidence, mechanical properties, and cost remain. Future advances in nanotechnology, smart and self-healing materials, artificial intelligence-assisted material selection, and personalized restorative dentistry are expected to further enhance the clinical performance and therapeutic potential of these materials.

Keywords: *Bioactive restorative materials, Remineralization, Glass ionomer cement, Biodentine, Mineral trioxide aggregate, Bioactive composites, Restorative dentistry*

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1. Introduction

The primary objective of restorative dentistry is to restore the form, function, and esthetics of teeth affected by caries, trauma, developmental defects, or wear while preserving as much healthy tooth structure as possible. Over the past century, restorative dental materials have undergone significant evolution, progressing from metallic restorations such as dental amalgam and cast gold to tooth-colored materials including composite resins, glass ionomer cements (GICs), ceramics, and resin-based hybrid systems. This evolution has been driven by increasing patient expectations for esthetic outcomes, advances in material science, and a growing emphasis on minimally invasive and biologically oriented dental care. [1]

Despite their widespread clinical success, conventional restorative materials possess inherent limitations. Composite resins, although highly esthetic and mechanically favorable, are susceptible to polymerization shrinkage, marginal leakage, secondary caries, and degradation over time. [2] Similarly, dental amalgam, while durable and cost-effective, lacks adhesive properties and has raised environmental and esthetic concerns. [2] Traditional restorative materials are generally considered bioinert, serving primarily as passive replacements for lost tooth structure without actively participating in the biological processes of the oral environment. Consequently, restoration failure due to recurrent caries, marginal deterioration, and restoration fracture remains a significant clinical challenge. [3]

In response to these limitations, the concept of bioactivity has emerged as a transformative approach in restorative dentistry. A bioactive material is broadly defined as a material capable of eliciting a favorable biological response at the interface between the material and surrounding tissues, thereby promoting tissue repair, regeneration, or remineralization. [4] Unlike conventional restorative materials, bioactive materials interact dynamically with the oral environment through mechanisms such as ion release, apatite formation, antibacterial activity, pH modulation, and stimulation of cellular responses. [5] These properties enable bioactive materials to contribute not only to structural restoration but also to the maintenance and enhancement of tooth vitality and oral health.

Bioactive restorative materials encompass a diverse range of products, including glass ionomer cements, resin-modified glass ionomers, calcium silicate-based materials such as mineral trioxide aggregate (MTA) and Biodentine, bioactive glass-containing materials, giomers, and newer bioactive composite systems. [6] Many of these materials release calcium, phosphate, fluoride, or other therapeutic ions that promote remineralization of demineralized dental tissues and may reduce the risk of secondary caries. Furthermore, certain bioactive materials have demonstrated the ability to stimulate dentin bridge formation, support pulp healing, and encourage regenerative processes within the dentin-pulp complex. [7]

The increasing emphasis on preventive, minimally invasive, and regenerative dentistry has heightened interest in bioactive restorative materials. Their potential to combine restorative function with therapeutic benefits represents a paradigm shift from passive restoration toward biologically active treatment strategies. [8] As research in material science continues to advance, bioactive restorative materials are expected to play an increasingly important role in contemporary dental practice, offering new opportunities for improving restoration longevity, preserving tooth vitality, and enhancing patient outcomes. Therefore, this review aims to provide a comprehensive overview of the principles, classification, mechanisms of action, clinical applications, and future perspectives of bioactive restorative materials in modern dentistry.

2. Methods

This narrative review was conducted through a comprehensive literature search to identify published evidence on bioactive restorative materials used in contemporary dentistry. Electronic databases including PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar were searched using combinations of the keywords bioactive restorative materials, bioactive dental materials, glass ionomer cement, resin-modified glass ionomer, mineral trioxide aggregate, Biodentine, bioactive composites, giomers, bioactive glass, calcium silicate, hydroxyapatite, calcium phosphate, remineralization, and restorative dentistry.

Original research articles, clinical trials, systematic reviews, meta-analyses, narrative reviews, and relevant *in vitro* and *in vivo* studies published in English were considered for inclusion. Conference abstracts, editorials, letters to the editor, non-English publications, duplicate records, and studies lacking sufficient methodological detail or relevance to restorative dentistry were excluded. Additional relevant studies were identified through manual screening of the reference lists of selected articles. The retrieved literature was critically evaluated and synthesized to provide a comprehensive overview of the principles, classification, mechanisms of action, clinical applications, advantages, limitations, and future perspectives of bioactive restorative materials in modern dentistry.

