ISSN :2584-2706 DOI: https://doi.org/10.67317/IJMSRT26NOV081

Bioactive Restorative Materials Beyond Laboratory Surrogates: A Critical Narrative Review Bridging in Vitro Ion Release and Clinical Prevention of Secondary Caries and Restoration Failure

Dr. Althaaf Khan, BDS (SMU), Assoc Fcgdent (UK)
Private Practice in South Africa

Corresponding Author

Abstract

Objective: Commercial marketing and laboratory studies increasingly promote "bioactive" resin composites, ion-releasing hybrids, cavity liners, and pit-and-fissure sealants for their capacity to release calcium, phosphate, fluoride, or hydroxyl ions. This critical narrative review evaluates whether these laboratory-measured ion-release and remineralization surrogates translate into measurable clinical reductions in secondary caries and restoration failure.

Methodology: A structured literature search of PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Library was conducted to synthesize mechanistic laboratory investigations, international consensus policy benchmarks, randomized controlled trials, and systematic reviews evaluating bioactive restorative materials across direct restoratives, pulp-capping liners, and occlusal sealants.

Major Findings: While bioactive glass-filled composites, alkasites, enhanced resin-modified glass ionomers, and resin-modified calcium silicates reliably elevate local pH and precipitate apatite-like phases in static immersion models, clinical translation remains inconsistent. In vitro testing routinely omits salivary pellicle fouling, continuous salivary clearance, cyclic occlusal fatigue, and patient-level cariogenic biofilm dynamics. Clinical trials demonstrate that material bioactivity does not compensate for compromised adhesive protocols; notably, an ion-releasing restorative placed without a dedicated adhesive exhibited an unacceptably high annual failure rate of 24.1%, whereas bonded restorations performed comparably to conventional composites. Similarly, hydraulic tricalcium silicates outperform light-cured resin-modified calcium silicate liners in vital pulp therapy, and sealant efficacy depends primarily on micromechanical retention rather than ion release.

Conclusion: Ion release alone is an insufficient surrogate for clinical caries prevention. Clinicians must prioritize proven adhesive sealing, mechanical durability, and patient-level caries risk management rather than relying on unsubstantiated bioactivity claims.

Keywords: *Bioactive Restorative Materials; Secondary Caries; Remineralization; Ion Release; Dental Composites;Clinical Translation.*

I. INTRODUCTION

Contemporary restorative dentistry has undergone a conceptual shift from passive, bio-inert defect replacement toward biologically interactive materials designed to support tissue preservation and interfacial stability [**1**, **2**]. Historically, Larry Hench's discovery of 45S5 Bioglass in 1969 established the classical definition of bioactivity as the capacity of an implanted biomaterial to elicit a specific biological response at its interface, culminating in a mechanically stable hydroxycarbonate apatite bond with living bone [**1**]. Over the past two decades, dental manufacturers and biomaterials researchers have extrapolated this concept to direct restorative dentistry, introducing a broad spectrum of commercial products marketed as "bioactive" composites, giomers, alkasites, enhanced resin-modified glass ionomers (RMGICs), calcium silicate liners, and ion-releasing pit-and-fissure sealants [**2**, **3**, **4**].

The primary clinical rationale driving the adoption of ion-releasing restoratives is the prevention of secondary caries, which remains the predominant cause of failure and replacement for resin-based composite restorations [**5**, **6**]. Unlike dental amalgam, whose corrosion products progressively seal marginal discrepancies over time, conventional methacrylate-based composites undergo polymerization shrinkage, hydrolytic degradation of the hybrid layer, and preferential accumulation of acidogenic biofilms along marginal gaps [**5**, **6**]. To counteract these vulnerabilities, manufacturers incorporate reactive fillers—such as calcium fluoroaluminosilicate glasses, melt-quenched or sol-gel bioactive glasses, amorphous calcium phosphate (ACP), pre-reacted glass-ionomer (S-PRG) fillers, and tricalcium silicates—intended to release calcium (Ca^{2+}), phosphate (PO^{3-}), fluoride (F^{-}), and hydroxyl (OH^{-}) ions during acidic challenges [**4**, **7**, **8**, **9**].

