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Zeolites as Natural Biomaterials in Conservative Dentistry: A Comprehensive Review

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Abstract

Conservative dentistry focuses on preserving tooth structure through preventive and minimally invasive strategies. A persistent challenge is preventing bacterial colonization and secondary caries at restoration margins. Zeolites, naturally occurring microporous aluminosilicate minerals, have recently gained attention for their ion-exchange capabilities and ability to provide sustained antimicrobial activity. Their natural origin, abundance, and eco-friendly properties position them as attractive alternatives to synthetic antimicrobial additives. This review summarizes the natural origin, structural and chemical properties of zeolites, their mechanisms of antibacterial action, and their integration into restorative systems including glass ionomer cements, resin composites, adhesives, and mineral trioxide aggregate. Benefits, challenges, and future research directions are discussed, highlighting zeolites as promising natural biomaterials for the next generation of minimally invasive restorative dentistry.

Keywords: Zeolites · Natural biomaterials · Conservative Dentistry · Restorative Dentistry · Antibacterial materials · Bioactive restoratives

1. Introduction

Dental materials have advanced considerably in recent decades, shifting from passive restorative substances toward bioactive systems designed to interact with the oral environment. One promising group of additives is zeolites—naturally occurring aluminosilicate minerals with a porous, crystalline structure that allows controlled ion exchange. Their ability to act as carriers for antimicrobial ions such as silver, zinc, or chlorhexidine has generated significant interest in conservative dentistry, where the goals extend beyond structural repair to long-term prevention of secondary caries and infection. Zeolites, being abundant and environmentally sustainable, also align with the growing demand for eco-friendly and patient-centered materials.

Traditional restorative materials—including glass ionomer cements (GICs), resin composites, and mineral trioxide aggregate (MTA)—offer excellent functional and esthetic outcomes. However, their inherent antibacterial performance is limited. For instance, fluoride release from GICs provides some protection against bacterial activity, but this effect is short-lived and insufficient to suppress long-term recolonization of cariogenic microorganisms [1,2]. Similarly, resin composites are prone to microleakage at the tooth–restoration interface, creating niches for biofilm growth [3].

To address these shortcomings, research has increasingly focused on incorporating bioactive or antimicrobial components into restorative materials. While synthetic additives such as quaternary ammonium compounds and metallic nanoparticles have shown promise, their long-term safety, biocompatibility, and environmental sustainability remain under debate [4]. This has spurred interest in natural biomaterials that combine bioactivity with safety and eco-friendliness.

Among these, zeolites have emerged as particularly attractive candidates. Zeolites are naturally occurring crystalline aluminosilicates with a unique porous framework capable of ion exchange. This structure enables them to serve as reservoirs and carriers for antimicrobial ions such as silver (Ag+), zinc (Zn2+), and chlorhexidine (CHX), releasing them gradually into the oral environment. This sustained release provides long-term antibacterial protection without compromising the biological compatibility of the restorative system [5–7].

This review synthesizes current knowledge on zeolites as natural biomaterials in conservative dentistry, examining their geological origin, structural and chemical properties, mechanisms of antibacterial action, applications in restorative systems, advantages, limitations, and future perspectives.

Natural Origin and Structure of Zeolites

Zeolites are formed when volcanic ash and other silicate-rich materials undergo chemical alteration in the presence of alkaline groundwater or seawater. This natural process produces a three-dimensional aluminosilicate framework characterized by interconnected channels and cavities. The negative charge of the framework is balanced by exchangeable cations such as sodium, calcium, or potassium, which can be substituted with therapeutic ions. More than 50 naturally occurring zeolite types have been identified, with clinoptilolite, chabazite, and mordenite being among the most studied for biomedical applications. Their microporous architecture, typically ranging from 3 to 10 Å in pore size, enables reversible hydration and makes them effective reservoirs for controlled release of ions and molecules. These structural features underpin their antimicrobial and bioactive roles in dentistry.

Chemical Composition and Structural Framework The basic building blocks of zeolites are SiO_4 and AlO_4 tetrahedra linked through shared oxygen atoms, forming a rigid, three-dimensional crystalline framework. The substitution of silicon (Si^{4+}) by aluminum (Al^{3+}) introduces negative charges into the framework, which are balanced by exchangeable cations such as Na^+, K^+, Ca^{2+}, and Mg^{2+} [11]. This unique arrangement generates a system of interconnected pores and channels ranging from 3 to 10 Å in diameter, capable of selectively adsorbing and exchanging cations, water, and small molecules [12].