3. Definition and Principles of Bioactivity

3.1. What is a Bioactive Material?

The concept of bioactivity was first introduced by Hench during the development of bioactive glass materials for orthopedic applications. A bioactive material is generally defined as a material capable of eliciting a specific biological response at the interface between the material and surrounding tissues, resulting in the formation of a bond between the material and the host tissue. [9] In dentistry, bioactive materials extend beyond their conventional restorative role by actively interacting with the oral environment to promote tissue repair, remineralization, and regeneration.

Unlike bioinert materials, which remain relatively passive after placement, bioactive restorative materials can release therapeutic ions, modulate the local pH, inhibit bacterial growth, stimulate mineral deposition, and enhance cellular activity within dental tissues. [10] These dynamic interactions enable the material to contribute to the maintenance of tooth vitality and restoration longevity. Consequently, bioactivity has emerged as a key characteristic in the development of next-generation restorative materials aimed at addressing both structural and biological aspects of dental disease.

Although definitions vary slightly among researchers, a dental restorative material is generally considered bioactive when it can induce a measurable biological effect that contributes to the preservation, repair, or regeneration of dental tissues without causing adverse local or systemic reactions. [11]

3.2. Requirements of Bioactive Restorative Materials

For a restorative material to be considered genuinely bioactive, it should possess several essential characteristics. First, the material must exhibit excellent biocompatibility, ensuring that it does not induce cytotoxic, inflammatory, or adverse tissue responses following placement [12]. Biocompatibility is particularly important in deep restorations where direct or indirect contact with the pulp-dentin complex may occur.

Second, bioactive materials should be capable of releasing therapeutic ions such as calcium, phosphate, fluoride, silicate, or strontium ions. These ions play crucial roles in promoting remineralization, enhancing mineral deposition, and maintaining the integrity of surrounding dental tissues [13].

Third, the material should demonstrate adequate mechanical properties, including sufficient compressive strength, wear resistance, fracture toughness, and dimensional stability to withstand functional stresses within the oral cavity. The biological benefits of a material must not compromise its clinical durability. Additionally, bioactive restorative materials should possess antibacterial or anti-biofilm properties to reduce microbial colonization and minimize the risk of secondary caries. Long-term ion release, chemical stability, resistance to degradation, and the ability to form a stable interface with tooth structure are also desirable features. Ideally, these materials should support natural healing processes while maintaining restorative function throughout their service life. [13]

3.3. Mechanisms of Action of Bioactive Restorative Materials

The clinical effectiveness of bioactive restorative materials is largely attributed to their ability to interact with the surrounding biological environment through multiple mechanisms. These mechanisms often occur simultaneously and contribute collectively to tissue preservation and regeneration.

3.3.1. Ion Release

Ion release is considered the fundamental mechanism underlying bioactivity. Many bioactive restorative materials continuously release calcium, phosphate, fluoride, silicate, sodium, and other ions into the surrounding environment [14]. These ions influence local biochemical processes and facilitate mineral deposition at the tooth-restoration interface. Calcium and phosphate ions contribute directly to hydroxyapatite formation, whereas fluoride ions enhance enamel resistance to acid dissolution and promote remineralization. The release of hydroxyl ions may increase local pH levels, creating an environment less favorable for cariogenic bacteria and supporting tissue healing. [15]

The extent and duration of ion release depend on material composition, environmental conditions, and exposure to oral fluids. Sustained ion release is particularly important for maintaining long-term therapeutic effects and supporting continuous mineral exchange between the restoration and dental tissues.

3.3.2. Remineralization

Remineralization refers to the restoration of mineral content within demineralized enamel or dentin. Bioactive restorative materials facilitate this process through the release of calcium, phosphate, and fluoride ions that precipitate as apatite crystals on tooth surfaces [16]. When exposed to saliva or dentinal fluid, many bioactive materials form a hydroxycarbonate apatite layer that closely resembles the mineral phase of natural tooth structure. This newly formed mineral layer can occlude dentinal tubules, strengthen weakened tissues, and improve the seal between the restoration and the tooth. [17]

The remineralization potential of bioactive materials is particularly valuable in minimally invasive dentistry, where preservation of affected but remineralizable dentin is preferred over extensive tissue removal. Through continuous mineral replenishment, these materials contribute to the prevention of recurrent caries and prolong restoration longevity.

