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REVIEW ARTICLE

BIOACTIVE RESTORATIVE MATERIALS IN CONTEMPORARY OPERATIVE DENTISTRY: A SCOPING REVIEW OF CLINICAL APPLICATIONS AND BIOLOGICAL OUTCOMES

Vahe Azatyan[1], Arpine Chraghyan[2]

[1]Professor of Department Therapeutic Dentistry, Yerevan State Medical University, Yerevan, Armenia

[2]Department Therapeutic Dentistry, Yerevan State Medical University after M. Heratsi, Yerevan, Armenia

Corresponding author: Vahe Azatyan **E-mail:** vahe.azatyan@gmail.com

Professor of Department Therapeutic Dentistry, Yerevan State Medical University,Yerevan, Armenia

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Abstract

Background: The development of bioactive restorative materials has introduced a significant paradigm shift in contemporary operative dentistry, moving beyond the traditional concept of passive replacement of lost tooth structure toward biologically active approaches capable of interacting with dental tissues and the oral environment. Unlike conventional restorative materials, bioactive materials are designed to release therapeutic ions, promote remineralization, enhance interfacial stability, modulate microbial activity, and potentially support dentin–pulp complex responses. Recent advances have resulted in the introduction of calcium silicate-based cements, bioactive glass-containing materials, ion-releasing composites, giomers, alkasite-based restoratives, and biomimetic restorative systems.

Objective: This scoping review aimed to map the available scientific evidence regarding contemporary bioactive restorative materials used in operative dentistry, with particular emphasis on their clinical applications, biological mechanisms, restorative performance, and reported clinical outcomes.

Methods: A scoping review was conducted according to the Joanna Briggs Institute (JBI) methodology and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. A comprehensive literature search was performed in PubMed, Scopus, Web of Science, ScienceDirect, Cochrane Library, and Google Scholar databases. Studies published between 2000 and 2026 evaluating bioactive restorative materials in permanent and primary dentition were considered eligible. The initial search identified 106 records, and after title/abstract screening, full-text assessment, and application of predefined eligibility criteria, 55 studies were included in the final evidence synthesis.

Results: The included evidence demonstrated that bioactive restorative materials represent a heterogeneous group with different compositions and biological potentials. Calcium silicate-based materials showed favorable outcomes in vital pulp therapy, dentin repair, and reparative dentin formation due to their calcium ion release and ability to induce mineralized tissue deposition. Bioactive glass-containing materials demonstrated potential for remineralization through calcium and phosphate ion release and hydroxyapatite formation. Glass ionomer-based materials and giomers exhibited clinically relevant fluoride release, chemical adhesion to tooth structures, and anticariogenic effects. Ion-releasing resin-based composites and newer bioactive restorative systems demonstrated promising laboratory findings; however, long-term clinical evidence remains limited and heterogeneous.

Conclusions: Bioactive restorative materials represent an important advancement in minimally invasive and biologically oriented operative dentistry. Current evidence supports their potential to enhance remineralization, improve restoration–tooth interaction, and contribute to improved biological outcomes. Nevertheless, variations in bioactivity assessment methods, limited long-term clinical trials, and insufficient standardization remain major challenges. Future investigations should focus on well-designed randomized

Keywords: Bioactive restorative materials; Operative dentistry; Calcium silicate cements; Bioactive glass; Ion-releasing materials; Remineralization; Biomimetic dentistry; Dental composites.

1.INTRODUCTION

Operative dentistry has undergone a substantial conceptual transformation over the past several decades. Conventional restorative treatment has traditionally focused on the mechanical replacement of lost or damaged tooth structure using materials selected primarily for their strength, durability, esthetic properties, and clinical handling. Although resin composites, glass ionomer-based materials, and other established restorative systems have demonstrated important clinical benefits, restoration longevity remains influenced by multiple factors, including polymerization shrinkage, marginal degradation, fracture, wear, patient-related caries risk, and secondary caries. These limitations have encouraged the development of restorative strategies that seek not only to replace lost tissue but also to interact with the biological environment of the tooth and support preservation of remaining dental structures[1–5].

The concept of bioactive restorative materials has emerged within this broader transition toward minimally invasive and biologically oriented dentistry. In contrast to conventional passive restorative materials, bioactive materials are intended to participate in dynamic interactions with dental tissues and the surrounding oral environment. Their proposed biological effects may involve the release of calcium, phosphate, fluoride, and other ions; formation of apatite-like mineral phases; modification of the local chemical environment; and support of remineralization or mineralized tissue formation [6–10]. The term “bioactive,” however, encompasses a heterogeneous group of materials with substantially different compositions, mechanisms of action, and levels of clinical evidence [6,7].

