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BIOCERAMIC ENDODONTIC SEALERS: A STRUCTURED NARRATIVE REVIEW OF PHYSICOCHEMICAL PROPERTIES, BIOLOGICAL BEHAVIOR, CLINICAL OUTCOMES, AND LIMITATIONS

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ABSTRACT

Bioceramic endodontic sealers have become increasingly important in contemporary root canal obturation because of their hydraulic setting, hydrophilicity, alkaline pH, calcium ion release, bioactivity, and potential interaction with dentin and periapical tissues. The aim of this structured narrative literature review was to evaluate current evidence regarding bioceramic endodontic sealers, with emphasis on their composition, physicochemical properties, biological behavior, sealing ability, obturation techniques, clinical outcomes, postoperative pain, retreatability, and limitations. A literature search was performed using PubMed, PubMed Central, and Europe PMC, focusing on English-language full-text articles published between 2022 and 2026. The reviewed literature suggests that calcium silicate-based sealers demonstrate favorable laboratory properties, including dentinal tubule penetration, calcium ion release, high alkalinity, apatite-forming ability, and acceptable cytocompatibility. However, these properties vary between commercial products and should not be generalized to the entire material class. Clinical studies indicate that bioceramic sealers can achieve outcomes comparable to traditional epoxy resin- and zinc oxide-eugenol-based sealers, particularly when used with single-cone or sealer-based obturation techniques. Current evidence supports bioceramic sealers as clinically viable alternatives rather than universally superior replacements. Further long-term clinical studies are needed to clarify product-specific performance, retreatability, extrusion behavior, and long-term treatment outcomes.

KEYWORDS

Bioceramic Sealer, Calcium Silicate-Based Sealer, Root Canal Obturation, Endodontic Sealer, Single-Cone Obturation

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1. Introduction

Root canal treatment is performed to prevent or treat apical periodontitis by eliminating infection from the root canal system and preventing reinfection after treatment. Apical periodontitis develops when endodontic infection induces an inflammatory reaction in the periapical tissues, leading to bone resorption and lesion formation. For this reason, successful endodontic treatment depends not only on mechanical instrumentation, but also on chemical disinfection and three-dimensional obturation of the prepared canal system. The obturation should seal the canal space from the coronal portion to the apical foramen and prevent the passage of microorganisms, fluids, and bacterial by-products toward the periapical tissues. Inadequate obturation is therefore clinically significant, because the quality of the root filling is considered an important prognostic factor in nonsurgical root canal treatment.

The root canal system has a complex anatomy. It may contain lateral canals, accessory canals, isthmuses, fins, oval extensions, apical irregularities, and dentinal tubules. These anatomical features cannot be predictably filled by gutta-percha alone. For this reason, root canal obturation is conventionally performed using a core filling material, most commonly gutta-percha, in combination with an endodontic sealer. The sealer fills the spaces between the gutta-percha and dentinal wall, improves adaptation of the root filling, and helps seal anatomical areas that the core material cannot occupy completely. A well-obtured root canal system is important for preventing coronal leakage and for creating a biocompatible environment that allows healing of existing periapical lesions or prevents development of new lesions.

The role of an endodontic sealer is therefore not secondary or incidental. Although gutta-percha provides the bulk of the obturation, the sealer is responsible for closing the interface between gutta-percha and root dentin. It may also penetrate dentinal tubules and increase the contact area between the filling material and dentin. Dentinal tubule penetration is considered relevant because it may improve sealing ability, restrict pathways for microbial penetration, and entomb residual microorganisms that remain after chemomechanical preparation. Parameters such as the depth, percentage, and area of sealer penetration are therefore commonly investigated when assessing the suitability of endodontic sealers.

Many types of root canal sealers have been introduced over time. These include zinc oxide-eugenol-based, calcium hydroxide-based, glass ionomer-based, silicone-based, epoxy resin-based, and calcium silicate-based materials. Epoxy resin-based sealers, such as AH Plus, have been widely used because of favorable physical properties, resistance to dissolution, radiopacity, sealing ability, and long clinical use. In combination with gutta-percha and warm vertical compaction, AH Plus has often been regarded as a standard reference material in obturation studies. However, traditional sealer systems are not without limitations. Some materials may show dissolution, limited bioactivity, lack of chemical bonding to dentin, technique sensitivity, or biological concerns before complete setting.