3.3.3. Antibacterial Effects

Secondary caries remains one of the leading causes of restoration failure. Therefore, the antibacterial properties of bioactive restorative materials represent a significant clinical advantage. Several mechanisms contribute to their antimicrobial activity, including ion release, pH elevation, fluoride release, and inhibition of bacterial adhesion. [18]

Calcium silicate-based materials such as mineral trioxide aggregate and Biodentine produce alkaline environments with pH values exceeding 11, which can suppress the growth of cariogenic microorganisms. Similarly, fluoride-releasing materials reduce bacterial metabolism and acid production while enhancing enamel resistance to demineralization. [19] Certain contemporary bioactive materials also incorporate antimicrobial nanoparticles, bioactive glass particles, or quaternary ammonium compounds to further enhance antibacterial performance. By limiting bacterial colonization and biofilm formation, these materials help reduce the risk of recurrent decay around restorations. [19]

3.3.4. Dentin-Pulp Complex Interaction

One of the most distinctive characteristics of bioactive restorative materials is their ability to interact with the dentin-pulp complex. Traditional restorative materials typically provide only a physical barrier, whereas bioactive materials can stimulate biological responses within underlying tissues [20].

Calcium silicate-based materials release calcium ions that activate cellular signaling pathways involved in odontoblastic differentiation and mineralized tissue formation. These signals promote the formation of tertiary or reparative dentin, which serves as a natural protective barrier against external stimuli and bacterial invasion [21]. Furthermore, bioactive materials have been shown to enhance pulp cell proliferation, migration, and differentiation while maintaining favorable conditions for tissue healing. These properties make them particularly valuable in vital pulp therapy procedures such as direct pulp capping, indirect pulp treatment, and pulpotomy.

3.3.5. Tissue Regeneration

Recent advances in biomaterials research have expanded the role of bioactive restorative materials beyond repair toward true tissue regeneration. Regeneration involves the restoration of both structure and function through activation of cellular and molecular pathways responsible for tissue development and healing. [22]

Many bioactive materials serve as scaffolds capable of supporting stem cell attachment, proliferation, and differentiation. Calcium silicate cements and bioactive glasses can stimulate the release of growth factors from dentin matrices, promoting angiogenesis, mineralization, and tissue regeneration. [23] The regenerative potential of these materials aligns with contemporary concepts of minimally invasive and biologically driven dentistry. As material science continues to evolve, future bioactive restorative systems may integrate smart biomaterials, nanotechnology, and regenerative medicine approaches to further enhance tissue repair and restoration outcomes.

Collectively, these mechanisms demonstrate that bioactive restorative materials function not merely as passive replacements for lost tooth structure but as active therapeutic agents capable of influencing biological processes within the oral environment. Their ability to release beneficial ions, promote remineralization, inhibit bacterial activity, interact with the dentin-pulp complex, and support tissue regeneration forms the scientific foundation for their growing role in modern restorative dentistry. Figure 1

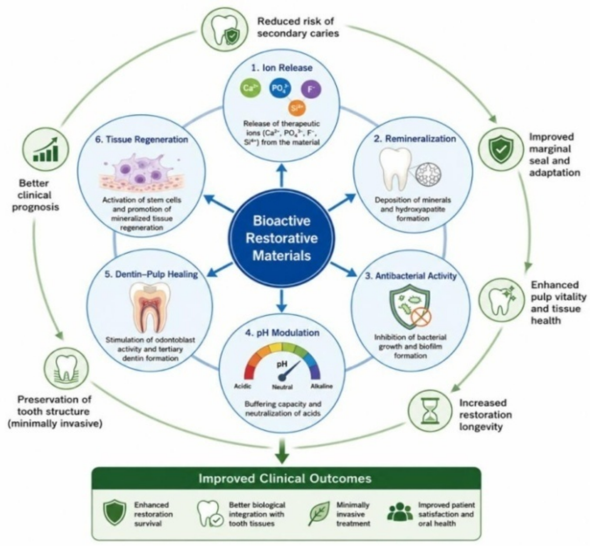

Figure 1. Mechanism of action of Bioactive restorative materials

4. Classification of Bioactive Restorative Materials

Bioactive restorative materials comprise a diverse group of biomaterials designed to interact beneficially with dental tissues through ion release, remineralization, antibacterial activity, and regenerative potential. Based on their chemical composition and primary mechanism of action, these materials can be broadly classified into four major categories: glass ionomer cements, calcium silicate-based materials, bioactive composite resins, and bioactive ceramics and glasses. Each category possesses unique physicochemical properties and clinical indications that contribute to the advancement of biologically driven restorative dentistry.

