REVIEW ARTICLES

Self – Healing Bioactive Composites: A Review Of Emerging Strategies In Restorative Dentistry

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ABSTRACT

Bioactive composite materials with self-healing capabilities have been suggested as an emerging solution to the drawbacks associated with traditional dental material, especially with regard to microcracking and degradation issues. The purpose of this review is to analyze peer-reviewed literature with respect to self-healing techniques, bioactive composites, and applications of these materials in restorative dentistry. This literature includes laboratory research, experimental studies, and reviews published between 2000 and 2026.
As seen from current evidence, the use of such materials ensures the occurrence of spontaneous self-repair along with bioactive properties such as ion release and remineralization under controlled laboratory conditions. However, these findings are mostly derived from in vitro models or studies, which cannot completely replicate or mimic the complex oral environment. While incorporation of self-healing agents and bioactive fillers has shown potential to improve material performance, robust clinical evidence supporting enhanced restoration longevity or prevention of secondary caries remains limited.
Therefore, although self-healing bioactive composites represent a promising area of research, further well-designed in vivo and clinical studies are required to validate their long-term clinical effectiveness.

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Introduction

Resin composites in dentistry have numerous significant uses, and these include, though are not limited to, fillings, cements of single or multiple tooth prostheses, orthodontic devices, inlays, onlays, cores and build-ups, root canal posts, and provisional restoratives (1). Generally, composite materials are prone to failure because of microcracks that develop as a consequence of thermal and mechanical fatigue. Various studies have sought to enhance the fracture toughness of composite materials, and these include enhancing the volume of filler materials, incorporating nanosized silica fillers, and incorporating reinforcing fillers such as whiskers, fibers, and nanotubes, enhancing resin-filler interfaces, and optimizing the monomer chemical composition and the polymerization reaction (2,3). Despite all the improvements, fracture and failure of composite materials are common occurrences that require further investigation to improve them.

The application of self-healing as a solution to prevent failure and improve the life of composite materials without affecting their properties is gaining popularity as a reliable option (4).

Self-healing polymer matrix composite is defined as a composite that is capable of healing damages caused by external factors. Such composite materials have the ability to heal themselves without any external assistance, thus creating a replica of the self-healing process that is naturally found in biological systems (5). With the self-healing property, it is expected that safety and reliability will be enhanced, the cost of maintaining artificial composite materials will reduce, and the lifespan of the materials will increase. This field has experienced tremendous development for more than a decade and has recorded various outstanding achievements (6). Apart from the self-healing properties, the materials can also have fillers for the development of other properties, such as reinforcing fibers. Research examining the benefits and limitations of self-healing properties across different matrix materials remains scarce, even though this review encompasses all three categories of composite materials.

Review Methodology

Literature Review and Data Collection

The review was conducted using a detailed literature search process. For this research, data focusing on self-healing approaches, bioactive composite systems, microcapsule-based materials, and their application in restorative dentistry were gathered from peer-reviewed publications.

Keyword Selection

For conducting the literature search, relevant keywords for this topic were generated by the research team. Keywords such as "self-healing dental composites," "bioactive restorative materials," "microcapsule-based healing," and "remineralizing dental materials" were used in the search strategy.

Article Selection

A search was conducted through scientific databases, including PubMed, Scopus, Web of science and Google Scholar, to select pertinent peer-reviewed articles. The search was limited to articles published within the last 26 years (2000–2026) to ensure retrieval of current and relevant information while avoiding duplication of findings.