ISSN :2584-2706 DOI: https://doi.org/10.67317/IJMSRT26NOV081

Despite compelling promotional narratives, substantial ambiguity surrounds what constitutes clinically meaningful bioactivity in restorative dentistry [**2**, **3**]. Promotional literature frequently equates short-term laboratory phenomena—such as superficial mineral precipitation in simulated body fluid (SBF), transient pH elevation in unbuffered solutions, or microhardness recovery in artificially demineralized dentin—with clinical protection against recurrent caries [**3**, **9**]. Recognizing the potential for commercial misuse and clinical misinterpretation, the FDI World Dental Federation issued a landmark Policy Statement restricting the designation "bioactive restorative material" to products with a clearly defined mechanism, documented duration of effect, absence of adverse biological or mechanical trade-offs, and clinical evidence demonstrating that primary restorative function is preserved [**3**].

The objective of this critical narrative review is to bridge the translational gap between laboratory remineralization surrogates and clinical restorative outcomes. Specifically, this review critically examines the physicochemical mechanisms and methodological limitations of *in vitro* bioactivity testing, synthesizes clinical trial evidence across bioactive direct restoratives, cavity liners, and pit-and-fissure sealants, and outlines an evidence-based framework for integrating ion-releasing materials into clinical practice.

II. MATERIALS AND METHODS

2.1. Study Design and Literature Search Strategy

This manuscript was structured as a critical narrative review designed to juxtapose laboratory biomaterials characterization against longitudinal clinical trial outcomes. Comprehensive electronic searches were performed across PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Library to identify foundational conceptual papers, *in vitro* mechanistic studies, randomized controlled trials (RCTs), prospective cohort studies, and systematic reviews published in English. Search terms combined Medical Subject Headings (MeSH) and free-text keywords, including *"bioactive restorative materials"*, *"ion-releasing composites"*, *"bioactive glass"*, *"alkasite"*, *"calcium silicate liner"*, *"pit and fissure sealants"*, *"secondary caries"*, *"remineralization"*, and *"restoration survival"*. Reference lists of key consensus statements and systematic reviews were hand-searched to ensure inclusion of seminal comparative clinical trials.

2.2. Inclusion and Appraisal Criteria

Sources were selected based on their direct relevance to translational evaluation across three restorative categories: (1) direct ion-releasing resin composites, giomers, alkasites, and modified RMGICs; (2) bioactive cavity liners and indirect/direct pulp-capping agents; and (3) ion-releasing pit-and-fissure sealants. Priority was given to *in vitro* studies investigating ion-release kinetics, apatite nucleation, and interfacial biofilm inhibition under simulated aging or mechanical loading, alongside clinical RCTs and systematic reviews reporting patient-centered endpoints (secondary caries incidence, marginal adaptation, retention/fracture rate, postoperative sensitivity, and pulp vitality). Non-peer-reviewed commercial white papers, anecdotal case reports, and studies confined strictly to endodontic root-end surgery or implant coatings were excluded.

2.3. Analytical Framework and Ethical Considerations

Extracted evidence was synthesized using a translational appraisal matrix mapping laboratory surrogate endpoints against the five regulatory benchmarks established by the FDI Policy Statement [**3**] and longitudinal clinical survival data. Because this investigation represents a critical synthesis of previously published, publicly accessible peer-reviewed literature and involved no human subjects, animal experimentation, or identifiable clinical records, institutional ethics committee approval and informed consent were not applicable.