4.1. Glass Ionomer Cements (GICs)

Glass ionomer cements (GICs) were introduced by Wilson and Kent in the early 1970s and remain among the earliest restorative materials recognized for their bioactive properties. [29]

These materials are formed through an acid-base reaction between a fluoroaluminosilicate glass powder and aqueous polyalkenoic acids, resulting in a chemically bonded restoration capable of releasing therapeutic fluoride ions over extended periods. [24]

4.1.1. Conventional Glass Ionomer Cements

Conventional GICs exhibit several properties that distinguish them from traditional restorative materials. Their ability to chemically bond to enamel and dentin eliminates the need for extensive cavity preparation and adhesive systems. Furthermore, continuous fluoride release contributes to enamel remineralization and reduces the incidence of secondary caries, making these materials particularly valuable for pediatric dentistry, atraumatic restorative treatment (ART), cervical lesions, and restorations in high-caries-risk patients. [25]

The bioactivity of conventional GICs is primarily attributed to sustained fluoride release, calcium and phosphate ion exchange, and their capacity to absorb fluoride from external sources and subsequently re-release it, a phenomenon commonly referred to as the "fluoride recharge" effect. In addition, the formation of an ion-exchange layer at the tooth-restoration interface contributes to a durable chemical bond and improved marginal sealing. [26]

Despite these biological advantages, conventional GICs possess relatively low flexural strength, poor fracture resistance, moisture sensitivity during initial setting, and inferior wear resistance compared with resin composites, thereby limiting their use in stress-bearing posterior restorations. [26]

4.1.2. Resin-Modified Glass Ionomer Cements

Resin-modified glass ionomer cements (RMGICs) were developed to overcome many of the mechanical shortcomings associated with conventional GICs. These materials combine the traditional acid-base reaction with resin polymerization, typically through incorporation of hydrophilic monomers such as 2-hydroxyethyl methacrylate (HEMA). [27]

Compared with conventional GICs, RMGICs exhibit improved mechanical strength, enhanced esthetics, greater wear resistance, reduced moisture sensitivity, and immediate light-activated setting. Importantly, they retain many of the biological properties of conventional GICs, including fluoride release, chemical adhesion to tooth structure, and remineralization potential. [27]

However, the presence of resin components may reduce overall ion release compared with conventional GICs, while polymerization shrinkage and potential cytotoxicity associated with residual HEMA monomers remain concerns. Nevertheless, RMGICs continue to serve as versatile restorative materials for cervical lesions, pediatric restorations, liners, bases, and intermediate restorations. [27]

4.2. Calcium Silicate-Based Materials

Calcium silicate-based materials represent one of the most biologically active classes of restorative and reparative dental materials. Their bioactivity results primarily from the release of calcium hydroxide during hydration, leading to an alkaline environment, antibacterial effects, hydroxyapatite formation, and stimulation of dentin regeneration. [28]

4.2.1. Mineral Trioxide Aggregate (MTA)

Mineral trioxide aggregate (MTA), introduced by Torabinejad and colleagues in the 1990s, revolutionized vital pulp therapy and endodontic repair procedures due to its exceptional biocompatibility and regenerative potential. MTA consists primarily of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and radiopacifying agents such as bismuth oxide. Upon hydration, calcium hydroxide is released, increasing local pH and promoting the deposition of hydroxyapatite crystals at the material-tooth interface. Numerous clinical and histological studies have demonstrated that MTA stimulates odontoblastic differentiation, tertiary dentin formation, angiogenesis, and pulp healing. Consequently, it has become the gold standard for direct pulp capping, pulpotomy, apexification, perforation repair, and root-end filling procedures. [29]

Despite its excellent biological performance, MTA exhibits several disadvantages, including prolonged setting time, difficult handling characteristics, relatively high cost, tooth discoloration associated with bismuth oxide, and limited compressive strength during early setting. [29,30]

4.2.2. Biodentine

Biodentine is a newer calcium silicate-based material developed to address many of the limitations associated with MTA. It contains highly purified tricalcium silicate, calcium carbonate, zirconium oxide, and water-soluble polymers that accelerate setting and improve handling characteristics.

Compared with MTA, Biodentine demonstrates shorter setting time, superior mechanical properties, improved handling, greater compressive strength, and reduced risk of tooth discoloration. It also releases calcium ions capable of stimulating mineralization, dentin bridge formation, and pulp healing. Due to these favorable properties, Biodentine is widely used for direct and indirect pulp capping, pulpotomy, dentin replacement beneath restorations, perforation repair, and management of deep carious lesions. Several clinical studies have reported comparable or superior outcomes to MTA in vital pulp therapy. [31,32]

4.2.3. Bio-C Repair Materials

Bio-C Repair represents a newer generation of premixed calcium silicate-based bioceramic repair materials. Unlike traditional powder-liquid systems, Bio-C Repair is supplied as a ready-to-use paste, reducing operator variability and improving clinical convenience. [33]