Ion Exchange and Adsorption Properties The ion-exchange capacity of zeolites makes them particularly attractive for biomedical applications. In dentistry, zeolites can be preloaded with therapeutic ions such as silver (Ag^+), zinc (Zn^{2+}), or chlorhexidine (CHX), which are gradually released in the oral environment. This controlled release mechanism extends antimicrobial activity far beyond the transient effects of fluoride or other conventional additives [13].

Biocompatibility and Medical Relevance Natural zeolites, especially clinoptilolite, have been widely studied in medicine as detoxifying agents, gastrointestinal stabilizers, and wound-healing materials [14]. Their stability in aqueous and biological environments, combined with low toxicity at appropriate concentrations, has supported their exploration in dental

applications. When incorporated in low percentages (≤2 wt%), zeolites have demonstrated good compatibility with restorative systems while maintaining desirable physical properties [15].

Mechanisms of Antimicrobial Action of Zeolites

Zeolites exert antimicrobial activity primarily through their cation-exchange capacity and controlled ion release. This unique mechanism allows zeolites to function as carriers of bioactive agents, which are released gradually into the surrounding environment, providing long-term antibacterial protection. The antimicrobial activity of zeolites is not due to the aluminosilicate framework itself, but rather to the biologically active ions incorporated within their porous structure [16].

Ion Exchange and Controlled Release The negatively charged

aluminosilicate framework of zeolites can exchange its resident cations (Na^+, K^+, Ca^{2+}) with antimicrobial ions such as silver (Ag^+), zinc (Zn^{2+}), or chlorhexidine (CHX). Once incorporated, these ions are released gradually into the aqueous oral environment in response to concentration gradients and pH changes [17]. This controlled release ensures a sustained antimicrobial effect, which is superior to the rapid but short-lived activity of conventional additives [18].

Antimicrobial Mechanisms of Released Ions Silver ions (Ag^+):

Bind to bacterial cell walls and membranes, increase permeability, and interfere with respiratory enzymes and DNA replication, ultimately causing cell death [19].

Zinc ions (Zn^{2+}): Inhibit bacterial glycolysis and acidogenic activity, reducing the cariogenic potential of Streptococcus mutans [20].

Chlorhexidine (CHX): Acts as a broad-spectrum antiseptic by disrupting bacterial cytoplasmic membranes and precipitating cytoplasmic contents [21].

Effects on Oral Microbiota and Biofilms In vitro studies have demonstrated that zeolite-modified dental materials significantly reduce the viability and metabolic activity of cariogenic bacteria such as S. mutans, S. mitis, and Lactobacillus spp., as well as fungal pathogens like Candida albicans [22,23]. Furthermore, zeolites suppress biofilm formation at the tooth– restoration interface, decreasing the risk of microleakage-associated secondary caries [24].

Synergistic Effects with Restorative Systems When incorporated into dental adhesives, glass ionomer cements, and composites, zeolites provide a dual benefit:

Antimicrobial action from sustained ion release.

Preservation of fluoride release and remineralizing capacity in GICs. This synergistic effect supports the long-term clinical success of conservative restorative procedures [25].

Applications in Conservative Dentistry

4.1 Glass Ionomer Cements (GICs)

Glass ionomer cements (GICs) are widely used in conservative dentistry due to their ability to chemically bond to enamel and dentin, fluoride release, and biocompatibility. However, a major limitation of conventional GICs is that fluoride release is rapid and short-lived, resulting in limited long-term antibacterial activity [26]. This allows bacterial recolonization at the margins, contributing to secondary caries and restoration failure.

To overcome this limitation, zeolite-modified GICs have been developed. The incorporation of zeolites enhances their antibacterial potential through sustained release of antimicrobial ions:

Silver-exchanged zeolites (Ag-zeolite): Provide strong, broad-spectrum antibacterial activity against Streptococcus mutans, Streptococcus mitis, and Candida albicans [27].