Bioceramic endodontic sealers, especially calcium silicate-based sealers, were introduced as an attempt to improve the biological and physicochemical behavior of root canal filling materials. These sealers are generally associated with hydrophilicity, hydraulic setting, alkaline pH, calcium ion release, bioactivity, and the ability to form hydroxyapatite-like deposits in contact with tissue fluids. Calcium silicate-based sealers are available in different formulations, including powder-liquid systems and premixed ready-to-use materials. Their composition may include calcium silicates, radiopacifiers, thickening agents, liquids or vehicles, and other additives. These variations are important because they may influence setting behavior, flow, solubility, film thickness, biological response, and clinical handling.

The development of bioceramic sealers has also influenced obturation concepts. Traditional obturation philosophy emphasized the placement of a dense gutta-percha core with a minimal sealer layer. In contrast, calcium silicate-based sealers have encouraged greater interest in single-cone and sealer-based obturation techniques. In these techniques, the sealer has a more active role in filling irregularities and contributing to the seal. This approach may simplify obturation, reduce chairside time, and avoid some risks associated with warm compaction techniques, such as excessive condensation forces or thermal effects. However, greater reliance on the sealer also raises important questions regarding extrusion, solubility, setting, retreatability, long-term stability, and clinical outcome.

Although bioceramic sealers have promising laboratory properties, their clinical superiority over established sealers has not been definitively proven. Current clinical evidence suggests that premixed bioceramic sealers may show similar survival, success, postoperative pain, and extrusion outcomes compared with standard sealers, while available studies remain limited by heterogeneity, short follow-up periods, and differences in clinical protocols. This creates the need for a balanced review of the literature, in which

bioceramic sealers are assessed not only as innovative materials, but also as clinically used products with advantages, limitations, and product-specific differences.

The aim of this literature review is to evaluate current evidence regarding bioceramic endodontic sealers, with particular focus on their composition, physicochemical properties, biological behavior, sealing ability, obturation techniques, clinical outcomes, postoperative pain, retreatability, and limitations. The review is performed to clarify whether the properties attributed to these materials are supported by available research and to determine how bioceramic sealers should be understood in relation to traditional endodontic sealers. Bioceramic sealers are not assessed as a single uniform material, but as a group of related calcium silicate-based materials whose performance depends on composition, formulation, clinical technique, and available evidence.

2. Research Materials and Methods

2.1 Type of review

This paper was prepared as a structured narrative literature review focused on bioceramic endodontic sealers. The purpose of the review was to collect, organize, and critically discuss recent evidence concerning calcium silicate-based and hydraulic calcium silicate endodontic sealers, with attention to their composition, physicochemical properties, biological behavior, sealing ability, obturation techniques, clinical outcomes, postoperative pain, retreatability, and limitations.

The review was not designed as a systematic review or meta-analysis. Therefore, no formal protocol registration, quantitative synthesis, or statistical pooling of results was performed. However, the literature search and article selection were conducted in an organized manner, and the included papers were grouped thematically according to their relevance to the objectives of the review.

2.2 Search strategy

The literature search was performed using freely accessible scientific databases. The databases used were PubMed, PubMed Central, and Europe PMC. The search focused on recent publications concerning bioceramic, calcium silicate-based, and hydraulic calcium silicate root canal sealers.

The following key phrases were used during the search:

- bioceramic sealer
- bioceramic root canal sealer
- calcium silicate sealer
- calcium silicate-based sealer
- hydraulic calcium silicate sealer
- bioactive endodontic sealer

The search was directed toward papers first published between 2022 and 2026. Titles and abstracts were initially screened to determine whether the article was relevant to the topic of endodontic sealers. Full texts were then assessed when available.

2.3 Inclusion criteria

Articles were included in the review when they met the following criteria:

- The paper had a direct focus on endodontic sealers.
- The article was first published between 2022 and 2026.
- The paper addressed at least one topic relevant to this review, including composition, physicochemical properties, biological behavior, sealing ability, obturation technique, postoperative pain, clinical outcome, retreatment, discoloration, or material limitations.
 - The full text was available.
 - The article was written in English.

Both laboratory and clinical studies were considered eligible. Review articles, systematic reviews, meta-analyses, umbrella reviews, randomized clinical trials, prospective clinical studies, and in vitro studies were included when they were directly relevant to the aims of the review.