These materials exhibit excellent sealing ability, dimensional stability, high alkalinity, sustained calcium ion release, and favorable cytocompatibility with human dental pulp stem cells. Experimental studies have demonstrated their capacity to induce mineralized tissue formation and support regenerative healing processes comparable to those observed with MTA and Biodentine. Although early laboratory and clinical evidence is promising, additional long-term randomized clinical trials are required to establish their durability and clinical performance across various restorative and endodontic applications. [34]

4.3. Bioactive Composite Resins

Conventional resin composites provide excellent esthetics and mechanical properties but generally lack intrinsic biological activity. Recent developments in material science have led to the incorporation of bioactive fillers capable of releasing therapeutic ions while preserving the favorable physical characteristics of composite restorations. [35]

4.3.1. Giomers

Giomers are hybrid restorative materials containing prereacted glass ionomer (PRG) fillers embedded within a resin matrix. These fillers are produced by reacting fluoroaluminosilicate glass with polyacrylic acid prior to incorporation into the composite resin. [36]

Giomers combine the esthetics and polishability of resin composites with the fluoride release and recharge capabilities of glass ionomer technology. In addition to fluoride release, they demonstrate moderate remineralization potential, reduced plaque accumulation, and improved resistance to recurrent caries. Clinically, giomers are widely used for Class III, IV, and V restorations, pediatric restorations, fissure sealants, and preventive resin restorations. [36]

4.3.2. ACTIVA BioACTIVE Restorative

ACTIVA BioACTIVE Restorative is a relatively new restorative material that combines a resilient resin matrix with bioactive ionic fillers and modified glass ionomer technology. The manufacturer claims that the material releases and recharges calcium, phosphate, and fluoride ions while exhibiting physical properties comparable to resin composites. [37]

Laboratory investigations have demonstrated favorable fracture resistance, ion release, marginal adaptation, and reduced microleakage. Furthermore, ACTIVA has shown the ability to form apatite-like mineral deposits on its surface under simulated oral conditions. However, independent long-term clinical evidence remains limited, and further randomized controlled clinical trials are necessary to validate the manufacturer's claims regarding superior bioactivity and restoration longevity. [38]

4.3.3. Emerging Bioactive Composite Resins

Recent research has focused on developing next-generation bioactive composites incorporating nanoparticles, bioactive glass fillers, amorphous calcium phosphate (ACP), nano-hydroxyapatite, calcium silicate particles, antibacterial monomers, and self-healing technologies. These materials aim to provide controlled ion release, enhanced remineralization, antibacterial activity, and improved resistance to polymerization shrinkage while maintaining excellent esthetic and mechanical performance. Although many remain experimental, they represent a promising direction toward multifunctional restorative materials capable of actively preventing restoration failure. [39]

4.4. Bioactive Ceramics and Glasses

Bioactive ceramics constitute another important class of restorative biomaterials characterized by their ability to chemically bond with mineralized tissues through apatite formation. These materials are increasingly incorporated into restorative, endodontic, and regenerative dental applications.

4.4.1. Bioactive Glass

Bioactive glass, originally developed by Hench as 45S5 Bioglass®, consists primarily of silica, calcium oxide, sodium oxide, and phosphorus pentoxide. Upon exposure to physiological fluids, the material undergoes controlled dissolution, releasing calcium and phosphate ions that facilitate hydroxycarbonate apatite formation on its surface. [40]

This apatite layer promotes strong bonding with hard tissues, enhances remineralization, occludes dentinal tubules, and exhibits antibacterial activity due to local pH elevation. Consequently, bioactive glass has found applications in restorative materials, air-polishing powders, desensitizing agents, periodontal regeneration, bone grafts, and implant coatings. [40]

4.4.2. Hydroxyapatite-Based Materials

Hydroxyapatite (HA) is chemically similar to the inorganic mineral phase of enamel and dentin, making it highly biocompatible and osteoconductive. Synthetic hydroxyapatite has been incorporated into restorative materials, adhesives, toothpastes, and preventive products because of its excellent remineralization potential. Nano-hydroxyapatite particles possess increased surface area and enhanced interaction with enamel crystals, allowing effective repair of early enamel lesions and reduction of dentin hypersensitivity through tubule occlusion. [41]

4.4.3. Calcium Phosphate Materials

Calcium phosphate-based materials include amorphous calcium phosphate (ACP), tricalcium phosphate (TCP), octacalcium phosphate, and other calcium phosphate derivatives capable of releasing calcium and phosphate ions under acidic conditions. Among these, ACP has received considerable attention because of its ability to maintain supersaturation of calcium and phosphate ions, thereby promoting rapid remineralization of early carious lesions. Calcium phosphate nanoparticles have also been incorporated into composite resins and adhesive systems to provide continuous mineral release while maintaining satisfactory mechanical performance. Ongoing research continues to optimize these materials by improving ion-release kinetics, mechanical strength, and long-term clinical stability. Their integration into restorative systems represents an important step toward developing multifunctional biomaterials capable of simultaneously restoring tooth structure and promoting biological repair. [42,43] [Table 1]