Zinc-exchanged zeolites (Zn-zeolite): Demonstrate inhibitory effects on acidogenic bacteria and contribute to caries prevention through suppression of bacterial glycolysis [28].

Chlorhexidine-loaded zeolites (CHX-zeolite): Offer an extended antibacterial effect and have been proposed for use in liners and fissure sealants, where long-term biofilm suppression is critical [29].

Mechanical considerations remain crucial. While low levels of zeolite incorporation (≤1 wt%) generally preserve the compressive and bond strength of GICs, higher concentrations (>3 wt%) have been associated with reductions in mechanical performance, including strength and wear resistance [30]. Therefore, optimization of zeolite loading is essential to balance antibacterial efficacy with physical durability.

Overall, Zeolite-modified GICs represent a promising advance in restorative dentistry, providing a more sustained antibacterial effect than conventional fluoride release, while maintaining acceptable mechanical and esthetic properties at appropriate concentrations.

4.2 Resin Composites and Adhesives

Challenge: Polymerization shrinkage and bacterial microleakage

Resin-based composites, although widely adopted as esthetic and functional restorative materials, continue to face inherent challenges. One of the most significant is polymerization shrinkage, which creates contraction stresses at the tooth–restoration interface. This often leads to marginal gaps, microleakage, secondary caries, and postoperative sensitivity [26,27].

Additionally, resin composites and adhesives, unlike glass ionomer cements, lack long-term antibacterial activity, which further predisposes restored teeth to recurrent decay, particularly in high-caries-risk patients [28].

Zeolite fillers in resin composites

The incorporation of zeolite-based fillers, especially those exchanged with antimicrobial ions (Ag^+, Zn^{2+}), has emerged as a promising strategy to address these limitations.

Ag-zeolite: Provides a sustained antibacterial effect by releasing silver ions, which disrupt bacterial cell walls and metabolic pathways, thereby reducing colonization of cariogenic bacteria such as Streptococcus mutans and Lactobacillus spp. [29].

Zn-zeolite: Offers broad-spectrum antibacterial activity while also contributing to remineralization potential by stabilizing apatite formation and modulating enzymatic activity involved in dentin degradation [30].

Ag–Zn dual-modified zeolite:

Demonstrates synergistic effects, combining the high potency of silver with the biocompatibility and remineralizing benefits of zinc, thereby reducing biofilm accumulation and lowering the risk of recurrent caries [31].

Zeolite-modified adhesives

Adhesive systems represent a critical link between tooth structure and resin composite. Conventional adhesives, however, remain vulnerable to bacterial infiltration and degradation of the hybrid layer due to matrix metalloproteinase (MMP) activation and biofilm formation [32].

Incorporating Ag-zeolite into adhesives transforms them into bioactive bonding systems with dual functionality:

Antibacterial activity at the interface:

Continuous low-level release of Ag^+ ions suppress the formation of biofilms, maintaining a sterile environment at the adhesive–dentin junction [33].

Preservation of bonding performance:

When used at optimal concentrations (≤1 wt%), Ag-zeolite does not significantly compromise the adhesive's polymerization or bond strength, while higher concentrations may risk mechanical weakening [34].

Overall implications

Zeolite incorporation into resin composites and adhesives represents a bioactive restorative approach, shifting the paradigm from purely mechanical sealing to therapeutic, antimicrobial, and remineralizing functions. This strategy not only minimizes polymerization shrinkage– associated complications but also provides long-term protection against bacterial microleakage and secondary caries, thereby enhancing the longevity and success of adhesive restorations [35,36].

4.3 Endodontic Sealers and Materials

Challenge: Persistent infection and microleakage in root canal therapy Successful endodontic treatment depends on effective elimination of microorganisms and sealing of the root canal system. However, residual bacteria, particularly Enterococcus faecalis, remain a significant cause of endodontic failure due to their ability to penetrate dentinal tubules, survive harsh environments, and form biofilms [37]. Conventional sealers (e.g., epoxy resin-based, zinc oxide–eugenol-based) provide good sealing ability but lack sustained antibacterial activity and may degrade over time, leading to reinfection and treatment failure [38].

Zeolite-modified endodontic sealers

Incorporating zeolites into endodontic sealers has shown promise in enhancing their antimicrobial, sealing, and bioactive properties:

Ag-zeolite: Provides continuous silver ion release with strong antibacterial action against resistant organisms such as E. faecalis and Candida albicans [39].