The biological rationale for these materials is closely related to the increasing recognition of the dentin–pulp complex as a dynamic tissue capable of responding to injury and participating in endogenous repair. Preservation of pulp vitality and conservation of sound dentin are fundamental principles of contemporary minimally invasive operative dentistry, particularly in the management of deep carious lesions and pulp exposure[11–14]. Materials that can establish favorable physicochemical conditions at the dentin–material interface and support mineralized tissue formation may therefore provide additional opportunities for tissue preservation and biologically based restorative treatment [10–14].

Calcium silicate-based materials constitute one of the most extensively investigated groups of bioactive dental materials. Mineral trioxide aggregate (MTA), originally developed for endodontic applications, demonstrated favorable physicochemical and biological characteristics, including alkaline pH, calcium ion release, biocompatibility, and the capacity to support hard-tissue formation [16–20]. These properties subsequently facilitated the broader application of calcium silicate-based materials in procedures involving pulp preservation and mineralized tissue repair. Clinical and experimental investigations have reported favorable outcomes following the use of MTA in direct pulp capping and other procedures involving the dentin–pulp complex [18,19,23,51].

The development of newer hydraulic calcium silicate materials has further expanded the clinical application of this material class. Biodentine was introduced as a dentin replacement and bioactive material with the objective of combining biological compatibility with improved handling and restorative characteristics[21,45]. Experimental investigations have demonstrated favorable interactions between Biodentine and dental pulp tissues, while clinical studies have evaluated calcium silicate materials as alternatives to calcium hydroxide in direct pulp capping and vital pulp therapy[22,23,51,52]. Nevertheless, differences in material composition, clinical protocols, case selection, and follow-up periods make direct comparison between studies difficult [21–23,45,46].

Bioactive glass represents another important category of biologically active dental materials. Bioactive glasses undergo surface reactions in aqueous environments that involve ion exchange, dissolution, and subsequent formation of calcium- and phosphate-rich mineral phases. These reactions can result in the formation of an apatite-like layer capable of interacting with mineralized dental tissues [24–26]. Consequently, bioactive glass-containing materials have been investigated for enamel and dentin remineralization, dentinal tubule occlusion, and modification of mineral-depleted dental surfaces [27–29,47]. Experimental evidence suggests that their remineralization potential is influenced by glass composition, particle characteristics, ion-release behavior, substrate condition, and exposure environment [24–29,47].

Ion-releasing restorative systems have extended the concept of bioactivity into direct restorative dentistry. Conventional resin composites continue to provide important esthetic and mechanical advantages; however, polymerization shrinkage and shrinkage stress remain relevant considerations in their clinical performance [1,2,35]. In response, restorative materials containing functional fillers and ion-releasing components have been developed to provide additional chemical and biological functions while maintaining the handling and esthetic characteristics expected from direct restorative materials [27,30–38].

Giomer-based materials are one example of this approach. These materials incorporate pre-reacted glass-ionomer fillers into resin-based formulations and have demonstrated fluoride release and recharge characteristics while retaining properties associated with resin-based restorative systems[30,34]. Fluoride-releasing materials may contribute to modification of the local cariogenic environment and potentially support remineralization; however, the magnitude and clinical relevance of ion release vary among formulations and experimental conditions [30–34]. Therefore, ion release alone should not be considered sufficient evidence of clinically meaningful bioactivity.

Other ion-releasing restorative systems, including calcium phosphate-containing resin composites and alkasite materials, have also attracted increasing attention. Calcium phosphate-based resin systems have been investigated for their capacity to release mineral-related ions and interact with dental tissues [50]. Alkasite restorative materials have demonstrated ion-release and alkalizing properties that may contribute to modification of the local environment and remineralization processes [37]. Similarly, resin-based and ormocer-containing restorative systems have been investigated with respect to their mechanical properties and ion-release behavior [38]. Although these materials demonstrate promising physicochemical characteristics, the available evidence remains heterogeneous and long-term clinical validation is still required.

The biological activity of restorative materials must also be considered in relation to their mechanical and clinical performance. A restorative material must function within a complex oral environment characterized by repeated mechanical loading, temperature fluctuations, moisture, bacterial activity, dietary challenges, and chemical changes. Consequently, increased ion release or mineral-forming potential does not necessarily translate into improved restoration survival or superior clinical outcomes. Conventional resin composites, glass ionomer-based materials, and newer bioactive systems each demonstrate different combinations of mechanical performance, esthetic properties, handling characteristics, ion release, and biological interaction [1–5,31,36,41].

An additional challenge is the lack of a universally accepted definition and standardized methodology for evaluating bioactivity in restorative dentistry. Studies have assessed bioactivity using diverse approaches, including measurements of ion release, alkalizing potential, apatite formation, mineral deposition, dentin remineralization, dentinal tubule occlusion, antimicrobial activity, cytocompatibility, and interfacial mineralization[8–10,27,28,37,46,48,53]. Although these methodologies provide important information about individual material properties, they do not necessarily represent the complete biological behavior of a restoration under clinical conditions. Differences in experimental models, immersion media, testing periods, analytical techniques, and outcome definitions further complicate comparison across studies.