Table 1. Classification of Bioactive Restorative Materials

Category	Representative Materials (Examples)	Primary Bioactive Components	Major Bioactive Mechanisms	Common Clinical Applications
Glass Ionomer Cements (GICs)	Conventional GICs (Fuji IX, Ketac Molar), Resin-modified GICs (Fuji II LC, Vitremer)	Fluoroalumin osilicate glass, polyalkenoic acid	Fluoride release and recharge, calcium/phosphate ion exchange, chemical bonding to tooth structure	Cervical restorations, ART, pediatric restorations, liners/bases, high-caries-risk patients
Calcium Silicate-Based Materials	Mineral Trioxide Aggregate (MTA), Biodentine, Bio-C Repair, MTA Repair HP	Tricalcium silicate, dicalcium silicate, calcium hydroxide	Calcium ion release, alkaline pH, hydroxyapatite formation, dentin bridge formation, pulp regeneration	Direct pulp capping, pulpotomy, perforation repair, apexification, root-end filling, dentin replacement
Bioactive Composit e Resins	Giomers (Beautifil), ACTIVA BioACTIVE Restorative, calcium phosphate-containing composites	PRG fillers, bioactive glass fillers, calcium phosphate nanoparticles	Fluoride/calcium/phos phate release, remineralization, antibacterial effects	Class I–V restorations, preventive resin restorations, pediatric restorations
Bioactive Glasses	45S5 Bioglass®, NovaMin®, Biomin®	Silica, calcium oxide, sodium oxide, phosphorus pentoxide	Hydroxycarbonate apatite formation, remineralization, dentinal tubule occlusion, antibacterial effects	Desensitizing agents, remineralization products, restorative fillers, regenerative applications
Hydroxya patite-Based Materials	Nano-hydroxyapatite (nHA), HA-containing composites and adhesives	Calcium phosphate apatite crystals	Enamel/dentin remineralization, mineral deposition, tubule occlusion	Early caries management, dentin hypersensitivity treatment,
				preventive dentistry
Calcium Phosphat e-Based Materials	Amorphous calcium phosphate (ACP), tricalcium phosphate (TCP), octacalcium phosphate	Calcium and phosphate reservoirs	Supersaturation of calcium/phosphate ions, apatite precipitation, remineralization	Remineralizing composites, adhesives, preventive materials

5. Clinical Applications of Bioactive Restorative Materials

Bioactive restorative materials have gained widespread clinical acceptance because of their ability to restore tooth structure while simultaneously promoting biological repair and reducing disease progression. Their unique properties, including ion release, remineralization, antibacterial activity, and stimulation of hard tissue formation, make them suitable for a variety of clinical applications.

5.1. Caries Management

Bioactive restorative materials play a significant role in contemporary caries management by promoting remineralization of demineralized tooth structure and reducing the risk of recurrent caries. Continuous release of calcium, phosphate, and fluoride ions facilitates hydroxyapatite formation and strengthens adjacent enamel and dentin. Furthermore, their antibacterial properties help suppress cariogenic microorganisms, thereby contributing to the prevention of secondary caries around restoration margins. In deep carious lesions, calcium silicate-based materials such as Biodentine and mineral trioxide aggregate (MTA) promote dentin bridge formation and pulp healing, supporting minimally invasive management strategies. [44]

5.2. Direct Restorations

Several bioactive restorative materials, including glass ionomer cements, resin-modified glass ionomers, giomers, and bioactive composite resins, are routinely used for direct restorations. These materials are particularly suitable for Class I–V restorations in patients with moderate to high caries risk because of their fluoride release and remineralization potential. Their ability to chemically bond to tooth structure and maintain marginal integrity contributes to improved restoration longevity and reduced incidence of secondary caries. [45]

5.3. Pediatric Dentistry

Bioactive restorative materials are extensively used in pediatric dentistry due to their biocompatibility, fluoride release, and ease of clinical application. Glass ionomer cements remain the material of choice for atraumatic restorative treatment (ART), particularly in community-based and resource-limited settings. Additionally, these materials are effective in the management of early childhood caries, where their cariostatic properties and chemical adhesion to tooth structure help preserve primary teeth while minimizing the need for extensive cavity preparation. [46]