Zn-zeolite: Contributes to antibacterial effects while reducing cytotoxicity compared to silver alone, and can promote remineralization within dentinal tubules [40].

Combination zeolite systems: Dual ion-exchange zeolites (Ag-Zn) demonstrate synergistic activity, achieving broader antimicrobial coverage while maintaining mechanical integrity [41].

Improved sealing and longevity

Zeolite fillers not only provide antibacterial benefits but also improve sealer performance by:

Reducing microleakage through enhanced dimensional stability and filler–matrix reinforcement.

Maintaining flow and adaptability to canal walls when incorporated in low concentrations (≤2 wt%) without impairing handling characteristics [42].

Inhibiting biofilm formation on sealer surfaces, thereby preventing secondary infections and extending the long-term success of root canal therapy [43].

Biocompatibility and bioactivity

Studies have shown that zeolite-modified sealers can support periapical healing by:

Promoting mineral deposition at the sealer–dentin interface.

Stimulating alkaline environments that favor bacterial suppression and dentin remineralization.

Reducing inflammatory responses compared to traditional sealers when used at controlled concentrations [44].

Overall implications

Zeolite incorporation transforms endodontic sealers into bioactive, antibacterial, and remineralizing materials, addressing persistent microbial challenges in root canal therapy. This dual function—mechanical sealing plus therapeutic action—represents a shift toward next-generation endodontic biomaterials that can significantly improve clinical outcomes and long-term tooth preservation [45,46].

4.4 Root Canal Sealers and Irrigation

Challenges in disinfection and sealing

The long-term success of root canal treatment depends on two critical factors: (1) effective elimination of microorganisms within the complex root canal system and (2) achieving a hermetic seal to prevent reinfection.

Despite advances in obturation materials and irrigants, residual bacteria— particularly Enterococcus faecalis and Candida albicans—remain difficult to eradicate. Furthermore, microleakage at the dentin–sealer interface compromises periapical healing and may lead to treatment failure [47,48].

Zeolite-based sealers (ZUT)

Recent research has introduced zeolite-based endodontic sealers, particularly those containing zeolite–urethanedimethacrylate (ZUT) formulations, which aim to enhance both sealing and antibacterial properties.

Improved bacterial resistance: Zeolite particles act as ion reservoirs, releasing antimicrobial ions (e.g., Ag^+, Zn^{2+}) that suppress bacterial growth along dentin margins, thereby reducing microleakage and reinfection [49].

Hybrid sealing function: ZUT sealers not only fill voids and adapt to canal walls but also create a bioactive interface capable of resisting bacterial penetration over longer durations compared to conventional sealers [50].

Ag-zeolite irrigants

Root canal irrigation is a cornerstone of chemomechanical preparation. While sodium hypochlorite (NaOCl) and chlorhexidine (CHX) remain the gold standards for antimicrobial irrigation, they present drawbacks such as cytotoxicity (NaOCl) and limited tissue-dissolving capacity (CHX) [51].

Silver-zeolite irrigants have been proposed as an alternative adjunctive strategy. They demonstrate superior antibacterial action compared to saline by gradually releasing Ag^+ ions that penetrate dentinal tubules and disrupt bacterial cell walls [52].

However, their effectiveness is inferior to NaOCl and CHX, meaning they may serve best as supplementary irrigants or in patients where reduced cytotoxicity is desired [53].

Clinical implications

The integration of zeolite-based technologies into both sealers and irrigants may help overcome two persistent challenges in endodontics:

Sustained antimicrobial defense at the dentin–sealer interface.

Biocompatible disinfection options for irrigation, especially in patients with hypersensitivity to conventional agents.

Although Ag-zeolite irrigants cannot yet replace NaOCl or CHX, their potential as adjunctive bioactive irrigants and the biofilm-resistant properties of ZUT sealers suggest a promising role for zeolite-modified materials in improving long-term root canal success [54,55].

Advantages of Natural Zeolites in Dentistry

Abundant and sustainable

Natural zeolites are crystalline aluminosilicates widely distributed in the Earth’s crust. Their abundance and relatively low processing costs make them a cost-effective alternative to synthetic additives [56]. Largescale extraction ensures a sustainable supply chain, supporting their integration into restorative, endodontic, and preventive dental materials without imposing significant economic burdens.