2.4 Exclusion criteria

Articles were excluded if they did not focus directly on endodontic sealers, were unrelated to the objectives of the review, were not available in full text, were not written in English, or were duplicate records. Papers focused only on general dental ceramics, restorative materials, or calcium silicate repair materials were excluded unless their content was relevant to the discussion of endodontic sealer properties, limitations, or expanded clinical applications.

2.5 Article selection and data organization

After the initial search, potentially relevant articles were screened by title and abstract. Full-text articles were then reviewed to confirm eligibility. Duplicate articles were removed. The selected papers were organized according to study design and main topic.

For each included article, the following information was extracted: author and year of publication, study type, investigated materials, methodology, main outcomes, key findings, clinical relevance, and limitations. The extracted information was then grouped into thematic categories corresponding to the structure of this review.

The final synthesis was narrative rather than quantitative. Findings from the included papers were compared to identify recurring patterns, agreements, contradictions, and gaps in the evidence. Special attention was given to whether conclusions were based on laboratory findings, clinical studies, or review-level evidence.

2.6. Use of artificial intelligence

Artificial intelligence was used as an auxiliary tool during the preparation of this literature review. Its role was limited to organizing articles, summarizing extracted information, assisting with thematic grouping of the literature, suggesting manuscript structure, and supporting language refinement.

AI-generated summaries were checked against the full-text articles before being used in the manuscript. The selection of articles, interpretation of findings, verification of scientific content, and final academic responsibility remained with the author. Artificial intelligence was not used as an independent source of scientific evidence, and no references were included solely on the basis of AI-generated content.

3. Research results

3.1. Classification and composition of bioceramic endodontic sealers

Endodontic sealers can be classified according to their dominant chemical constituents and setting reactions. Traditional groups include zinc oxide-eugenol-based, calcium hydroxide-based, glass ionomer-based, silicone-based, methacrylate resin-based, and epoxy resin-based sealers. More recently, calcium silicate-based sealers have become widely discussed as a distinct group and are frequently referred to as “bioceramic” or “bioceramic-based” sealers because they contain bioactive ceramic components intended to interact favorably with dentin and periapical tissues [5,23]. In the contemporary literature, the term “bioceramic sealer” is therefore often used as a broad clinical and material-science category rather than as the name of one uniform material.

Within this broad category, calcium silicate-based sealers represent the most important subgroup for endodontic obturation. Their development is related to the earlier introduction of mineral trioxide aggregate (MTA), which was originally used mainly for procedures such as perforation repair, pulp capping, root-end filling, and apical barrier formation. However, conventional MTA could not function ideally as a root canal sealer because of its coarse particle size and limited flowability. Newer hydraulic calcium silicate sealers were developed to overcome these limitations, with smaller particle size, improved flow, and formulations suitable for orthograde canal obturation [23].

The general composition of calcium silicate-based sealers includes tricalcium silicate and/or dicalcium silicate, radiopacifying agents, liquids or vehicles, and additional modifiers. Ashkar et al. summarized that calcium silicate-based sealers usually contain varying proportions of tricalcium or dicalcium silicates, a radiopacifier, a mixing liquid in powder-liquid systems, and additives [2]. These components are responsible for many of the characteristic properties of this material group, including hydraulic setting, alkaline pH, calcium ion release, and bioactivity. In several studies included in this review, commonly investigated calcium silicate-based sealers included BioRoot RCS, TotalFill BC Sealer, EndoSequence BC Sealer/iRoot SP, CeraSeal, Bio-C Sealer, EndoSeal TCS, Well-Root ST, AH Plus Bioceramic Sealer, C-Root SP, and KP-Root SP.

A second way to classify bioceramic sealers is according to their formulation and method of delivery. The literature repeatedly distinguishes between powder-liquid materials, paste-to-paste materials, and premixed ready-to-use sealers. Zamparini et al. noted that premixed bioceramic sealers usually incorporate one or more bioactive agents, especially calcium silicates, together with radiopacifiers and thickening agents, and that these materials can be categorized according to composition, formulation, and clinical use [1].

Powder-liquid sealers, such as BioRoot RCS, begin their setting reaction after the powder and liquid are mixed. According to Ashkar et al., BioRoot RCS contains tricalcium silicate, zirconium dioxide, and povidone in the powder, with water, calcium chloride, and polycarboxylate in the liquid [2]. Premixed systems, by contrast, are supplied in syringes or tubes and are intended to simplify clinical delivery. Examples include EndoSequence BC Sealer/iRoot SP, TotalFill BC Sealer, CeraSeal, Bio-C Sealer, and AH Plus Bioceramic Sealer. These materials require moisture from dentinal tubules or tissue fluids to complete their hydraulic setting reaction. This moisture dependence is one of their defining characteristics, but it also introduces clinical uncertainty because excessive drying or insufficient moisture may influence complete setting and material behavior [1].