III. RESULTS AND DISCUSSION

3.1. Conceptual Ambiguity and the FDI Regulatory Benchmark

A foundational barrier to evaluating bioactive dental materials is the conflation of passive chemical ion leaching with true biological tissue regeneration [**2**,]. While classical osteoconductive biomaterials form an integrated biological bond with vascularized bone via cellular osteoblast recruitment [], dental enamel is acellular and cannot biologically regenerate its prismatic architecture through chemical precipitation alone []. Within restorative dentistry, the FDI Policy Statement clarifies that bioactive mechanisms operate across three distinct tiers: purely biological (exogenous growth factors or pharmaceuticals), mixed biological-chemical (materials that elevate local pH and stimulate endogenous dentin-pulp repair, such as hydraulic calcium silicates), and strictly chemical (materials releasing ions that shift local saturation equilibria toward mineral precipitation or inhibit biofilm metabolism) [,].**31334**

Critically, the FDI framework stipulates that any claimed bioactive effect is secondary to the material's principal engineering mandate: restoring lost tooth form, occlusal function, and marginal seal without accelerating mechanical degradation [**3**]. Incorporating soluble or reactive glass phases into a hydrophobic dimethacrylate network introduces an inherent physicochemical paradox: ion release requires water diffusion into the resin matrix and partial dissolution of filler particles, processes that concurrently promote hydrolytic degradation of the silane coupling interface, water sorption, swelling, and reductions in flexural strength and fracture toughness [**3**, **9**, **10**].

3.2. Methodological Disconnect Between In Vitro Surrogates and the Oral Environment

Laboratory evaluations of bioactive restoratives routinely rely on accelerated, simplified surrogates that poorly replicate the complex thermodynamic and microbiological environment of the human oral cavity [**5**, **8**, **9**]. In standard immersion assays, specimens are stored in small volumes of static deionized water, Tris buffer, or acellular SBF already supersaturated with respect to hydroxyapatite [**8**, **9**]. Under these closed-system conditions, leached calcium and hydroxyl ions rapidly accumulate to supersaturation thresholds, producing dramatic scanning electron microscopic images of surface mineral spherulites within days [**8**, **9**].

ISSN :2584-2706 DOI: https://doi.org/10.67317/IJMSRT26NOV081

In vivo, however, continuous salivary flow rapidly dilutes released ions away from restoration margins, while salivary proteins and acquired pellicle macromolecules adsorb onto reactive glass surfaces, obstructing ion-exchange channels [**3**, **5**]. Furthermore, laboratory demineralization models frequently utilize abiotic lactic or acetic acid gels or single-species *Streptococcus mutans* biofilms without pH cycling or cyclic occlusal loading [**5**, **7**]. As demonstrated by Ferracane [**5**] and Khvostenko et al. [**7**], masticatory loading induces cyclic fluid pumping along interfacial micro-gaps, driving multispecies acidogenic biofilms deep along cavity walls where transient, burst-phase ion release is rapidly exhausted. Table 1 summarizes the major translational discrepancies between laboratory surrogates and clinical oral conditions.

Table 1. Translational Gap Between Common In Vitro Bioactivity Surrogates and Clinical Oral Conditions

Evaluation Domain	Standard In Vitro Surrogate Model	Clinical Oral Reality & Translational Impact
Immersion Medium & Fluid Dynamics	Static immersion in small-volume Tris buffer, deionized water, or supersaturated SBF without replenishment [**8**, **9**].	Continuous salivary clearance (0.3–1 .5 mL/min) dilutes eluted Ca^{2+}, PO^{3-}, and $OH^{-}4$ ions, preventing local supersaturation at exposed margins [**3**, **5**].
Surface Protein Interaction	Protein-free aqueous media allowing unimpeded glass dissolution and apatite nucleation [**8**].	Immediate formation of salivary pellicle fouls reactive filler surfaces, altering ion-diffusion kinetics and crystal growth [**3**].
Biofilm & Acid Challenge	Short-term (1 –4 week) monoculture *S. mutans* biofilms or continuous abiotic acid gels without pH recovery [**5**, **7**].	Complex polymicrobial biofilms experiencing episodic dietary sucrose surges and salivary buffering; ion release is often depleted within months [**5**, **6**].
Mechanical & Hydrolytic Aging	Unloaded specimens tested within days to weeks of polymerization [**5**].	Cyclic occlusal fatigue pumps fluid into interfacial gaps while sustained filler dissolution compromises matrix integrity and wear resistance [**5**, **9**].
Outcome Endpoint	Surface microhardness recovery, ion ppm curves, or SEM apatite precipitation [**8**, **10**].	Radiographic/visual cavitated secondary caries, marginal breakdown, loss of retention, or irreversible pulpitis over multi-year service [**6**, **11**].