Inclusion Criteria

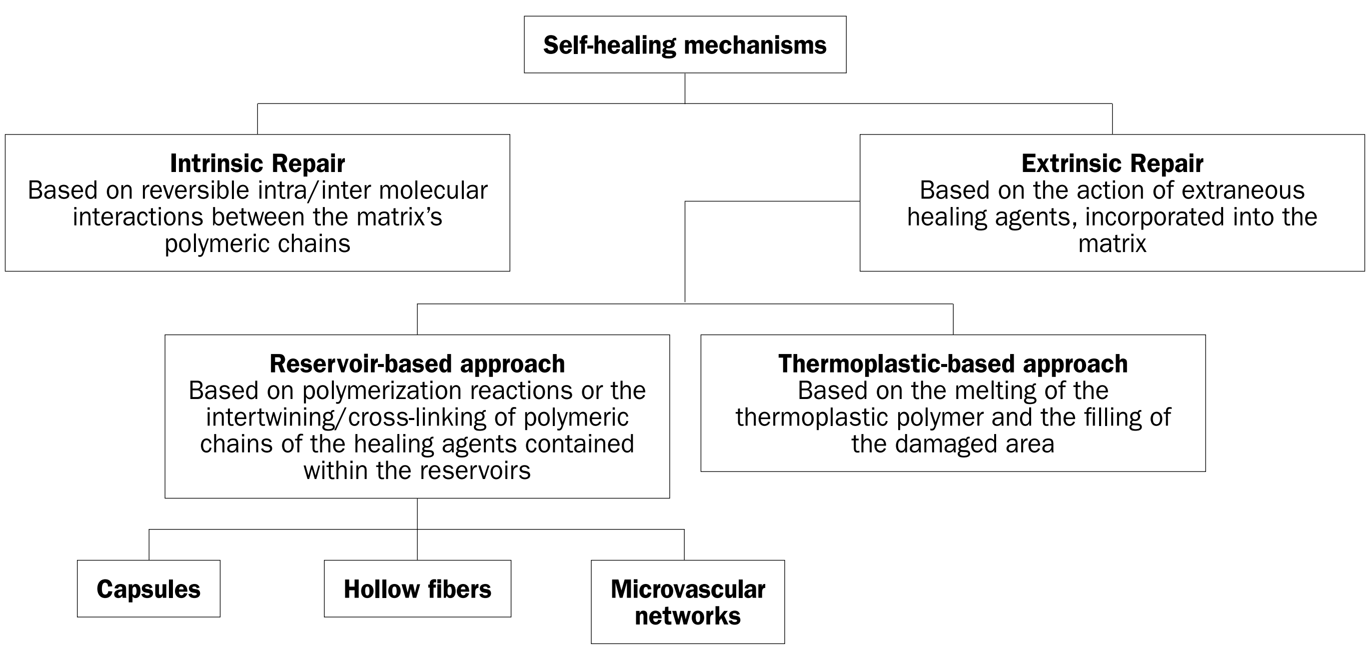
Articles chosen for inclusion into this review include laboratory investigations, experiments, literature reviews, and systematic reviews published during the past 26 years (2000–2026). In addition, selected articles were published in English and obtained from scientific databases and search engines. This category of articles were selected to ensure a thorough understanding of self-healing and bioactive composite properties as they pertain to restorative dentistry.

Exclusion Criteria
Peer-reviewed papers that focus exclusively on the application of self-healing composite materials in engineering but do not address their use in dental restorations and oral health, were not considered.
Study selection involved the identification of relevant literature, where the mechanism of action, material properties, and translational relevance received priority. Given the heterogeneity of study designs and outcomes, a qualitative synthesis approach was adopted rather than a quantitative meta-analysis.

Fundamental Mechanisms Of Self-Healing
Self-healing in polymer composites refers to the ability of a material to repair damage autonomously or in response to external stimuli, thereby restoring its structural integrity. These mechanisms are broadly classified into extrinsic (autonomous) and intrinsic (non-autonomous) systems (4,5) (Figure 1).

Extrinsic (Autonomous) Healing Systems
Extrinsic systems rely on the incorporation of external healing agents within the material matrix, typically in the form of microcapsules or vascular networks. Upon crack formation, these reservoirs rupture and release healing agents into the damaged region, where they polymerize and seal the crack.
Microcapsule-based systems are the most extensively studied approach. These typically consist of polymeric shells encapsulating monomers or reactive agents, which are released upon mechanical damage. The concept of autonomic self-healing via microcapsules was first proposed by White et al. in 2001. In this approach, microcapsules composed of a urea–formaldehyde shell encapsulate a healing agent, typically dicyclopentadiene combined with a catalyst. Following the formation of the crack, the rupturing of the microcapsules results in the release of the healing agent, which is further pulled into the plane of the crack by capillary forces. (7) Wertzberger et al. (2010) used White's self-healing mechanism in a highly filled dental resin composite for investigating the healing capacity and