Eco-friendly and aligned with "green dentistry"

The growing movement toward sustainability in healthcare has increased interest in environmentally friendly dental materials. Zeolites align well with this concept. Their extraction is non-toxic, they can be reused in certain industrial applications, and they offer a natural substitute for synthetic antimicrobials or heavy metals [57]. Unlike synthetic nanoparticles, which may accumulate in the environment, zeolites are mineral-based and therefore present a lower ecological footprint, advancing the principles of "green dentistry."

Long-lasting antimicrobial release

A defining advantage of zeolites is their ion-exchange capability. They can be preloaded with bioactive ions such as silver (Ag^+), zinc (Zn^{2+}), or chlorhexidine (CHX) and subsequently release them in a controlled, sustained manner [58]. This gradual release allows zeolite-modified materials—such as composites, adhesives, and sealers—to maintain antibacterial activity long after placement. In contrast to the short-lived burst effect of conventional agents (e.g., fluoride release from glass ionomers), zeolites provide extended protection against secondary caries, endodontic reinfection, or peri-implant disease.

Biocompatible and patient-friendly

Natural zeolites, particularly clinoptilolite, have demonstrated good biocompatibility in medicine and dentistry when incorporated at optimized concentrations (≤2 wt%) [59]. Their mineral origin enhances acceptance among patients who increasingly favor biomimetic and "natural" materials in line with minimally invasive and health-conscious dental care [60].

Overall implications

By combining sustainability, eco-friendliness, long-term antimicrobial performance, and biocompatibility, natural zeolites offer clear advantages over conventional additives. They not only improve the functional performance of restorative and endodontic systems but also contribute to the broader vision of preventive, bioactive, and environmentally responsible dentistry [61].

6. Limitations and Challenges Heterogeneity of natural zeolites

A key limitation of natural zeolites is their variability in purity and

composition, which depends on geological origin and extraction methods. Raw zeolites may contain impurities such as heavy metals (e.g., lead, arsenic, cadmium) that pose potential toxicity risks [62]. Therefore, extensive purification and pre-treatment are often required before clinical use, which can increase production costs and complexity. This heterogeneity also complicates standardization, as differences in mineral composition may result in inconsistent biological and mechanical performance.

Mechanical trade-offs

Although zeolite incorporation provides significant antibacterial and bioactive benefits, excessive loading (typically >3 wt%) may adversely affect the mechanical properties of restorative materials. In resin composites or adhesives, high zeolite concentrations can reduce flexural strength, compressive resistance, and bond durability due to particle agglomeration and interference with polymerization [63]. Optimized formulations are therefore essential to balance antimicrobial efficacy with long-term mechanical integrity.

Discoloration and esthetic concerns

Silver-exchanged zeolites are particularly effective in providing sustained antimicrobial release. However, their incorporation may cause discoloration of restorative materials, manifesting as grayish or yellowish tints that compromise esthetics—especially in anterior teeth [64]. This drawback reduces patient acceptance and limits widespread clinical application in areas where high esthetic outcomes are required.

Clinical evidence gaps

Most current research on zeolite-modified dental materials is limited to in vitro studies using bacterial models or laboratory-based mechanical testing. While these findings are promising, there is a scarcity of in vivo studies and randomized controlled clinical trials [65]. Without robust clinical evidence, it remains difficult to confirm the safety, long-term performance, and cost-effectiveness of zeolite-based systems. Bridging this evidence gap is critical before these materials can achieve regulatory approval and widespread clinical adoption.

Overall implications

Zeolites represent promising bioactive additives with multifunctional benefits, but challenges related to raw material variability, mechanical optimization, esthetics, and insufficient clinical validation remain.

Addressing these limitations through advanced material engineering, purification strategies, and well-designed clinical trials will be essential for translating zeolite-based biomaterials from laboratory prototypes into reliable clinical solutions [66].