The term “bioceramic sealer” also includes materials with additional bioactive or functional components. For example, Well-Root ST is described as a tricalcium silicate-based sealer containing bioactive glass, while C-Root SP incorporates strontium and KP-Root SP incorporates calcium silicate nanoparticles into ceramic matrices [5]. These modifications illustrate that contemporary bioceramic sealers are not chemically identical, even when grouped under the same clinical label. Their different additives, vehicles, radiopacifiers, and particle structures may influence properties such as flow, solubility, calcium ion release, dentinal tubule penetration, interfacial adaptation, cytocompatibility, and push-out bond strength.

Radiopacifiers are another important compositional element. Zirconium oxide, tantalum oxide, bismuth oxide, and related compounds are incorporated to make the sealer visible radiographically. Zamparini et al. emphasized that the percentage and type of radiopacifier may influence the radiographic appearance of the material in the canal and periapical area [1].

For the purposes of this review, the term “bioceramic endodontic sealer” will primarily refer to calcium silicate-based root canal sealers used for orthograde obturation, including both powder-liquid and premixed formulations. However, bioceramic sealers should not be treated as a single interchangeable material class. Their classification by chemistry, presentation form, and functional additives is essential for understanding the physicochemical, biological, and clinical findings discussed in the following sections.

3.2. Physicochemical properties

The physicochemical behavior of bioceramic endodontic sealers is central to their clinical use, because these materials are expected not only to fill the space between gutta-percha and dentin, but also to interact with moisture, release ions, adapt to canal irregularities, penetrate dentinal tubules, and maintain dimensional stability over time. In contrast to traditional epoxy resin-based sealers, calcium silicate-based sealers are hydraulic materials. Their setting reaction depends on water and hydrophilic inorganic components, and this moisture-dependent behavior influences several clinically relevant properties, including setting time, flow, solubility, ion release, adaptation, and bioactivity. Ashkar et al. emphasized that premixed calcium silicate-based sealers require an external source of water, generally from dentinal tubules, to complete their setting reaction, whereas powder-liquid systems begin setting after their components are mixed before placement into the canal [2].

3.2.1 Setting reaction and moisture dependence

The hydraulic setting reaction is one of the defining characteristics of calcium silicate-based sealers. When these materials contact water, calcium silicate hydration products are formed, and calcium hydroxide may subsequently contribute to alkalinity and apatite formation. This feature explains the good compatibility of bioceramic sealers with the moist environment of the root canal system, but it also creates a potential clinical limitation: the degree of canal dryness may affect material performance. Unlike epoxy resin-based sealers, which typically require a dry field for optimal behavior, calcium silicate-based sealers require a controlled amount of moisture.

The importance of moisture control was demonstrated by Wang et al., who investigated iRoot SP after two different drying protocols. Their results showed that paper-point drying was more favorable for adhesion, spreading, penetration, and mineralization of iRoot SP than 95% ethanol drying. Excessive drying reduced the sealer’s ability to penetrate and mineralize within dentinal tubules. The same study found that iRoot SP increased the elastic modulus and hardness of dentin near the sealer interface and improved the compressive strength of prepared roots compared with prepared but unfilled roots [8].

3.2.2 Flow, film thickness, and handling

Flowability is essential for a root canal sealer because the canal system contains fins, lateral canals, isthmuses, and microscopic irregularities that gutta-percha cannot fully occupy. Ashkar et al. noted that sealer flow allows the material to penetrate difficult-to-access spaces, including narrow dentinal irregularities and accessory canals, and that flow rate may be influenced by particle size, temperature, and mixing time [2]. In this sense, the development of bioceramic sealers with smaller particle sizes and premixed delivery systems can be understood as an attempt to improve placement and adaptation when compared with older calcium silicate cements such as MTA, which had limited flowability and therefore could not function ideally as a sealer.