Figure 1
Classification of Self-healing Composites



mechanical properties of the system (8). Similarly, H. Hu et al. have designed an epoxy-based composite that includes dual microcapsules which contains epoxy monomers (12 wt%) and an amine curing agent (8 wt%), where rupture of the microcapsules causes chemical reaction within the crack plane resulting in the in situ polymerization and crack repair (9).
Most extrinsic self-healing systems use microcapsules loaded with curing agents (10–300 µm diameter) whose core is composed of a polymeric shell such as poly(urea-formaldehyde), encapsulating liquid monomers. Following the development of the crack, the microcapsules are ruptured releasing the healing agent, which polymerizes using the embedded catalyst thereby sealing the crack and partially restoring the material's mechanical integrity (10). (Figure 2) Although these systems exhibit significant healing efficiency, they can be utilized only once due to the limitation in the quantity of the healing agents present in them.
Another form of extrinsic approach is the vascular network systems where hollow channels/fibers (40–200 µm) are incorporated in the structure facilitating controlled and repetitive delivery of healing agents to the cracks (12,13). (Figure 3) Although these systems offer better healing capacity, their clinical translation in dental materials is restricted by the fabrication process.
In general, the extrinsic self-healing process is more efficient, cost-effective, and more suitable for a wide range of materials. On the other hand, intrinsic healing requires reversible interactions at the molecular level and typically require specific activation conditions, often depending on external stimuli such as heat or UV light which may limit their application for clinical use.

Intrinsic (Non-Autonomous) Healing Systems

In contrast, intrinsic systems rely on reversible physical or chemical interactions within the material itself, eliminating the need for embedded healing agents (14). These systems typically involve dynamic covalent bonds or supramolecular interactions that can reform upon exposure to external stimuli such as heat, light, or mechanical stress (15). Extrinsic systems have been used in dental composites. However, currently, more research is being conducted on extrinsic systems due to their simplicity (16) (Figure 4).
Intrinsic systems offer the advantage of repeatable healing and better mate-