The distinction between laboratory evidence and clinical effectiveness is therefore particularly important. A substantial proportion of research on bioactive restorative materials has been performed using in vitro or experimental models that provide valuable information regarding material chemistry and biological mechanisms but cannot fully reproduce the oral environment. Clinical outcomes such as restoration survival, marginal integrity, postoperative sensitivity, maintenance of pulp vitality, secondary caries, wear, fracture, and patient-centered outcomes require longer-term clinical investigation [3–5,18,23,41,51,52]. Evidence from systematic reviews and clinical studies also indicates that established restorative materials remain clinically relevant, and the introduction of bioactive functionality should therefore be evaluated in the context of overall restorative performance rather than ion release alone [3,41].

The increasing diversity of bioactive restorative materials has consequently created a broad and heterogeneous evidence base encompassing material science, laboratory investigations, biological studies, and clinical research. Calcium silicate cements, bioactive glasses, glass ionomer-derived systems, giomers, alkasite materials, and ion-releasing resin composites differ considerably in their mechanisms of action and intended clinical applications. A comprehensive mapping of this evidence is therefore necessary to clarify the current state of the field, identify areas of relatively strong evidence, and recognize domains in which clinical validation remains insufficient.

A scoping review methodology is particularly appropriate for such an emerging and heterogeneous field because it permits systematic mapping of evidence across different study designs and research domains without restricting the review to a narrowly defined clinical intervention or outcome. The methodological framework initially proposed by Arksey and O'Malley and subsequently refined by Levac et al. provides a structured approach for identifying, selecting, and charting evidence across broad research questions [42,43]. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) further provides guidance for transparent reporting of scoping review methodology and results [44].

Therefore, this scoping review aimed to systematically

map the available evidence regarding bioactive restorative materials used in contemporary operative dentistry. Specifically, the review sought to characterize the principal categories of bioactive restorative materials, summarize their proposed biological mechanisms and clinical applications, describe reported biological and restorative outcomes, and identify important limitations and evidence gaps. By integrating laboratory, experimental, and clinical evidence, this review aims to provide a comprehensive overview of the current role of bioactive restorative materials and to identify priorities for future clinical research and material development.

2. MATERIALS AND METHODS

2.1 Study Design and Reporting Framework

This study was designed as a scoping review to systematically map the available evidence on bioactive restorative materials used in contemporary operative dentistry. The review was conducted in accordance with the methodological guidance of the Joanna Briggs Institute (JBI) Evidence Synthesis Manual for Scoping Reviews and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) recommendations.

A scoping review design was considered appropriate because the available literature encompasses a broad range of materials, clinical indications, biological mechanisms, experimental models, and study designs. The review therefore aimed to characterize the existing evidence rather than determine the comparative effectiveness of a specific intervention. The methodological process comprised formulation of the review question, definition of eligibility criteria, systematic literature searching, screening and selection of studies, data charting, and descriptive synthesis of the identified evidence.

The review protocol and methodological framework were established before initiation of the literature search. The predefined approach was applied throughout the study selection and data extraction processes to ensure consistency and transparency.

2.2 Review Question and PCC Framework

The review question was developed according to the Population–Concept–Context (PCC) framework recommended by the JBI for scoping reviews.

Population:
The population comprised patients undergoing operative dental treatment involving permanent or primary teeth, as well as experimental models used to investigate interactions between restorative materials and dental tissues.

Concept:
The concept of interest was bioactive restorative materials used in operative dentistry. This included calcium silicate-based materials, mineral trioxide aggregate (MTA), hydraulic calcium silicate cements, bioactive glass-containing materials, glass ionomer-derived systems, giomers, alkasite restorative materials, ion-releasing resin composites, calcium phosphate-containing restorative materials, and other biomimetic restorative systems.

Context:
The context included clinical and experimental applications relevant to operative dentistry, including direct restorative procedures, vital pulp therapy, dentin repair and replacement, remineralization, prevention or management of secondary caries, restoration–tooth interface interactions, and biological responses of dental tissues.

The primary review question was:

What is the current evidence regarding the clinical applications, biological properties, and outcomes of bioactive restorative materials used in contemporary operative dentistry?

2.3 Information Sources and Search Strategy

A comprehensive electronic literature search was conducted using six information sources: PubMed/MEDLINE, Scopus, Web of Science Core Collection, ScienceDirect, Cochrane Library, and Google Scholar.