Film thickness is closely related to flow and handling. A sealer with low film thickness can more easily occupy the thin interface between gutta-percha and canal wall. Hamdy et al. compared AH Plus Bioceramic Sealer, Bio-C Sealer, and the resin-based ADseal sealer and found that AH Plus Bioceramic showed the least film thickness, while ADseal demonstrated the greatest film thickness. In the same study, Bio-C Sealer showed intermediate film thickness [13]. This suggests that at least some premixed calcium silicate-based sealers may possess favorable handling characteristics for thin-film adaptation. However, flow and film thickness must be interpreted together with extrusion risk. A highly flowable sealer may adapt well to canal anatomy but may also be more prone to extrusion beyond the apex, particularly in open apices, wide foramina, or overinstrumented canals. This relationship will be discussed further in the sections on obturation techniques and clinical outcomes.

3.2.3 Solubility, alkalinity, and calcium ion release

Solubility is one of the most debated physicochemical properties of bioceramic sealers. Ideally, a root canal sealer should remain dimensionally stable and resist dissolution after setting. Ashkar et al. highlighted that, according to ISO 6876, the solubility of a root canal sealer should not exceed 3% mass fraction after 24 hours of water immersion, because excessive dissolution may create gaps at the dentin-sealer-gutta-percha interface and potentially allow bacterial products to reach periapical tissues [2]. At the same time, calcium silicate sealers are valued for calcium ion release and alkaline pH, both of which are linked to bioactivity and mineral deposition.

Hamdy et al. provide a useful comparison of this balance. In their in vitro evaluation, AH Plus Bioceramic Sealer demonstrated the highest alkalinity and highest calcium ion release, together with the lowest film thickness. Bio-C Sealer also showed high alkalinity, but had higher solubility, intermediate calcium ion release, and intermediate film thickness. ADseal, the resin-based comparator, showed the lowest solubility but also lower alkalinity and calcium ion release [13].

3.2.4 Bioactivity and apatite-related sealing

A distinctive physicochemical feature of calcium silicate-based sealers is their ability to form hydroxyapatite-like deposits in the presence of phosphate-containing fluids. Singhal et al. evaluated the sealing ability of BioRoot RCS, CeraSeal, and Bio-C Sealer after immersion in simulated body fluid. Immediately after 48 hours, AH Plus used with warm vertical compaction showed significantly lower microleakage than the bioceramic sealer groups. However, after 30 days of immersion in simulated body fluid, the microleakage of the bioceramic groups improved and became comparable to AH Plus [11].

It is important to note that many laboratory comparisons evaluate sealers shortly after setting. If bioceramic sealers improve their adaptation or sealing ability after exposure to phosphate-containing fluids, immediate testing may underestimate their long-term sealing potential. Conversely, simulated body fluid models remain laboratory approximations and cannot fully reproduce the biological complexity of periapical tissues.

3.2.5 Dentinal tubule penetration

Dentinal tubule penetration is frequently investigated because it may improve contact between the sealer and dentin, enhance micromechanical retention, and entomb residual bacteria within tubules. Ashkar et al.'s systematic review found that calcium silicate-based sealers generally show favorable dentinal tubule penetration, but penetration is influenced by several factors, including irrigation protocol, sealer activation, obturation technique, and root canal morphology. The authors also noted that confocal laser scanning microscopy is commonly used to evaluate penetration because fluorescently labeled sealers allow visualization of material distribution inside dentinal tubules [2].

A recurring finding across the selected studies is that sealer penetration is not uniform throughout the root. Verma et al. compared BIO-C ION+, AH Plus, and NanoSeal-S and found that penetration followed the pattern coronal > middle > apical. BIO-C ION+ showed the greatest dentinal tubule penetration among the tested sealers, while AH Plus showed lower penetration than BIO-C ION+ but higher penetration than NanoSeal-S [17]. Similarly, Wang et al. reported that, among four bioceramic-based sealers, the coronal third showed significantly greater dentinal tubule penetration than the apical third [5].

The reduced penetration in the apical third can be explained by anatomical and procedural factors. The apical third generally has fewer and narrower dentinal tubules, greater anatomical complexity, and more difficulty in irrigant penetration and smear layer removal.

Irrigation and activation protocols may also affect penetration. Ashkar et al. summarized evidence that activation of final irrigation, including passive ultrasonic irrigation and photoacoustic techniques, may improve penetration of sealers into dentinal tubules when compared with conventional needle irrigation. They also discussed evidence that chelating solutions may increase penetration, although they cautioned that sealer penetration alone should not be treated as the only determinant of treatment success [2].