3.3. Bioactive Composites, Giomers, and Alkasites: Laboratory Promise Versus Clinical Reality

Direct restorative materials marketed as bioactive encompass several distinct chemical architectures, including bioactive glass-containing resin composites [**7**, **9**], S-PRG filler-based giomers, urethane dimethacrylate (UDMA)-based alkasites containing alkaline calcium fluorosilicate glass (e.g., Cention N) [**8**], and ionic resin-modified glass ionomer hybrids (e.g., Activa BioActive-Restorative) [**8**, **11**, **12**]. In laboratory bioreactors subjected to cyclic loading, experimental resin composites containing 15 wt% bioactive glass significantly reduced *S. mutans* biofilm penetration depth into pre-formed 15–20 µm marginal gaps compared with non-bioactive controls (mean penetration 61% vs. 100%) [**7**]. Similarly, comparative characterization by Tiskaya et al. [**8**] demonstrated that Cention N released substantial calcium, fluoride, and hydroxyl ions in acidic media (pH 4) and formed an apatite-like phase in artificial saliva at pH 7, whereas Activa BioActive exhibited minimal apatite formation and lower ion release over comparable immersion intervals.

When translated into clinical trials, however, ion-release superiority has not consistently yielded lower secondary caries rates or improved restoration longevity. A pivotal cautionary example is the randomized controlled trial by van Dijken et al. [**11**], which evaluated Class II restorations placed with Activa BioActive-Restorative according to the manufacturer's original instructions—using brief phosphoric acid etching without a separate adhesive bonding agent—against a conventional nanohybrid resin composite. Despite the material's marketed ionic-resin bioactivity and phosphate acid groups, the non-bonded bioactive group suffered a catastrophic 24.1% failure rate at 1 year (predominantly due to loss of retention, fracture, and secondary caries), prompting the manufacturer to revise its instructions to mandate a dedicated adhesive system [,]. Conversely, when placed with a conventional etch-and-rinse or self-etch adhesive system, 1-year randomized trials in Class II and cervical cavities have reported acceptable survival rates comparable to nanohybrid composites and conventional RMGICs, without demonstrating statistically significant reductions in secondary caries [,].**3111216**

These clinical observations align with the comprehensive analysis by Nedeljkovic et al. [**6**], who concluded that while restorative material chemistry can modulate local interfacial phenomena, patient-level factors—specifically individual caries risk, dietary fermentable carbohydrate frequency, oral hygiene efficacy, and salivary buffering capacity—coupled with operator adhesive technique remain the primary determinants of secondary caries development. Moreover, commercial bioactive composites typically exhibit an initial "burst release" of ions during the first weeks following placement, followed by an exponential decline as surface-accessible glass particles are depleted [**8**, **9**]. Because clinical secondary caries typically manifests 2 to 5 years after restoration placement, early burst-phase ion elution is poorly synchronized with the timeline of clinical restoration failure [**5**, **6**].

ISSN :2584-2706 DOI: https://doi.org/10.67317/IJMSRT26NOV081

3.4. Cavity Liners and Pulp-Capping Agents: Hydraulic Versus Resin-Modified Formulations

Vital pulp therapy represents the clinical domain where bioactive mechanisms—specifically mixed biological and chemical induction of reparative dentinogenesis—possess the strongest histological and clinical validation [**3**, **13**]. Hydraulic tricalcium silicate cements, such as mineral trioxide aggregate (MTA) and Biodentine, undergo hydration reactions that generate calcium silicate hydrate gel and sustained dissociation of calcium hydroxide, maintaining a strongly alkaline microenvironment (pH > 11) that neutralizes bacterial acids, solubilizes endogenous transforming growth factor-beta 1 (TGF-β1) from dentin matrix, and stimulates odontoblast-like cell differentiation and reparative dentin bridge formation [**4**, **13**, **14**].