The search strategy combined controlled vocabulary, including MeSH terms where applicable, with free-text terms related to bioactive restorative materials, operative dentistry, remineralization, and dentin–pulp interactions. The principal search terms included:

- “bioactive restorative materials”
- “bioactive dental materials”
- “bioactive restorative dentistry”
- “calcium silicate cement”
- “mineral trioxide aggregate”
- “MTA”
- “Biodentine”
- “hydraulic calcium silicate”
- “bioactive glass”
- “ion-releasing restorative material”

- "giomer"
- "alkasite restorative material"
- "calcium phosphate composite"
- "remineralization"
- "dentin repair"
- "pulp-dentin complex"
- "operative dentistry"
- "restorative dentistry"

The terms were combined using the Boolean operators AND and OR to maximize retrieval of potentially relevant publications. The search covered studies published between January 2000 and March 2026. Search strategies were adapted to the specific indexing systems and search interfaces of each database.

The initial electronic search identified 106 records. The complete database-specific search strategies and retrieval results were documented to facilitate reproducibility of the search process.

2.4 Eligibility Criteria

Eligibility criteria were established before study screening.

Inclusion Criteria

Studies were eligible for inclusion when they:

1. investigated bioactive restorative materials relevant to operative dentistry;
2. evaluated clinical applications, biological properties, restorative performance, or interactions with dental tissues;
3. involved permanent or primary teeth or relevant dental tissue models;
4. assessed outcomes such as ion release, remineralization, mineralized tissue formation, dentin repair, pulp response, antimicrobial activity, restoration integrity, or clinical performance;
5. used in vitro, ex vivo, in vivo, animal, clinical trial, observational, or translational study designs;
6. were published as full-text articles in peer-reviewed journals; and
7. were available in English.

Exclusion Criteria

Studies were excluded when they:

1. investigated biomaterials unrelated to operative restorative procedures;
2. focused exclusively on implantology, orthodontics, oral surgery, or prosthodontics;
3. evaluated only mechanical properties without addressing biological or restorative relevance;
4. were conference abstracts, letters, editorials, expert opinions, or other non-peer-reviewed publications; or
5. did not provide accessible full-text information.

2.5 Study Selection Process

All records retrieved from the electronic databases were compiled in a reference management system, and duplicate records were identified and removed before screening. Study selection was subsequently performed in two sequential stages.

Title and abstract screening:

Two reviewers independently assessed the titles and abstracts of the retrieved records against the predefined eligibility criteria. Publications that were clearly unrelated to the review question or failed to meet the inclusion criteria were excluded at this stage.

Full-text assessment:

The full texts of potentially eligible publications were subsequently examined in detail. Studies were included when they fulfilled all predefined eligibility criteria. Any disagreements between the reviewers were resolved through discussion and consensus. When consensus could not be achieved, a third reviewer was consulted.

The electronic search identified 106 records. After removal of 21 duplicates, 85 records underwent title and abstract screening, of which 18 were excluded. Sixty-seven full-text articles were subsequently assessed for eligibility, and 12 were excluded following full-text evaluation. A total of **55 studies** met the predefined eligibility criteria and were included in the final scoping review synthesis.

The overall study selection process was documented using a PRISMA-ScR flow diagram **Figure** 1**.**

2.6 Data Extraction and Charting Process

Data were extracted using a standardized data-charting form developed in accordance with the JBI methodology for scoping reviews. The charting process was designed to capture both the characteristics of the included studies and the principal findings relevant to the review question.

The following variables were extracted:

- first author and year of publication;
- country or geographic setting of the study;
- study design;
- sample characteristics;
- type and category of bioactive restorative material;
- chemical composition or principal active components;
- clinical or experimental application;
- evaluation and analytical methods;
- biological outcomes;
- restorative and clinical outcomes;
- principal findings; and
- reported limitations.

Two reviewers independently extracted the relevant information from the included studies. The extracted data were subsequently compared, and discrepancies were resolved through discussion and consensus.

2.7 Data Synthesis and Presentation

Because substantial heterogeneity was anticipated across the included studies with respect to material composition, experimental conditions, clinical indications, study designs, outcome measures, and follow-up periods, quantitative pooling of the results was not considered appropriate. Accordingly, no meta-analysis was performed.

The extracted evidence was synthesized descriptively and organized according to the principal objectives of the review:

1. categories and characteristics of bioactive restorative materials;
2. mechanisms underlying their biological activity;
3. clinical and experimental applications;
4. reported biological and restorative outcomes; and
5. limitations, evidence gaps, and priorities for future research.

The findings were presented through narrative synthesis and structured evidence-mapping tables. This approach allowed comparison of the principal material categories and identification of consistent findings, areas of uncertainty, and gaps in the current evidence base concerning the clinical application of bioactive restorative materials in contemporary operative dentistry.