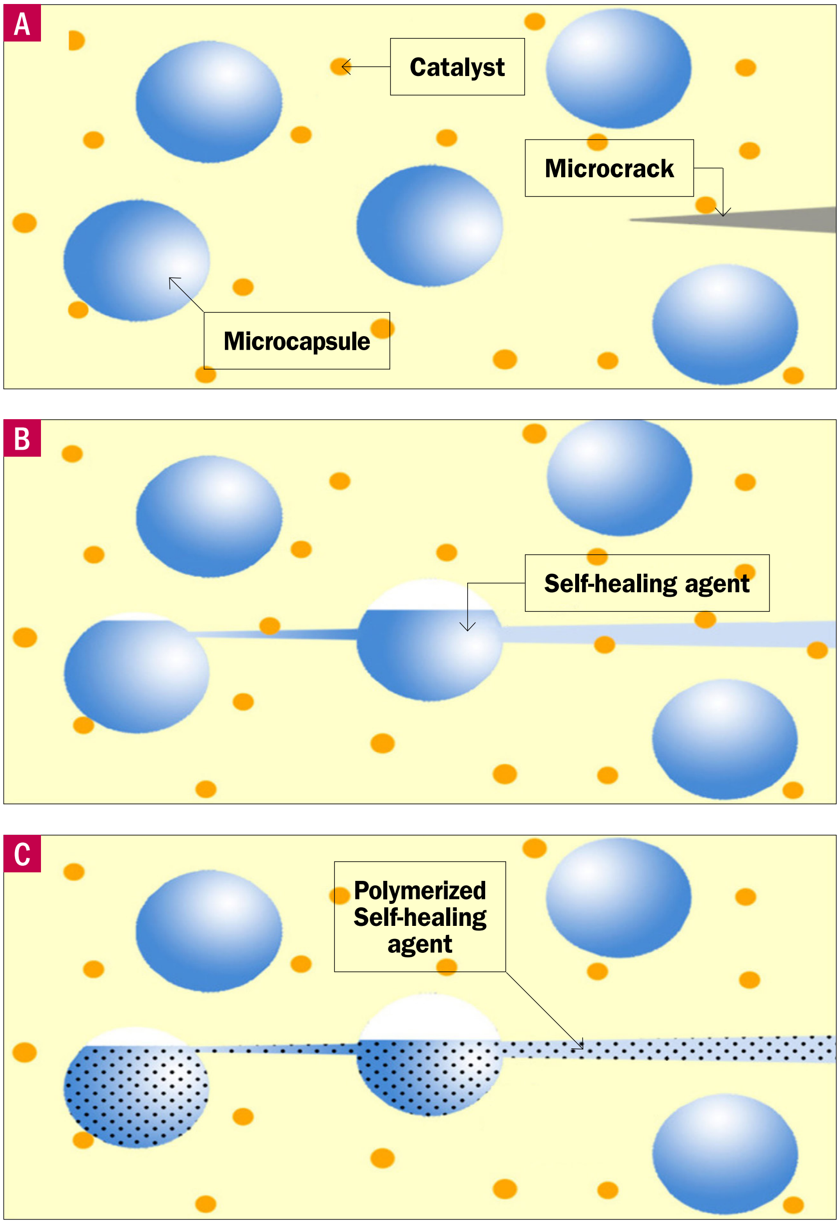
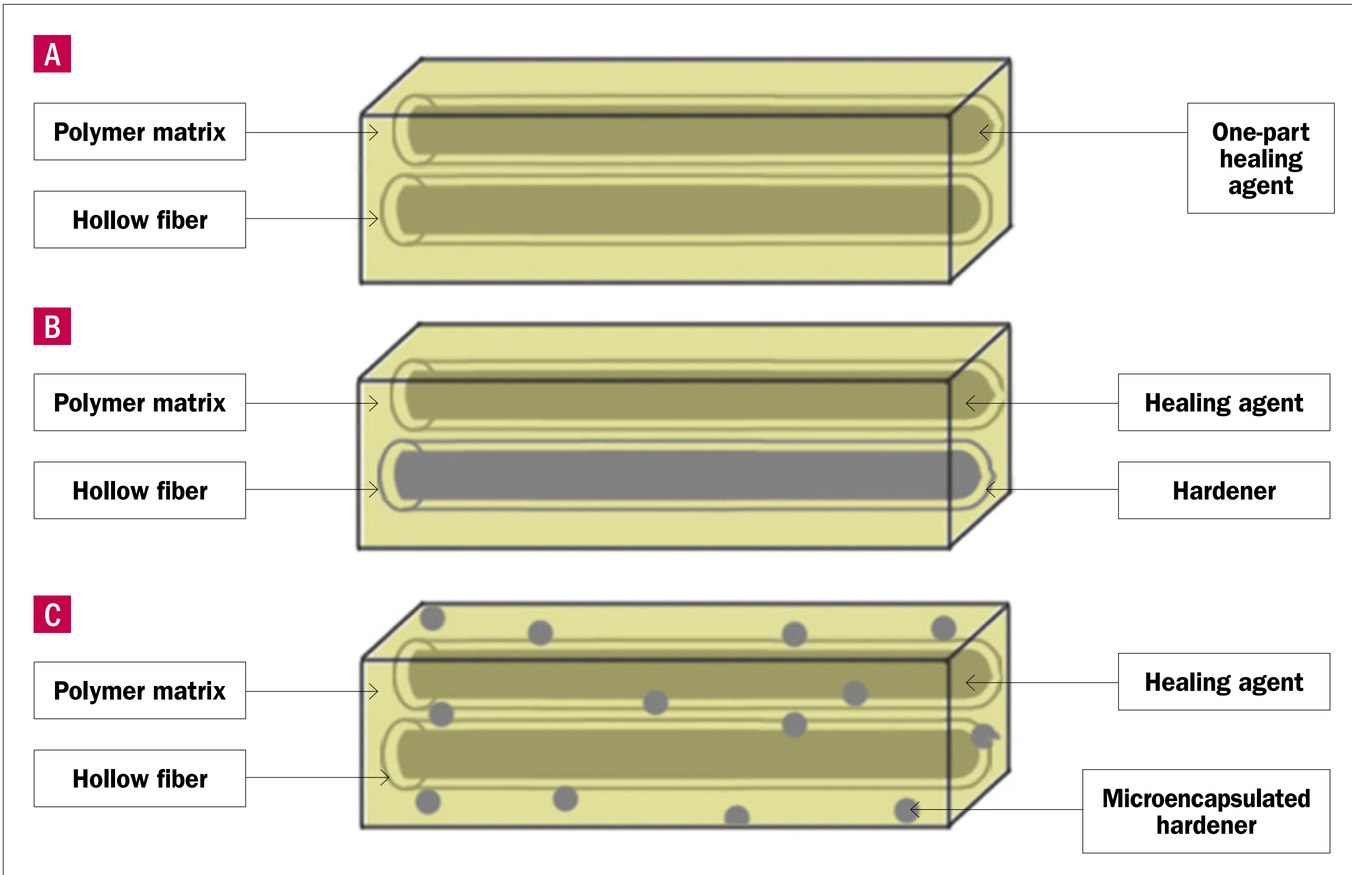