To overcome the prolonged setting times and handling challenges of pure hydraulic cements, manufacturers introduced light-curable resin-modified calcium silicate liners (most notably TheraCal LC) that release calcium ions in aqueous immersion assays [**13**,]. However, incorporating tricalcium silicate particles into a hydrophobic methacrylate monomer matrix severely restricts water sorption required for complete hydration, preventing true calcium hydroxide crystallization and substantially reducing sustained calcium and hydroxyl ion availability compared with hydraulic cements [,]. Simultaneously, unpolymerized resin monomers leached across thin residual dentin bridges exert dose-dependent cytotoxicity toward human dental pulp stem cells []. Clinical retrospective and randomized trials evaluating direct pulp capping confirm that hydraulic cements (Biodentine and MTA) achieve significantly higher clinical and radiographic success rates with superior, continuous dentin bridge formation compared with resin-modified calcium silicate liners []. Thus, superficial *in vitro* calcium-ion detection in a resin-modified liner does not equate to the biological pulp-healing performance of pure hydraulic calcium silicates [, ,].**141314141331314**

3.5. Ion-Releasing Pit-and-Fissure Sealants

Pit-and-fissure sealants represent a primary preventive intervention targeting deep occlusal morphology susceptible to biofilm stagnation. Commercial formulations increasingly incorporate soluble fluoride salts, S-PRG fillers, amorphous calcium phosphate, or bioactive glass particles to confer "active" enamel remineralization around sealant margins. In laboratory demineralization models, ion-releasing sealants consistently elevate enamel microhardness and reduce lesion depth adjacent to the material compared with non-fluoridated resin sealants [**9**].

Nevertheless, high-certainty clinical synthesis from the Cochrane Oral Health Group by Ahovuo-Saloranta et al. [**15**] demonstrates that the caries-preventive efficacy of pit-and-fissure sealants is governed primarily by physical micromechanical retention and hermetic isolation of susceptible pits and fissures from the oral biofilm, rather than chemical ion release. Resin-based sealants reduced occlusal caries incidence in permanent molars by 11% to 51% at 24 months compared with unsealed controls, whereas comparisons between fluoride-releasing glass ionomer sealants and conventional resin sealants yielded inconclusive differences in caries prevention, largely because lower mechanical retention of glass ionomer sealants offset their chemical fluoride-release advantage [**15**]. Incorporating high loadings of soluble bioactive fillers into low-viscosity resin sealants risks increasing viscosity, impairing tag penetration into acid-etched enamel prisms, and accelerating hydrolytic wear, thereby undermining the physical barrier mechanism responsible for clinical success [**3**, **15**]. Table 2 synthesizes the mechanistic claims, clinical trial findings, and translational limitations across all evaluated material classes.

Table 2. Comparative Synthesis of Laboratory Mechanisms, Clinical Trial Outcomes, and Translational Limitations Across Bioactive Material Classes

Material Class & Examples	Claimed Bioactive Mechanism & Lab Surrogates	Clinical Trial Evidence (Caries & Survival)	Key Translational Limitations
Bioactive Glass Resin Composites (Experimental BAG / commercial hybrids)	SiO_2–CaO–Na_2O–P_2O_5 dissolution; pH rise; apatite precipitation; reduced *S. mutans* gap penetration in vitro [**7**, **9**].	Limited long-term RCT data; experimental formulations show promise, but commercial translation lacks multi-year RCT superiority over conventional composites [**9**].	Trade-off between glass dissolution and flexural strength/wear; rapid depletion of surface-accessible glass particles [**9**, **10**].
Alkasite Restoratives (e.g., Cention N)	Alkaline calcium fluorosilicate glass releases OH^-, Ca^{2+}, and F^- in acidic media; apatite formation in artificial saliva [**8**].	Short-term (1–2 yr) clinical studies show survival comparable to composites/RMGICs; insufficient multi-year RCT evidence of secondary caries reduction [**8**].	Requires adhesive bonding for optimal marginal integrity; long-term hydrolytic stability under occlusal load remains under study [**3**].
Enhanced RMGIC / Ionic Resin Hybrids (e.g., Activa BioActive)	Phosphate-acid ionic resin matrix with reactive glass fillers releasing Ca^{2+}, PO^{3-}, and F^- [**8**, 4	24.1 % 1 -yr failure without adhesive [**11**]; acceptable 1 -yr survival when bonded, with no significant secondary caries advantage over controls [**12**].	Low apatite nucleation in neutral artificial saliva [**8**]; self-adhesive claims disproven clinically, necessitating bonding