3. RESULTS

3.1 Study Selection

The initial electronic search identified **106 records** potentially relevant to bioactive restorative materials in operative dentistry. Following the removal of duplicate records, the remaining publications were screened by title and abstract according to the predefined eligibility criteria. Records that did not address bioactive restorative materials, lacked relevant biological or clinical outcomes, or were outside the scope of operative dentistry were excluded.

Potentially eligible publications subsequently underwent full-text assessment. Studies were retained when they satisfied all predefined inclusion criteria. Following completion of the screening and eligibility assessment process, 55 studies were included in the final scoping review synthesis.

The included evidence encompassed a broad range of research designs, including in vitro and ex vivo investigations, animal studies, randomized clinical trials, prospective clinical studies, and observational research.

The study selection process was documented according to the PRISMA-ScR framework and is presented in the corresponding PRISMA-ScR flow diagram **Figure** 1**.**

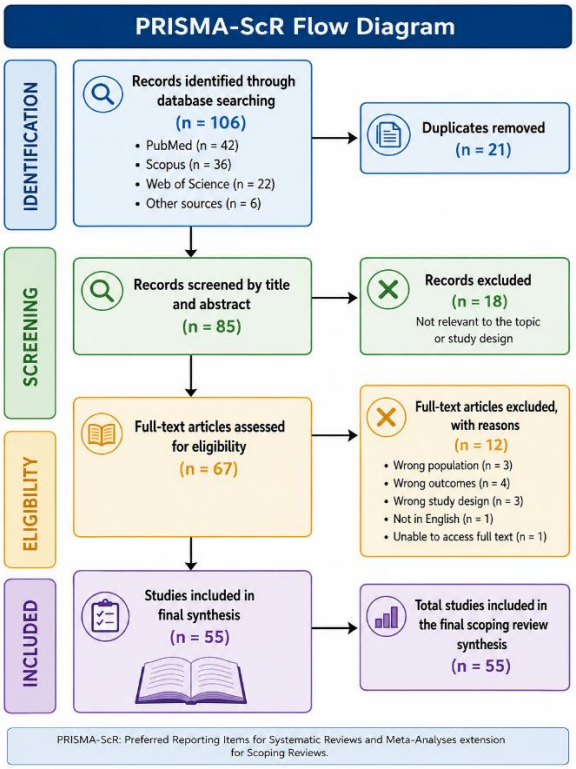


Figure 2. Overview of the major categories, biological mechanisms, and clinical applications of bioactive restorative materials.

3.4 Biological Outcomes of Bioactive Restorative Materials

Mineral deposition and remineralization were among the most frequently investigated biological outcomes across the included studies. Calcium silicate-based materials demonstrated calcium release and alkaline reactions associated with mineralized tissue formation and favorable responses of pulp and dentin tissues. These characteristics supported their continued investigation in procedures intended to preserve pulp vitality and promote reparative dentin formation.

Bioactive glass-containing materials demonstrated the capacity to release calcium and phosphate ions and to promote the formation of apatite-like mineral phases under appropriate experimental conditions. These properties provided a biological basis for their investigation in enamel and dentin remineralization and mineral-loss prevention.

Ion-releasing restorative materials demonstrated variable biological effects depending on their composition, filler characteristics, surrounding environment, and experimental conditions. Fluoride release, acid-neutralizing capacity, mineral deposition, and antimicrobial activity were reported among the principal outcomes. However, the magnitude and persistence of these effects varied considerably between materials and study protocols.

The principal biological outcomes identified across the included evidence are summarized in Table 3.

Table 3. Reported Biological Outcomes of Included Studies

Biological outcome	Main findings
Calcium ion release	Frequently reported for calcium silicate-based materials and associated with mineralization and tissue-repair processes
Phosphate release	Mainly reported for bioactive glass and calcium phosphate-containing materials
Remineralization potential	Demonstrated through mineral deposition, apatite formation, or recovery of mineral content in experimental enamel/dentin models
Pulp–dentin response	Calcium silicate-based materials generally demonstrated favorable tissue responses and reparative dentin formation
Antimicrobial activity	Reported for selected materials, particularly those producing alkaline conditions or releasing biologically active ions
Cytocompatibility	Generally favorable cellular responses were reported in experimental models, although results varied according to material composition and test conditions
Restoration–tooth interaction	Several studies reported mineral deposition or modification of the interface and, in selected experimental models, improved sealing-related outcomes

3.5 Clinical Applications of Bioactive Restorative Materials

The clinical evidence indicated that bioactive restorative materials have been investigated across several areas of operative dentistry. Vital pulp therapy represented an important clinical application, particularly in the management of deep carious lesions and exposed pulp tissue. Calcium silicate-based materials were frequently investigated because of their favorable biological compatibility, calcium release, and potential to support hard-tissue barrier formation.