3.2.6 Interfacial adaptation and push-out bond strength

Interfacial adaptation and push-out bond strength provide additional information about the interaction between sealer and dentin. Good adaptation reduces interfacial gaps, while push-out bond strength reflects resistance to dislodgement under mechanical stress. However, these two properties do not always correlate directly with tubule penetration. A material may penetrate dentinal tubules well but still show lower bond strength than another sealer.

This discrepancy was demonstrated by Verma et al. Although BIO-C ION+ showed the greatest dentinal tubule penetration, AH Plus demonstrated the highest push-out bond strength, with reported mean values exceeding those of BIO-C ION+ and NanoSeal-S in coronal, middle, and apical sections [17]. The finding also suggests that dentinal tubule penetration alone should not be used as a surrogate for bonding effectiveness.

Among bioceramic sealers, product-specific differences are also evident. Wang et al. compared iRoot SP, Well-Root ST, C-Root SP, and KP-Root SP. They found no significant difference in depth or circumferential percentage of dentinal tubule penetration between the materials overall, although the coronal third showed significantly greater penetration than the apical third. However, Well-Root ST demonstrated superior interfacial adaptation compared with C-Root SP, and push-out bond strength followed the order Well-Root ST > iRoot SP > KP-Root SP > C-Root SP [5].

3.2.7 Fracture resistance and dentin reinforcement

Studies suggest that calcium silicate-based sealers may influence the mechanical behavior of root dentin. Wang et al. found that roots filled with iRoot SP had compressive strength similar to unprepared and unfilled roots, but higher than prepared and unfilled roots. They also found increased elastic modulus and hardness in dentin adjacent to iRoot SP, suggesting that mineralization associated with the sealer may contribute to reinforcement of prepared roots [8]. Kashaf et al. also evaluated fracture resistance and sealer penetration, comparing AH Plus, TotalFill BC HiFlow, and an experimental injectable bioactive glass sealer. Their study found favorable penetration for the experimental bioactive glass sealer and reported that TotalFill BC HiFlow showed better overall fracture resistance than AH Plus at 90 days [19].

3.3. Biological properties

Biological behavior is one of the main reasons calcium silicate-based sealers have attracted attention in contemporary endodontics. Unlike traditional sealers that are primarily expected to provide a physical seal, bioceramic sealers are frequently described as bioactive materials because they may release calcium ions, maintain an alkaline pH, induce apatite-like mineral deposition, and interact with dentin and periapical tissues. The discussed studies show that biological performance varies according to sealer composition, setting state, eluate concentration, exposure time, and the cell model used.

3.3.1 Bioactivity and mineralization

The bioactivity of calcium silicate-based sealers is closely related to their hydration reaction and ion release. In contact with moisture, calcium silicate materials may release calcium ions and form alkaline products. In phosphate-containing environments, this can promote precipitation of apatite-like deposits on the sealer surface or at the dentin-sealer interface. Bardini et al. described calcium silicate-based sealers as hydraulic materials that set in the presence of moisture and demonstrate bioactivity through calcium ion release,

calcium hydroxide production, and apatite formation on their surfaces. These processes may contribute to the formation of an interfacial layer between the sealer and dentinal walls [21].

Wang et al. provided direct laboratory evidence for this mineralizing behavior using iRoot SP. In their in vitro study, mineral deposition in dentinal tubules was greater after iRoot SP filling than in controls. When root canals were dried with paper points rather than 95% ethanol, iRoot SP showed better penetration and mineralization within dentinal tubules. Energy-dispersive spectroscopy showed that the new minerals in the paper-point drying group contained calcium and phosphorus, whereas phosphorus was not detected in the ethanol-dried group [8].

The same study also linked bioactivity with changes in dentin mechanics. After filling with iRoot SP, the elastic modulus and hardness of dentin adjacent to the sealer were higher than those in dentin farther from the sealer interface. The authors attributed this effect to biomineralization of dentinal tubules [8].

3.3.2 Biocompatibility and stem-cell response

Biocompatibility is essential because endodontic sealers may contact periapical tissues through apical extrusion, lateral canals, accessory canals, or dissolution products. Mora et al. evaluated the biocompatibility, bioactivity, and immunomodulatory properties of CeraSeal, TotalFill BC Sealer, and Well-Root ST using human periodontal ligament stem cells (hPDLSCs). This cell type is particularly relevant because periodontal ligament stem cells participate in periapical tissue repair and may differentiate into osteoblast- and cementoblast-like cells [3].