7. Future Directions

Nanostructured zeolites for improved performance

The development of nanostructured zeolites represents a promising strategy to overcome the mechanical drawbacks associated with larger zeolite particles. At the nanoscale, zeolites achieve better dispersion within resin matrices, reduce agglomeration, and preserve or even enhance mechanical strength while maintaining antimicrobial functionality [70]. Their higher surface-to-volume ratio also increases ion-exchange efficiency, thereby amplifying antibacterial effects.

Smart release systems

Next-generation dental materials may employ zeolite carriers within stimuli- responsive systems, where therapeutic ion release is triggered only under pathological conditions. For example, pH-responsive zeolite composites could preferentially release Ag^+ or Zn^{2+} ions in acidic environments generated by cariogenic biofilms, thereby providing targeted antimicrobial action without continuous ion leakage [71]. This “on-demand” mechanism may improve longevity and reduce potential cytotoxicity.

Zeolite–bioactive glass hybrids

A particularly exciting direction is the design of zeolite–bioactive glass hybrid materials. These combine the remineralization potential of bioactive glass with the antimicrobial ion-exchange capacity of zeolites [72]. Such dual-function systems could simultaneously suppress bacterial colonization and promote apatite formation, advancing biomimetic restorative concepts that rebuild tooth structure while maintaining a protective antibacterial environment.

Clinical validation and translation

Despite encouraging in vitro findings, the translation of zeolite-based materials into routine practice requires robust clinical evidence. Well- designed randomized controlled trials (RCTs) are essential to evaluate safety, antimicrobial durability, and long-term clinical performance [73]. Interdisciplinary collaboration among material scientists, microbiologists, and clinicians will be critical to accelerate the path from experimental prototypes to clinically approved biomaterials.

Overall outlook

Zeolites are poised to play a central role in the evolution of restorative dentistry, shifting the paradigm from passive fillers toward bioactive, smart, and sustainable materials. By integrating nanotechnology, controlled-release strategies, and hybrid systems with rigorous clinical validation, zeolite-based innovations may significantly influence the future of conservative and preventive dentistry [74].

8. Conclusion

Zeolites are naturally occurring aluminosilicate biomaterials with considerable promise in conservative dentistry. Their unique microporous framework enables sustainable ion release, prolonged antimicrobial activity, and effective biofilm suppression, making them attractive additives for restorative systems such as glass ionomer cements, resin composites, adhesives, and mineral trioxide aggregate. Their natural origin further enhances their value as eco-friendly alternatives to synthetic antimicrobials, aligning with the principles of minimally invasive and green dentistry.

Despite these advantages, challenges remain—particularly in optimizing mechanical performance, ensuring esthetic stability, and generating robust clinical evidence. Addressing these limitations through advanced material design, purification methods, and well-structured clinical trials will be essential for clinical translation. Overall, zeolites represent a promising pathway toward the next generation of bioactive, sustainable restorative materials capable of enhancing both patient outcomes and environmental responsibility.

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Tables

Table 1. Natural origin and properties of zeolites relevant to dentistry

Feature	Description	Relevance in dentistry
Geological source	Formed from volcanic ash interacting with alkaline groundwater or seawater (e.g., clinoptilolite, mordenite, chabazite, sodalite)	Abundant, sustainable, and eco-friendly mineral resource
Structure	Three-dimensional aluminosilicate framework with interconnected micropores (3–10 Å)	Functions as a reservoir and carrier for ions and small molecules
Ion-exchange	Negative framework charge balanced by exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}); can be substituted with Ag^+, Zn^{2+}, or CHX	Enables controlled, sustained release of therapeutic or antimicrobial ions
Biocompatibility	Clinoptilolite widely studied in medicine; safe at ≤2 wt% incorporation in dental applications	Suitable for direct intraoral use in restoratives, liners, and sealants
Stability	Chemically stable in saliva and oral pH; capable of reversible hydration/dehydration	Ensures long-lasting activity and compatibility within the oral environment

Table 2. Applications of zeolite-modified restorative materials in conservative dentistry

Material	Zeolite additive	Benefits	Limitations
Glass ionomer cements (GICs)	Ag-zeolite, Zn-zeolite, CHX-zeolite	Sustained antibacterial activity, prolonged ion release, synergistic effect with fluoride	High concentrations (>3 wt%) may reduce compressive and bond strength
Resin composites & adhesives	Ag-zeolite, Zn-zeolite, Ag–Zn dual	Reduces *S. mutans* and *Lactobacillus* colonization; potential for bioactive adhesives	Excess loading may interfere with polymerization and bonding