Additional applications included dentin replacement in deep cavities, use as liners or bases, cervical restorations, restoration of non-carious cervical lesions, and direct restorative procedures. Glass ionomer-derived materials, giomers, alkasite restoratives, and ion-releasing resin-based materials were predominantly evaluated in relation to ion release, remineralization potential, and restorative performance.

The principal clinical applications identified in the included studies are summarized in Table 4.

Table 4. Clinical Applications of Bioactive Restorative Materials

Clinical application	Frequently investigated materials	Reported outcomes
Direct pulp capping	MTA, Biodentine, hydraulic calcium silicate materials	Pulp vitality preservation and reparative hard-tissue formation
Indirect pulp therapy	Calcium silicate-based materials and bioactive liners	Dentin preservation and favorable pulpal responses

Deep carious lesion management	Biodentine and MTA-based materials	Favorable biological responses and mineralized tissue formation
Dentin replacement	Calcium silicate-based materials	Biological compatibility and sealing-related properties
Cervical restorations	Glass ionomer-derived materials and bioactive composites	Fluoride release, chemical adhesion, and restorative performance
Direct restorative procedures	Giomers, alkasite materials, and bioactive resin composites	Ion release, remineralization potential, and acceptable restorative performance

3.6 Mechanical and Clinical Performance

Although biological activity represented a major focus of the literature, a proportion of the included studies also assessed mechanical properties, handling characteristics, marginal adaptation, and clinical performance. The results varied substantially according to material composition and intended application.

Calcium silicate-based materials generally demonstrated favorable biological characteristics and suitability for applications involving the dentin–pulp complex. However, certain materials may present practical limitations related to setting characteristics, handling, and mechanical performance when compared with conventional resin-based restorative materials.

In contrast, bioactive resin-based materials and other ion-releasing restorative systems generally offered advantages in terms of esthetics, handling, and integration into conventional direct restorative procedures. Nevertheless, the extent to which their ion-release characteristics translate into clinically meaningful biological benefits remains insufficiently established.

Evidence concerning long-term restoration survival, wear resistance, marginal integrity, and comparative clinical performance was limited for several newer bioactive restorative systems.

The principal advantages and limitations identified across the major material categories are presented in Table 5.

Table 5. Summary of Reported Advantages and Limitations

Material group	Main advantages	Main limitations
Calcium silicate materials	Favorable biocompatibility, calcium release, pulp preservation, and mineralized tissue formation	Handling and setting limitations; mechanical limitations in selected restorative applications
Bioactive glass materials	Mineral deposition, apatite formation, and remineralization potential	Limited long-term clinical evidence and dependence on material composition and application conditions
Giomers	Fluoride release and recharge, esthetics, and conventional resin-based handling	Biological effects vary according to formulation; long-term clinical superiority remains uncertain
Alkasite materials	Multiple ion release and acid-neutralizing potential	Limited independent long-term clinical evidence
Bioactive resin composites	Esthetic properties, restorative versatility, and ion-release potential	Need for further long-term clinical validation of biological benefits

3.7 Evidence Gaps Identified

The evidence mapping identified several important gaps in the current literature. A substantial proportion of the available evidence was derived from laboratory-based investigations, whereas long-term clinical studies were comparatively limited. This imbalance restricts the ability to determine whether biological effects demonstrated under controlled experimental conditions translate into clinically meaningful improvements in restoration longevity, pulp preservation, secondary caries prevention, or patient-centered outcomes.

Considerable heterogeneity was also observed in the terminology and criteria used to define bioactivity. Studies differed in their assessment of ion release, mineral deposition, apatite formation, antimicrobial activity, cellular responses, and clinical outcomes. Differences in experimental models, testing conditions, follow-up periods, and outcome definitions further limited direct comparison between material categories.

The available evidence therefore supports continued investigation of bioactive restorative materials but does not establish a uniform clinical advantage for any single material category. Future research should emphasize standardized definitions and assessment protocols, adequately powered randomized clinical trials, long-term follow-up, direct comparison with established restorative materials, and clinically relevant patient-centered outcomes.

4. DISCUSSION

The findings of this scoping review demonstrate the expanding role of bioactive restorative materials in contemporary operative dentistry and reflect a gradual shift from conventional restorative concepts toward biologically oriented treatment strategies. Rather than functioning solely as passive substitutes for lost tooth structure, contemporary restorative materials are increasingly designed to interact with dental tissues and the surrounding oral environment through ion release, mineral deposition, modulation of the restoration–tooth interface, and, in selected applications, support of tissue repair. This transition is consistent with the broader principles of minimally invasive dentistry, in which preservation of tooth structure and maintenance of biological function are considered fundamental components of restorative treatment.