In that study, the tested sealers showed adequate cytocompatibility. Cell metabolic activity, migration, attachment, morphology, and cytoskeletal organization were broadly comparable to the negative control. CeraSeal and TotalFill BC Sealer upregulated at least one osteo/cementogenic marker and produced significantly greater calcified nodule formation than both negative and positive control groups. The effects were most pronounced for CeraSeal, which showed higher marker expression and mineralization than TotalFill BC Sealer. Well-Root ST showed results closer to the control group [3].

The same study also assessed inflammatory cytokine release. CeraSeal- and TotalFill BC-treated cells showed significant downregulation of interleukin-6 after 72 hours compared with the negative control, suggesting potential anti-inflammatory activity [3].

Nevertheless, the results also show product-specific variation. CeraSeal demonstrated stronger osteo/cementogenic and mineralization effects than TotalFill BC Sealer, while Well-Root ST behaved more similarly to the control group in several assays [3].

3.3.3 Alkalinity, calcium release, and potential antimicrobial relevance

The biological properties of bioceramic sealers are also linked to their alkalinity and calcium ion release. Hamdy et al. emphasized that alkaline pH is considered one of the main advantages of calcium silicate-based sealers because it may support apatite-like deposit formation, promote apical healing and tissue mineralization, and provide bacteriostatic effects. They also noted that calcium ion release is important for chemical bonding and bioactivity through precipitation of an apatite-like layer with dentin [13].

Although the selected studies do not provide extensive direct antimicrobial testing of standard orthograde bioceramic sealers, several findings are relevant to infection control. Wang et al. stated that sealer penetration into dentinal tubules may create a physical barrier that entraps remaining bacteria and prevents their proliferation [5]. Mansour et al. also evaluated bacterial sealing ability in an apical surgery model and found that calcium silicate-based sealer approaches showed sealing ability comparable to MTA retrofilling, with dead bacteria being the prominent feature in the experimental groups on CLSM analysis [6].

3.3.4 Cytotoxicity and genotoxicity concerns

Despite the generally favorable biological profile attributed to bioceramic sealers, the literature also shows that some products may produce adverse cellular responses under certain experimental conditions. Radwanski et al. compared AH Plus with several calcium silicate-based sealers, including TotalFill BC Sealer, AH Plus Bioceramic Sealer, BioRoot Flow, and BioRoot RCS. Their study used human gingival fibroblasts and a monocyte/macrophage peripheral blood cell line to assess cytotoxicity, genotoxicity, apoptosis, and cell cycle effects [4].

Their findings complicate the simple assumption that bioceramic sealers are always less cytotoxic than conventional materials. BioRoot Flow significantly reduced human gingival fibroblast viability and was considered locally moderately cytotoxic. The authors suggested that this may be related to components such as acrylamide, which functions as a thickening or flocculating agent. Other tested calcium silicate-based sealers

met the ISO cytotoxicity criterion of more than 70% viable cells. TotalFill BC Sealer showed non-cytotoxic behavior in accordance with some previous findings discussed by the authors, while AH Plus Bioceramic Sealer and AH Plus both showed no cytotoxicity greater than 90% against the tested cells in their model [4].

The same study also assessed genotoxicity. Although several sealers produced statistically significant differences compared with negative controls, the authors considered BioRoot Flow and BioRoot RCS potentially genotoxic for human gingival fibroblasts after 48 hours because DNA damage exceeded the 20% threshold discussed in their paper [4].

Radwanski et al. also noted that discrepancies between biological studies may arise from differences in sample preparation, exposure time, concentration of eluates, and cell culture models [4].

3.4. Sealing ability and obturation techniques

The sealing ability of an endodontic sealer depends not only on its chemical composition, but also on the obturation technique, root canal anatomy, final irrigation protocol, moisture conditions, and time after placement. Bioceramic sealers have influenced contemporary obturation concepts because they are frequently used with simplified single-cone or sealer-based obturation techniques. This differs from the older concept that a root filling should contain as much gutta-percha and as little sealer as possible. With calcium silicate-based sealers, the sealer is expected to play a more active role in sealing, adaptation, and possibly biomineralization at the dentin interface.