Material	Zeolite additive	Benefits	Limitations
Mineral trioxide aggregate (MTA)	Ag-zeolite	Strong antibacterial effect against *E. faecalis* and *Candida albicans*; useful for pulp capping and apexification	May alter setting time and reduce compressive strength
Root canal sealers	Ag-zeolite (e.g., ZUT formulations)	Improved antibacterial seal at dentin interface, reduced microleakage	Less effective than NaOCl or CHX irrigants alone
Preventive sealants	Zeolite nanoparticles	Provides long-term antibacterial action in fissure sealants	Still experimental, limited in vivo validation
Toothpastes/varnishes	Clinoptilolite powder	Natural remineralization potential; detoxifying effect	Limited clinical studies available

Table 3. Comparison of natural zeolites vs. synthetic antimicrobial additives in dentistry

Property	Natural zeolites	Synthetic antimicrobials (e.g., QAS, nanoparticles)
Source	Naturally occurring volcanic aluminosilicate minerals	Chemically synthesized compounds or nanoparticles
Eco-friendliness	Abundant, sustainable, and environmentally safe	Less sustainable; may generate chemical residues and environmental accumulation
Mechanism	Controlled ion release (Ag^+, Zn^{2+}, CHX)	Direct bactericidal effect (membrane disruption, oxidative stress, cytotoxicity)
Duration of effect	Sustained, long-term antimicrobial release	Often short-term, with rapid burst release

Biocompatibility	High; widely studied in medicine and dentistry (e.g., clinoptilolite)	Variable; some agents show cytotoxicity to host tissues

Property	**Natural zeolites**	**Synthetic antimicrobials (e.g., QAS, nanoparticles)**
Mechanical impact	Neutral at ≤1–2 wt%; higher loading may reduce strength or alter polymerization	Can alter shrinkage, curing, or bonding properties
Patient acceptance	Positive, associated with “natural” and “green dentistry”	Moderate, as synthetic additives may be perceived as less biocompatible or eco-friendly

Figures

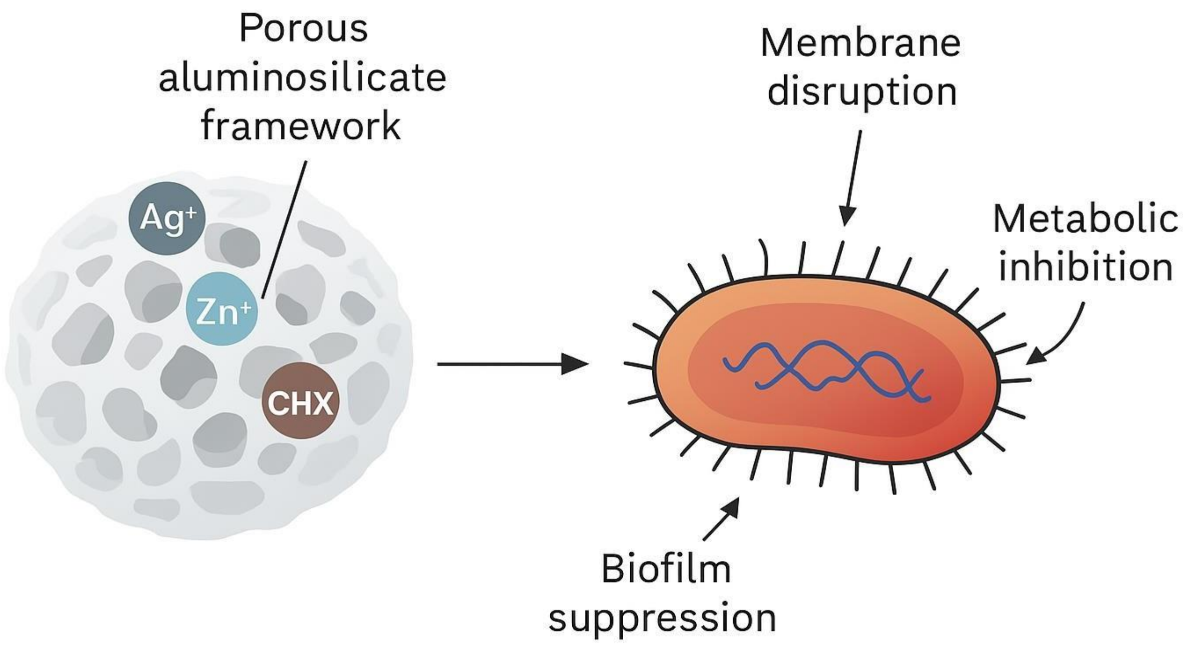

Figure 1. Mechanism of antibacterial action of zeolites

Mechanism of antibacterial action of zeolites.