Figure 2
Principal diagram of microcapsule-based self-healing materials. (11) (**A**) Perception stage. (**B**) Delivery stage. (**C**) Reaction stage.



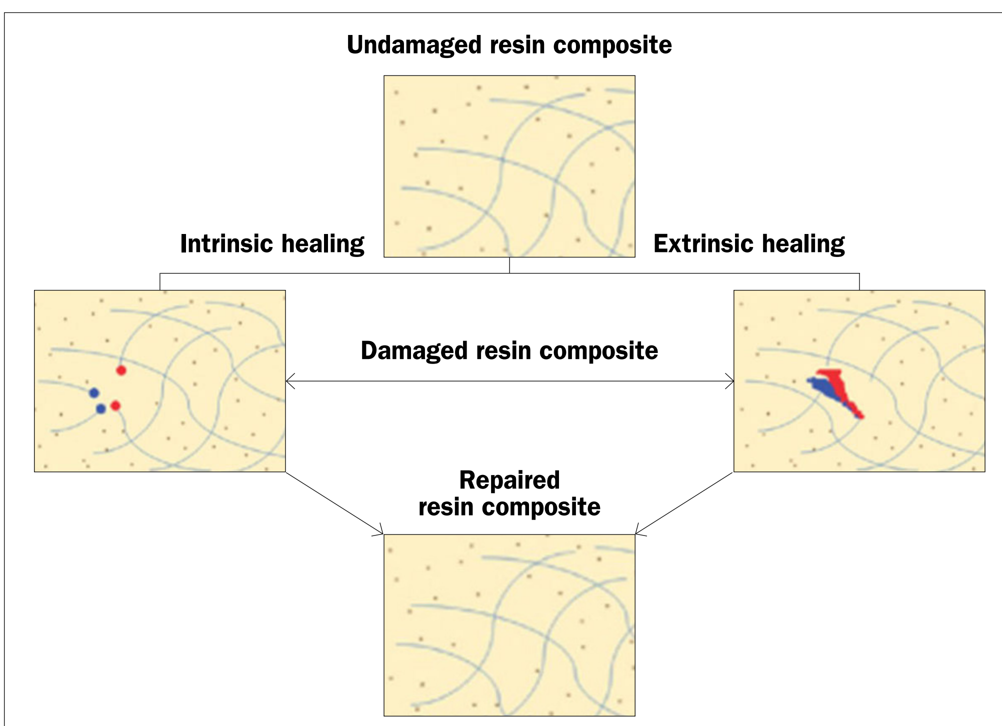


Figure 3
Diagram illustrating hollow-fiber–based self-healing systems (13): (**A**) encapsulation of a single healing agent within hollow fibers; (**B**) separate encapsulation of resin and hardener within hollow fibers; (**C**) encapsulation of the healing agent in hollow fibers with a catalyst uniformly dispersed in the polymer matrix.

Figure 4
Diagram illustrating self-healing resin composites, highlighting both intrinsic and extrinsic mechanisms. (16)

rial homogeneity. However, they often require specific environmental triggers and may involve more complex material design, which has limited their widespread application in dental composites compared to extrinsic systems (17,18,19).