ISSN :2584-2706 DOI: https://doi.org/10.67317/IJMSRT26NOV081

	12].		agents [11].
Pulp-Capping Liners (Hydraulic Biodentine/MTA vs. resin-modified TheraCal LC)	Ca^{2+} and OH^{-} release; alkaline pH; TGF-β1 solubilization; reparative dentin bridge induction [13, 14].	Hydraulic tricalcium silicates achieve high clinical/histological pulp survival; resin-modified TheraCal LC shows inferior direct pulp-capping outcomes [13].	Resin matrix in light-cured liners restricts hydration and leaches cytotoxic monomers despite Ca^{2+} detection in vitro [13, 14].
Ion-Releasing Pit & Fissure Sealants (Fluoride, ACP, S-PRG, BAG sealants)	Continuous $F^{-}/Ca^{2+}/PO_4^{3-}$ release; reduced adjacent enamel demineralization in lab acid models [9].	Cochrane review confirms physical retention of resin sealants drives caries prevention; ion-releasing sealants show no clear clinical superiority [15].	Soluble fillers can increase viscosity and wear, compromising micromechanical enamel tag retention [3, 15].

3.6. Clinical Implications and Future Research Directions

For practicing clinicians, the central lesson emerging from this translational synthesis is that "bioactivity" should be viewed as a secondary, adjunctive attribute rather than a substitute for fundamental operative and preventive principles [3, 6]. Specifically, clinicians should apply four evidence-based safeguards when selecting restorative materials:

- **Never Compromise Adhesive Protocols:** Ion-releasing composites and modified RMGICs must be used in strict conjunction with validated enamel and dentin bonding systems; relying on intrinsic self-adhesive bioactivity risks catastrophic early debonding and marginal leakage [11, 12].
- **Match Material Selection to Clinical Indication:** In deep carious lesions approaching or exposing the dental pulp, pure hydraulic tricalcium silicate cements (such as Biodentine or MTA) remain the evidence-based standard over light-cured resin-modified calcium silicate liners [13, 14]. In high-caries-risk cervical or non-stress-bearing cavities where moisture control is compromised, conventional or high-viscosity glass ionomer cements remain reliable, cost-effective options [16].
- **Prioritize Physical Sealing in Preventive Sealants:** When placing pit-and-fissure sealants, isolation, thorough enamel etching, and low-viscosity resin penetration remain paramount to long-term occlusal caries prevention [15].
- **Target Patient-Level Caries Drivers:** Because secondary caries is fundamentally a biofilm-mediated, diet-driven disease, restorative material selection must be paired with individualized caries risk assessment, topical fluoride regimens, and dietary counseling [6].

To close the translational gap, future biomaterials research must move beyond static immersion assays toward standardized, clinically predictive testing models incorporating human salivary pellicle, dynamic pH cycling, multispecies biofilms, and cyclic mechanical loading, followed by adequately powered, multi-year randomized clinical trials reporting standardized FDI criteria and caries endpoints [3, 5, 10].

IV. CONCLUSION

Although contemporary bioactive composites, alkasites, cavity liners, and sealants consistently demonstrate ion release, acid buffering, and surface mineral precipitation in laboratory surrogate models, current clinical evidence does not support claims that these materials independently reduce secondary caries or restoration failure in vivo. The discrepancy between laboratory performance and clinical outcomes stems from simplified *in vitro* testing conditions that neglect salivary clearance, protein fouling, cyclic occlusal fatigue, and patient-level cariogenic risk, alongside intrinsic trade-offs between filler solubility and mechanical durability. Until multi-year randomized clinical trials validate durable therapeutic benefits, clinicians should adhere strictly to the FDI Policy Statement criteria, maintain rigorous adhesive and isolation protocols, and anchor secondary caries prevention in comprehensive patient-centered risk management.