5.4. Endodontic Applications

Calcium silicate-based bioactive materials have transformed vital pulp therapy and endodontic treatment. Materials such as MTA and Biodentine are widely used for direct and indirect pulp capping, pulpotomy, apexification, perforation repair, and root-end filling procedures. Their ability to release calcium ions, induce hard tissue formation, and provide an excellent biological seal promotes pulp vitality, tissue regeneration, and long-term treatment success. [47]

5.5. Minimally Invasive Dentistry

The philosophy of minimally invasive dentistry emphasizes preservation of healthy tooth structure and biological repair rather than extensive tissue removal. Bioactive restorative materials support this approach by enabling selective caries removal and facilitating remineralization of affected dentin. Their regenerative and antibacterial properties allow clinicians to preserve tooth vitality while achieving durable restorations, making them integral components of modern conservative dental practice. [48] Figure 2

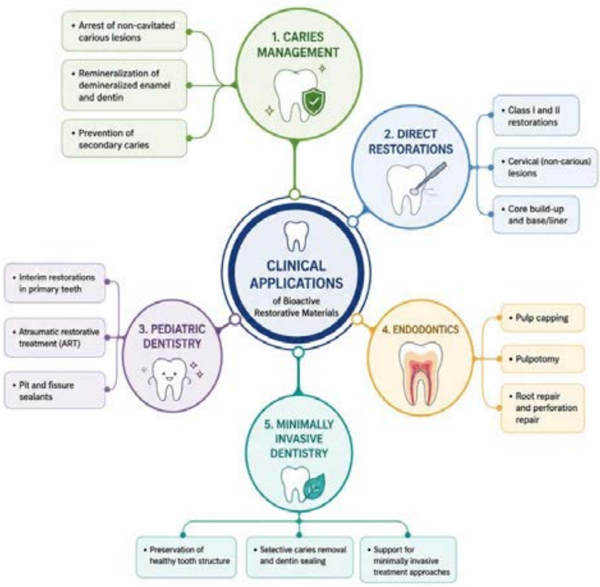

Figure 2. Clinical application of Bioactive restorative materials

6. Advantages and Limitations of Bioactive Restorative Materials

Bioactive restorative materials have gained considerable attention because they offer both therapeutic and restorative benefits, distinguishing them from conventional restorative materials. Their ability to promote remineralization, release bioactive ions, and support tissue healing has expanded their clinical applications in restorative, pediatric, and endodontic dentistry. However, despite these advantages, several limitations related to mechanical properties, cost, esthetics, and long-term clinical evidence continue to influence their widespread adoption. [49,50,51,52] Table 2

Table 2. Summary of the advantages and limitations of bioactive restorative materials

Advantages	Limitations
Remineralization potential: Continuous release of calcium, phosphate, and fluoride Ions promotes remineralization of	Higher cost: Many bioactive restorative materials, particularly calcium silicate-based materials and bioactive composites, are more
demineralized enamel and dentin, helping preserve tooth structure.	expensive than conventional restorative materials.
Fluoride release and recharge: Glass ionomer-based materials and giomers release fluoride over time and can be recharged with topical fluoride, providing prolonged cariostatic effects.	Limited long-term clinical evidence: Although laboratory and short-term clinical studies are promising, robust long-term randomized clinical trials are still limited for many newer bioactive materials.
Reduced risk of secondary caries: Antibacterial activity and sustained ion release decrease bacterial colonization and help minimize recurrent caries at restoration margins.	Variable mechanical properties: Some bioactive materials exhibit lower compressive strength, wear resistance, and fracture toughness than conventional resin composites, limiting their use in high-stress areas.
Excellent biological compatibility: Most bioactive materials are highly biocompatible, supporting pulp vitality and minimizing inflammatory responses.	Technique sensitivity: Certain materials require careful handling, moisture control, or specific placement protocols to achieve optimal clinical performance.
Potential regenerative effects: Calcium silicate-based materials stimulate odontoblastic differentiation, tertiary dentin formation, and tissue repair, making them suitable for vital pulp therapy.	Material-specific limitations: Individual materials may present drawbacks such as prolonged setting time (MTA), possible tooth discoloration, moisture sensitivity (conventional GICs), or polymerization shrinkage (bioactive resin-based materials).
Chemical adhesion to tooth structure: Glass ionomer-based materials chemically bond to enamel and dentin, reducing microleakage and improving marginal integrity.	Esthetic limitations: Conventional glass ionomer cements generally exhibit inferior translucency, polishability, and color stability compared with modern resin composites.
Support for minimally invasive dentistry: Their remineralization and sealing abilities allow preservation of affected dentin and reduce unnecessary removal of healthy tooth structure.	Limited ion-release duration: The therapeutic ion release of some materials gradually decreases over time, potentially reducing their long-term bioactive effects.
Versatile clinical applications: Bioactive materials are suitable for restorative dentistry, pediatric dentistry, endodontics, cervical lesions, and preventive procedures.	Need for further innovation: Improvements in mechanical performance, esthetics, handling characteristics, and long-term durability are still needed for widespread clinical adoption.