While extrinsic systems are currently more widely explored due to their simplicity and immediate healing response, intrinsic systems present a promising direction for achieving long-term, repeatable self-repair. A clearer distinction between these mechanisms is essential, as each presents unique advantages and limitations relevant to clinical translation.

Bioactive Self-Healing Composites

In addition, the occurrence of secondary caries is another significant reason for the failure of restoratives, which is often related to the accumulation of biofilm. Therefore, the exploration of self-healing restorative materials with bioactivity is one of the major trends in the field of restorative dentistry. In recent years, some researchers have proved that microcapsule-based self-healing restorative materials with the addition of bioactive substances, such as 2-methacryloyloxyethyl phosphorylcholine, can not only exhibit self-healing properties but also reduce the accumulation of plaque (20).

Additionally, the bioactive fillers, such as amorphous calcium phosphate, bioactive glass, and calcium silicate, allow for the therapeutic release of ions, thus facilitating remineralization in the tooth-restoration interface (21). Such an approach, where structure and biological activity are improved, will lead to the increased lifespan of the restoration.

Huyang G et al. developed a microcapsule-based self-healing resin composite incorporating silica microcapsules filled with polyacrylic acid and a resin matrix containing strontium fluoroaluminosilicate glass. Upon microcrack formation, capsule rupture released the healing agent, which reacted with the glass to form a glass ionomer–like phase that sealed cracks and partially restored mechanical properties. While demonstrating effective autonomous crack repair with acceptable baseline strength in vitro, limitations remain regarding long-term durability, repeat healing potential, and clinical translation (22).

Properties Of Self-Healing Bioactive Composites

Self-healing dental composites have demonstrated promising mechanical and biological properties, particularly in terms of fracture toughness recovery (7, 23, 24) and bioactivity. Studies report recovery of approximately 50–80% of original mechanical strength, depending on factors such as microcapsule concentration, size, and distribution (25, 26).

Overall, these studies have proven that self-healing efficiency is highly dependent on material composition and microcapsule distribution. Renewable efficiency, as shown by Wu et al. in their study, showed that there was a 65% recovery of the initial fracture toughness and that there was no adverse effect on the elastic modulus and flexural strength of the resin if the microcapsules are less than 15wt% (25).

In contrast, Kang Ning et al. reported healing efficiencies of up to 76%, attributed to increased microcapsule diameter and concentration. Larger microcapsules (~198 ± 43 μm) significantly enhanced fracture toughness and overall self-healing performance of the resin composites (27).

Despite these improvements in healing efficiency, a trade-off with mechanical properties is evident. Althaqafi et al. examined the correlation of the mechanical properties of the self-healing dental composite with SiO_2 nanoparticles with the amount of microcapsules with TEGDMA monomer and DHEPT amine. The mechanical properties were not significantly affected, apart from the reduction in flexural strength from 80 MPa to 55 MPa with an increase in

microcapsules up to 10 wt% (28).
As for the biocompatibility of these materials, Menikheim et al showed that the polyurethane nanocapsule-based self-healing dental resin system showed good in vitro biocompatibility with human epithelial cells, implying low cytotoxicity and potential for clinical use (29).
The bioactivity of the composite is mainly ascribed to the calcium- and phosphate-releasing fillers. These fillers not only enhance the remineralization properties of the composite material but also display antibacterial properties. Studies on amorphous calcium phosphate (ACP) nanoparticles have demonstrated that this material can exhibit self-healing, antibacterial, and remineralization capabilities. The reported healing efficiency of ACP-based systems ranges between approximately 65% and 81% (25). However, the optimized composite material also displays properties such as flexural strength, elastic modulus, and wear resistance comparable to the conventional composite material. Self-healing property further makes it possible for the material to show high fatigue resistance by stopping the crack propagation (30).
One of the major drawbacks of current research in this field is the inconsistency between the in vitro efficiency of self-healing and its clinical utility. While self-healing capacity and bioactivity are always shown to be consistent in the laboratory experiments, it is still difficult to predict how the material would behave under in vivo conditions, particularly when the material is exposed to various physical parameters including moisture, pH variation, enzyme activity, multispecies biofilms, and mechanical loading. Moreover, interactions between biofilm development and self-healing properties need to be studied extensively. These factors can weaken microcapsule integrity, alter healing agent release, and influence the durability of the material. Additionally, the effect of bacterial biofilms on self-healing processes is still not well-understood, and the antibacterial or ion-releasing properties demonstrated in vitro cannot always be replicated in vivo. Consequently, the predominance of short-term laboratory evidence limits confidence in clinical performance, highlighting the need for standardized in vitro models that better simulate oral conditions and, critically, well-designed long-term in vivo and clinical studies to establish true translational potential.