V. ACKNOWLEDGEMENTS

The author acknowledges the open-access biomedical literature repositories and international dental biomaterials consensus working groups whose published clinical and laboratory investigations enabled this critical synthesis.

Funding Statement

This research received no specific grant or financial support from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The author declares no financial, professional, institutional, or personal conflicts of interest that could have influenced the preparation, analysis, or interpretation of this manuscript.

ISSN :2584-2706 DOI: https://doi.org/10.67317/IJMSRT26NOV081

REFERENCES

[1]. Hench LL. The story of Bioglass. J Mater Sci Mater Med. 2006;17(11):967-78.
[2]. Vallittu PK, Boccaccini AR, Hupa L, Watts DC. Bioactive dental materials—Do they exist and what does bioactivity mean? Dent Mater. 2018;34(5):693-4.
[3]. Schmalz G, Hickel R, Price RB, Platt JA. Bioactivity of dental restorative materials: FDI policy statement. Int Dent J. 2023;73(1):21-7.
[4]. Spagnuolo G. Bioactive dental materials: the current status. Materials (Basel). 2022;15(6):2016.
[5]. Ferracane JL. Models of caries formation around dental composite restorations. J Dent Res. 2017;96(4):364-71.
[6]. Nedeljkovic I, Teughels W, De Munck J, Van Meerbeek B, Van Landuyt KL. Is secondary caries with composites a material-based problem? Dent Mater. 2015;31(11):e247-77.
[7]. Khvostenko D, Hilton TJ, Ferracane JL, Mitchell JC, Kruzic JJ. Bioactive glass fillers reduce bacterial penetration into marginal gaps for composite restorations. Dent Mater. 2016;32(1):73-81.
[8]. Tiskaya M, Al-Eesa NA, Wong FSL, Hill RG. Characterization of the bioactivity of two commercial composites.
[9]. Dent Mater. 2019;35(12):1757-68.
[10]. Tiskaya M, Shahid S, Gillam D, Hill R. The use of bioactive glass (BAG) in dental composites: a critical review.
[11]. Dent Mater. 2021;37(2):296-310.
[12]. Braga RR, Fronza BM. The use of bioactive particles and biomimetic analogues for increasing the longevity of resin-dentin interfaces: a literature review. Dent Mater J. 2020;39(1):62-8.
[13]. van Dijken JWV, Pallesen U, Benetti A. A randomized controlled evaluation of posterior resin restorations of an altered resin modified glass-ionomer cement with claimed bioactivity. Dent Mater. 2019;35(2):335-43.
[14]. Bhadra D, Shah NC, Rao AS, Dedania MS, Bajpai N. A 1-year comparative evaluation of clinical performance of nanohybrid composite with Activa bioactive composite in Class II carious lesion: a randomized control study. J Conserv Dent. 2019;22(1):92-6.
[15]. Paula A, Carrilho E, Laranjo M, Abrantes AM, Casalta-Lopes J, Botelho MF, et al. Direct pulp capping: which is the most effective biomaterial? A retrospective clinical study. Materials (Basel). 2019;12(20):3382.
[16]. Ghilotti J, Sanz JL, López-García S, Guerrero-Gironés J, Pecci-Lloret MP, Lozano A, et al. Comparative surface morphology, chemical composition, and cytocompatibility of Bio-C Repair, Biodentine, and ProRoot MTA on hDPCs. Materials (Basel). 2020;13(9):2189.
[17]. Ahovuo-Saloranta A, Forss H, Walsh T, Nordblad A, Mäkelä M, Worthington HV. Pit and fissure sealants for preventing dental decay in permanent teeth. Cochrane Database Syst Rev. 2017;7(7):CD001830.
[18]. Perdigão J, Dutra-Corrêa M, Saraceni SH, Ciaramicoli MT, Kiyan VH. Randomized clinical trial of two resin-modified glass ionomer materials: 1-year results. Oper Dent. 2012;37(6):591-601.