Figure 2: Applications in conservative dentistry (diagram of tooth showing restorations with zeolites).

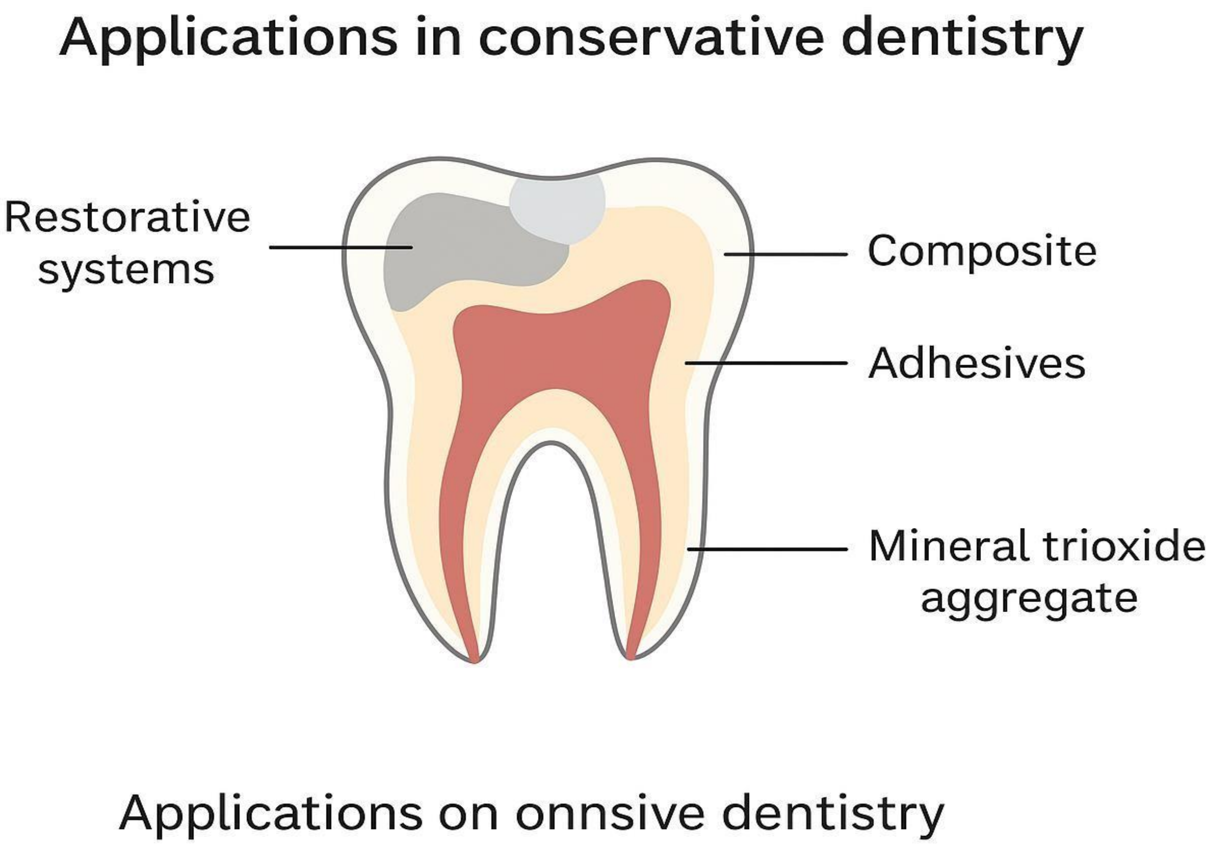

Figure 3: Natural vs. synthetic additives (eco-friendly comparison).