Bioinspired Self-Healing Composites
Bacteria-induced biomineralization has shown promise as a technique for the creation of self-healing dental resin-based composites, as this technique utilizes the potential of certain bacteria to induce mineralization of calcium carbonate within the microcracks. In this technique, bacterial spores or active cells are added to the resin along with a nutrient source. Once the microcrack occurs and the bacteria are exposed to the oral fluids, the bacteria are activated and start the calcium precipitating mechanism, leading to mineralization. This leads to the closing of the microcrack, thus restoring the integrity of the structure (31).
Han Y et al developed and optimized a novel class of microbial self-healing dental resin composites utilizing bacteria-induced mineralization to repair structural damage. The study incorporated multiple bacterial strains capable of precipitating calcium carbonate ($CaCO_3$) into resin matrices and systematically evaluated their healing efficiency under simulated oral conditions. Upon formation of microcracks, ingress of moisture and oxygen activated the embedded bacteria, triggering biomineralization that effectively sealed the cracked site. The findings suggest that such composites not only restore mechanical integrity after damage but also hold significant clinical potential in reducing fracture propagation, minimizing secondary caries, and extending the longevity of dental restorations (32).

Triple Benefit Dental Composites

Recently a new class of composites has been developed, with three functional and beneficial characteristics: self-repair, antibacterial properties, and remineralization abilities (21). The self-healing resin composite was formulated by incorporating poly(urea–formaldehyde) (PUF) microcapsules encapsulating triethylene glycol dimethacrylate (TEGDMA), along with the antibacterial monomer dimethylaminohexadecyl methacrylate (DMAHDM) and the remineralizing agent nanoparticles of amorphous calcium phosphate (NACP). DMAHDM was integrated into the BisGMA–TEGDMA resin matrix at a mass fraction of 10%. (33). Additionally, the BisGMA-TEGDMA resin system contained 20% NACP for the release of Ca and P ions and the remineralization process, along with 35% glass fillers for reinforcement. Subsequently, the BisGMA–TEGDMA resin system was blended with the microcapsule phase at mass fractions of 0%, 2.5%, 5%, 7.5%, and 10%. Flexural testing demonstrated no significant differences in strength or elastic modulus among groups containing up to 7.5% microcapsules. However, at a 10% microcapsule loading, a significant reduction in mechanical properties was observed (21). The enhanced self-healing performance and restoration of load-bearing capacity were attributed to the substantial in situ polymerization of the released TEGDMA, triggered by free-radical initiation. The liberated healing agents subsequently polymerized within the crack, effectively arresting crack propagation and facilitating repair of the fractured interfaces. In addition, the composite exhibited pronounced antimicrobial activity. Both the metabolic activity and acid production of biofilms formed on DMAHDM-containing composites were significantly reduced compared to conventional composites. Furthermore, incorporation of DMAHDM at all evaluated mass fractions resulted in a 3–4 log reduction in biofilm colony-forming units (CFU) relative to the control composite lacking DMAHDM (21). This was accomplished with a mass fraction of microcapsules ranging from 0 to 10%, thus demonstrating that incorporation of the microcapsule did not interfere with the antibacterial activity.

As for the effectiveness of antibacterial agents, the efficacy of DMAHDM is attributed to its positive charge from the quaternary ammonium groups that interacts with the negative charge of the bacterial cell membrane, thereby causing disruption and leakage of cytoplasm. (34) In addition to its self-healing and antibacterial functions, the composite demonstrated a third advantage through the release of calcium (Ca) and phosphate (P) ions, facilitating remineralization. Notably, the incorporation of the remineralizing agent (NACP) and the antibacterial monomer (DMAHDM) into the self-healing composite did not compromise its healing performance, which remained comparable to that of formulations lacking these functional additives.