The evidence mapped in this review indicates that calcium silicate-based materials remain among the most extensively investigated bioactive systems. Their clinical relevance is primarily related to their interaction with the dentin–pulp complex, calcium ion release, alkaline activity, and ability to promote mineralized tissue formation. These characteristics have supported their widespread application in vital pulp therapy, direct and indirect pulp protection, dentin repair, and related procedures aimed at maintaining pulp vitality. Clinical investigations of materials such as mineral trioxide aggregate and Biodentine have reported favorable biological responses and clinically relevant outcomes. Nevertheless, the available evidence also indicates that calcium silicate-based materials are not universally optimal for all restorative situations. Handling characteristics, setting behavior, mechanical strength, moisture sensitivity, and material-specific properties may influence their clinical application, particularly in areas exposed to substantial functional loading [45,46,51–53].

Bioactive glass and ion-releasing restorative materials constitute another important component of the current evidence base. Bioactive glass systems can release calcium and phosphate ions and promote the formation of apatite-like mineral phases under appropriate conditions. These mechanisms provide a biological rationale for their application in remineralization and dentin surface modification. Similarly, giomers, alkasite materials, and other ion-releasing restorative systems have been developed to combine conventional restorative characteristics with the potential biological benefits of ion release. However, the clinical relevance of these mechanisms should be interpreted cautiously. Ion release, apatite precipitation, or remineralization demonstrated under laboratory conditions does not necessarily indicate superior restoration survival, reduced secondary caries, or improved patient-centered outcomes. The magnitude and duration of ion release are influenced by material composition, pH, moisture, surface area, aging, and environmental conditions [24–31,33,34,37,47,50].

An important finding emerging from the mapped literature is the lack of a universally accepted definition of “bioactivity” for restorative materials. The term is currently used to describe a broad range of material behaviors, including ion release, apatite formation, remineralization, antimicrobial activity, cellular responses, and interactions with mineralized dental tissues. These outcomes are biologically relevant but are not equivalent measures of clinical effectiveness. For example, a material may demonstrate substantial ion release without producing a clinically meaningful improvement in restoration longevity. Similarly, apatite formation in an artificial solution may not accurately reproduce the biological and mechanical conditions encountered in the oral cavity. Standardized definitions and evaluation protocols are therefore required to facilitate meaningful comparisons between materials and to establish clearer relationships between laboratory findings and clinical outcomes [10,24–28,46–50,53,54].

The relationship between biological activity and mechanical performance represents another important consideration. A restorative material must provide an appropriate balance between biological function, structural stability, esthetics, handling, adhesion, and resistance to degradation. Calcium silicate-based materials may provide substantial biological advantages but are not necessarily suitable as definitive restoratives in all load-bearing situations. Conversely, resin-based bioactive materials generally offer favorable handling, esthetics, and mechanical characteristics but have less consistently demonstrated long-term biological benefits. Consequently, the current evidence does not support the concept of a single universally superior bioactive restorative material. Material selection should instead be based on the clinical indication, remaining tooth structure, pulpal status, functional loading, caries risk, moisture control, and the specific biological objective of treatment [1–3,21,31,35,36,38,41,50,54,55].

The present review also identified an important discrepancy between the volume of laboratory research and the availability of clinically meaningful evidence. A substantial proportion of the literature focuses on physicochemical characterization, ion release, mineral deposition, cytocompatibility, antimicrobial activity, or other surrogate outcomes. Such investigations are essential for understanding mechanisms of material activity, but they cannot independently establish clinical effectiveness. From a clinical perspective, outcomes such as restoration survival, marginal integrity, postoperative sensitivity, maintenance of pulp vitality, incidence of secondary caries, wear, fracture, and patient satisfaction are more directly relevant to treatment success. The limited number and relatively heterogeneous nature of long-term clinical investigations therefore remain important barriers to definitive conclusions regarding the clinical superiority of newer bioactive restorative systems.

Limitations of the Current Evidence

Several limitations should be considered when interpreting the evidence mapped in this review. First, substantial heterogeneity was observed among the included studies with respect to material composition, study design, experimental conditions, clinical indications, follow-up periods, and outcome assessment methods. This heterogeneity limits direct comparison between individual materials and prevents reliable quantitative synthesis.

Second, a considerable proportion of the available evidence was generated using in vitro or other experimental models. Although these models provide valuable information regarding mechanisms such as ion release, mineral deposition, antimicrobial activity, and cytocompatibility, they cannot fully reproduce the complex oral environment. Salivary composition, bacterial biofilms, pH fluctuations, thermal cycling, occlusal loading, moisture variation, and long-term material degradation may substantially influence clinical behavior.

Third, long-term clinical evidence remains insufficient for several recently introduced restorative systems. Short- and medium-term investigations may demonstrate acceptable biological and restorative performance, but these findings cannot be assumed to predict long-term restoration survival or resistance to degradation. Direct comparisons with well-established restorative materials are also limited for some newer products.