7. Future Directions

The field of bioactive restorative materials is rapidly evolving with advances in biomaterials science, nanotechnology, artificial intelligence (AI), and regenerative medicine. Future research aims to develop restorative materials that not only replace lost tooth structure but also actively monitor, repair, and regenerate dental tissues, ultimately improving long-term clinical outcomes.

7.1. Nanotechnology-Enhanced Bioactive Materials

Nanotechnology has emerged as a promising approach to improve the biological and mechanical properties of restorative materials. Incorporation of nanoparticles such as nano-hydroxyapatite, bioactive glass nanoparticles, calcium phosphate nanoparticles, and silver nanoparticles enhances ion release, remineralization, antibacterial activity, and mechanical strength. Owing to their high surface-area-to-volume ratio, nanoparticles facilitate greater interaction with dental tissues, resulting in improved mineral deposition and restoration longevity. Future developments are expected to focus on controlled ion-release systems and multifunctional nanocomposites with enhanced durability and therapeutic efficacy. [53]

7.2. Smart Restorative Materials

Smart restorative materials are designed to respond dynamically to changes in the oral environment. These materials can detect variations in pH, temperature, moisture, or bacterial activity and subsequently release therapeutic ions or antimicrobial agents when needed. Such "responsive" behavior allows targeted remineralization during acidic challenges and enhanced protection against recurrent caries. Continued research into stimuli-responsive biomaterials may significantly improve the longevity and clinical performance of restorative treatments. [54,55]

7.3. Self-Healing Materials

One of the most exciting innovations in restorative dentistry is the development of self-healing materials capable of repairing microcracks before they progress to restoration failure. These materials incorporate microcapsules, healing agents, or dynamic polymer networks that are activated when structural damage occurs. Self-healing technology has the potential to increase restoration lifespan, reduce replacement frequency, and minimize treatment costs while preserving tooth structure. Although still largely experimental, this technology represents a promising direction for future restorative materials. [56]

7.4. AI-Guided Material Selection

Artificial intelligence is increasingly being integrated into clinical decision-making in dentistry. AI-based systems may assist clinicians in selecting the most appropriate restorative material by analyzing patient-specific factors such as caries risk, occlusal loading, tooth location, esthetic requirements, and medical history. Machine learning algorithms can also predict restoration longevity and treatment outcomes using large clinical datasets, thereby facilitating evidence-based and personalized treatment planning. As digital dentistry continues to advance, AI is expected to play an important role in optimizing restorative material selection and improving clinical outcomes. [57]

7.5. Personalized Restorative Dentistry

The future of restorative dentistry is shifting toward personalized treatment approaches tailored to individual patient characteristics. Advances in genomics, salivary diagnostics, oral microbiome analysis, and digital technologies may enable clinicians to select restorative materials based on each patient's biological profile, caries susceptibility, and regenerative capacity. Combined with chairside digital workflows and three-dimensional (3D) printing technologies, personalized restorative dentistry has the potential to improve treatment predictability, restoration longevity, and patient satisfaction. The integration of bioactive materials with regenerative therapies and precision dentistry is expected to redefine restorative dental care in the coming decades. [58]

Overall, future bioactive restorative materials are likely to evolve from passive restorative agents into multifunctional therapeutic systems capable of preventing disease, promoting tissue regeneration, and adapting to the dynamic oral environment. Continued interdisciplinary research involving material scientists, engineers, clinicians, and artificial intelligence experts will be essential for translating these innovations into routine clinical practice.

8. Conclusion

Bioactive restorative materials have transformed modern restorative dentistry by combining structural restoration with therapeutic functions such as ion release, remineralization, antibacterial activity, and tissue regeneration. Current evidence suggests that materials including glass ionomer cements, calcium silicate-based materials, bioactive composite resins, and bioactive ceramics can improve restoration longevity while preserving tooth vitality.

Clinically, these materials are particularly beneficial in minimally invasive dentistry, caries management, pediatric dentistry, and vital pulp therapy due to their biological compatibility and regenerative potential. However, their selection should be based on the clinical indication and the available scientific evidence.

Future research should focus on long-term clinical studies, enhancement of mechanical properties, and the development of advanced technologies such as nanotechnology-based materials, smart and self-healing restoratives, and AI-assisted personalized treatment approaches. These innovations are expected to further expand the role of bioactive restorative materials in contemporary dental practice.

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