Advantages With Self-Healing Composites

Self-healing bioactive composites also provide a number of advantages that contribute to enhanced clinical performance. These materials are effective in enhancing resistance to crack propagation and fatigue failure. Therefore, the longevity of the restoration is increased. In addition, the bioactive composites are effective in providing antibacterial and remineralization properties. Therefore, marginal integrity and the occurrence of secondary caries are minimized. Finally, the bioactive composites are effective in mimicking the principles of biomimetic and regenerative dentistry.

Limitations

Despite their promising potential, self-healing bioactive composites face several constraints that limit clinical applicability. High microcapsule loading can adversely affect mechanical properties, particularly flexural strength and wear resistance (25). In addition, extrinsic self-healing systems are inherently limited by the finite availability of healing agents, resulting in diminished efficacy over repeated damage cycles. The incorporation of bioactive fillers and microcapsules may also compromise optical properties such as translucency and polishability, restricting their use in esthetically demanding regions (35). It is important to note that current data have been mostly obtained through in vitro tests with short durations, which cannot accurately mimic the complex oral environment, especially considering variations in pH levels, enzymatic functions, and masticatory muscle fatigue, among other factors.

Knowledge gaps

Many challenges exist in translating self-healing dental composites into clinical practice. There is still a need for long-term in vivo data on restoration survival in response to thermal, mechanical, and oral environmental stresses. Currently, the healing systems exhibit partial and short term recovery of the mechanical properties, where the duration and durability of the multiple healing processes are unclear.

Biocompatibility and safety concerns about the newly introduced chemical formulations for the healing process also need more investigation. In addition to that, the absence of standardized testing procedures, which include crack generation, loading scenarios, and healing efficiencies, is another barrier towards the application of such restorative material in clinical practice.

Materials-wise, optimizing microcapsule parameters (size, distribution, concentration) is difficult because it might compromise structural performance. Manufacturing consistency, storage stability, and scalability also hinder clinical translation.

Future research should prioritize biocompatible, durable systems supported by standardized evaluation methods and robust long-term clinical studies.

Future trends:

The next generation of self healing dental materials are likely to employ complementary techniques or mechanisms as opposed to a sole mechanism; microcapsules will be used as part of a rapid autonomous crack sealing , which will also include dynamic covalent bonding systems (e.g., disulfide exchange) for delayed stimulus-responsive repair of larger defects. The inclusion of bioactive fillers, which are capable of releasing calcium and phosphate ions in an acidic environment, further supports apatite formation, enhancing marginal sealing and reducing secondary caries. To ensure effective clinical translation, there is a need for standardized in vitro models simulating fatigue loading, thermocycling, and biofilm formation, along with rigorous evaluations of biocompatibility going further than cytotoxicity tests and including genotoxicity, immunogenicity, and interaction with microbiomes. Equally important is the cooperation between academia and industry addressing issues related to scale-up and regulatory pathways. It is imperative that any self-healing material undergoes extensive preclinical and clinical testing , demonstrating both self-healing properties and superior longevity and cost-effectiveness compared to the existing materials (16).

Conclusion

Self-healing bioactive dental composite resins constitute a relatively novel but theoretically intriguing approach in modern restorative dentistry, characterized by self-repairing capabilities alongside bioactivity. Laboratory trials and studies have confirmed their capacity to regain mechanical integrity following damage and facilitate ion-dependent remineralization under controlled conditions.

Nevertheless, the existing body of research on the subject matter consists

mainly of in vitro experiments, rendering it unclear how well they would perform in vivo. Claims regarding improved restoration longevity and prevention of secondary caries should therefore be interpreted cautiously, as they are not yet supported by robust long-term clinical data.
Future research should focus on standardized testing protocols, long-term in vivo studies, and clinical trials for evaluating their translational possibilities and ascertaining their superiority over current restorative systems.

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Not Applicable.

Informed Consent Statement
Not Applicable. This is a literature review and does not involve human participants or identifiable patient data.

IRB Statement
Not Applicable. This is a literature review and does not involve primary research with human participants, animals, or biological material.

Data Availability Statement
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Conflicts of Interest
The authors have no competing interests to declare.

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