Another important limitation is the variability among commercially available materials classified as “bioactive.” Differences in filler composition, resin matrix, glass phase, manufacturing procedures, particle size, ion-release mechanisms, and formulation may result in substantially different biological and mechanical behavior. Therefore, conclusions based solely on a broad material category should be interpreted with caution.

Finally, the present investigation was designed as a scoping review. Its primary purpose was to map the breadth and characteristics of the available evidence rather than to estimate treatment effects or determine the superiority of individual materials. Consequently, quantitative pooling and formal comparative efficacy assessment were not performed.

Future Trends and Emerging Directions

Future research in bioactive restorative dentistry is likely to focus on multifunctional materials that integrate biological activity with mechanical reliability, esthetic performance, adhesion, and long-term stability. Rather than optimizing a single property, next-generation materials are expected to incorporate multiple complementary functions within a single restorative system.

One promising direction is the development of stimuli-responsive or “smart” restorative materials capable of modifying their behavior in response to environmental changes. Variations in pH, bacterial activity, ionic concentration, or mineral saturation may potentially be used as triggers for controlled ion release or localized therapeutic activity. Such approaches could provide more sustained biological effects while reducing unnecessary release under stable conditions.

Nanotechnology may further expand the biological capabilities of restorative materials. Nanostructured fillers, calcium- and phosphate-containing particles, bioactive glass nanoparticles, and controlled-release systems may improve remineralization, ion delivery, antimicrobial performance, and interfacial mineralization. However, future development should consider not only the magnitude of these effects but also their long-term stability, safety, interaction with the resin matrix, and influence on mechanical performance.

Another important research direction is the convergence of bioactive restorative materials with regenerative dentistry. Future materials may be designed to create microenvironments that support endogenous dentin repair and cellular responses rather than simply depositing mineral on the restoration surface. Such systems could potentially combine ion delivery, growth-factor-related signaling, cellular modulation, and structural reinforcement within a single therapeutic platform.

Digital dentistry may also contribute to more

individualized restorative treatment. Integration of advanced diagnostic imaging, minimally invasive preparation techniques, digital restorative workflows, and patient-specific risk assessment may allow clinicians to select restorative materials according to the biological and functional characteristics of individual teeth. This approach could move restorative dentistry toward more personalized material selection rather than the routine use of a single material across heterogeneous clinical situations.

Artificial intelligence and computational materials science represent additional emerging areas of interest. Machine-learning approaches may assist in identifying relationships between material composition, physicochemical characteristics, clinical variables, and treatment outcomes. Computational modelling could also contribute to the optimization of material formulations and prediction of degradation, ion-release behavior, and restoration performance. At present, however, these applications remain largely developmental and require clinical validation before routine implementation.

Future clinical research should therefore prioritize multicenter randomized controlled trials, adequately powered comparative studies, standardized definitions of bioactivity, harmonized outcome measures, and long-term follow-up. Direct comparisons with established restorative materials should incorporate clinically meaningful outcomes rather than relying exclusively on laboratory surrogate measures. Such research will be essential for determining whether the biological properties demonstrated experimentally translate into measurable improvements in restoration longevity, preservation of tooth vitality, prevention of recurrent disease, and patient-centered outcomes.

5. CONCLUSIONS

Bioactive restorative materials represent an important development in contemporary operative dentistry, extending the objectives of restorative treatment beyond the mechanical replacement of lost tooth structure. The evidence mapped in this scoping review indicates that different bioactive systems can interact with dental tissues and the oral environment through mechanisms including ion release, mineral deposition, remineralization, and modulation of the restoration–tooth interface.

Calcium silicate-based materials currently have the strongest clinical association with biologically oriented procedures, particularly vital pulp therapy and dentin repair. Bioactive glass, giomers, alkasite materials, ion-releasing resin composites, and other biomimetic systems further broaden the range of available approaches. However, their biological properties and clinical performance vary substantially according to material composition, indication, and evaluation methodology.

The available evidence supports the biological potential of these materials but does not yet establish uniform clinical superiority over conventional restorative systems. The principal limitations are the heterogeneity of study designs and outcome measures, the predominance of laboratory investigations, the absence of standardized criteria for defining bioactivity, and the limited availability of long-term clinical data.

Future progress should therefore focus on standardized evaluation methods, clinically relevant outcome measures, well-designed comparative trials, and long-term assessment of restoration survival and biological outcomes. The development of multifunctional materials that simultaneously provide biological activity, mechanical durability, esthetic quality, and predictable clinical performance may ultimately strengthen the role of bioactive restorative materials in minimally invasive and biologically based operative dentistry.

DECLARATIONS

Ethical Approval
Not applicable.
Competing Interests
The authors declare no conflict of interest.
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