3.4.1 Single-cone and sealer-based obturation

Single-cone obturation has become closely associated with the clinical use of calcium silicate-based sealers. The rationale is that these sealers are hydrophilic, dimensionally stable, bioactive, and able to penetrate canal irregularities and dentinal tubules. Because of these properties, they are considered more suitable for a sealer-dependent obturation technique than many traditional sealers. In the literature included in this review, single-cone obturation is repeatedly used with materials such as BioRoot RCS, EndoSeal TCS, CeraSeal, TotalFill BC Sealer, Bio-C Sealer, EndoSequence BC Sealer/iRoot SP, and other premixed calcium silicate-based sealers.

The attraction of this approach is practical as well as material-based. A single-cone technique is simpler, faster, and less operator-dependent than warm vertical compaction or continuous wave techniques. It also requires less equipment and may reduce procedural complexity. Mansour et al. described the single-cone technique as commonly advised for calcium silicate-based sealers because of their limited shrinkage, dentinal tubule penetration, micromechanical locking, and simpler clinical execution [6].

However, single-cone obturation also has an important theoretical limitation: the quality of the root filling becomes more dependent on the sealer. If the canal anatomy is round and matched to the master cone, this may be acceptable. In oval canals, isthmuses, fins, and C-shaped canals, the volume of sealer may increase and voids may become more likely. Therefore, single-cone obturation with bioceramic sealers should not be interpreted as universally equivalent to three-dimensional compaction in all anatomical situations.

3.4.2 Comparison with warm vertical and continuous wave techniques

Warm vertical compaction and continuous wave condensation have traditionally been considered strong obturation methods because thermoplasticized gutta-percha can adapt to irregularities and lateral anatomy. In contrast, sealer-based obturation with bioceramic sealers relies more heavily on the sealer's flow, adaptation, and bioactivity. Several studies in this review directly or indirectly address this comparison.

Ashkar et al., in their systematic review of dentinal tubule penetration, reported that some included studies found greater calcium silicate-based sealer penetration when warm vertical compaction was used instead of single-cone obturation. This was observed for EndoSequence BC HiFlow, Bio-C Sealer, MTA Fillapex, and EndoSequence BC Sealer in some studies. However, other studies included in the same review found no significant difference in penetration between obturation techniques. The authors therefore concluded that the relationship between filling technique and dentinal tubule penetration remains inconsistent and requires further investigation [2].

3.4.3 Void formation in complex canal anatomy

The obturation of complex canal systems remains one of the major challenges in endodontics. C-shaped canals are particularly difficult because the anatomy may contain fins, webs, isthmuses, and irregular cross-sectional shapes. Gharechahi et al. investigated obturation techniques using 3D-printed C-shaped canal replicas and compared EndoSeal TCS and EndoSeal MTA with single-cone obturation, ultrasonic activation, and cold

hydraulic compaction. Their results showed significant differences in void and sealer percentages among groups. EndoSeal TCS with ultrasonic activation produced the lowest void percentage in the apical and middle thirds, while EndoSeal TCS with cold hydraulic compaction produced the lowest void percentage in the coronal third [7].

This study also demonstrates that obturation quality with bioceramic sealers is not determined only by the material. Technique and anatomy strongly influence the final filling. The authors emphasized that voids are clinically relevant because bacteria and by-products may remain in void areas and affect treatment success. They also noted that C-shaped canal obturation with bioceramic sealers remains relatively underinvestigated [7].

3.4.4 Sealer activation and extrusion risk

Sealer activation has been proposed as a way to improve the distribution of bioceramic sealers inside the root canal system. Ultrasonic activation may reduce viscosity, generate acoustic streaming, and improve adaptation to the canal wall. Gharechahi et al. found that ultrasonic activation of EndoSeal TCS produced favorable void reduction in C-shaped canals, especially in the apical and middle thirds. The technique was also relatively less time-consuming than cold hydraulic compaction [7].

However, the same study found that sealer extrusion differed significantly between groups. Ultrasonic activation increased the tendency toward extrusion, and the authors associated lower viscosity with higher risk of apical extrusion. EndoSeal TCS, which had lower viscosity than EndoSeal MTA, showed a higher extrusion tendency, and ultrasonic activation amplified this effect [7].

3.4.5 Sealing ability and time-dependent behavior

Some evidence suggests that the sealing ability of bioceramic sealers may improve after exposure to phosphate-containing fluids. Singhal et al. compared BioRoot RCS, CeraSeal, and Bio-C Sealer used with single-cone obturation against AH Plus used with warm vertical compaction. After 48 hours, the AH Plus control group showed the least microleakage, and the difference was significant compared with the experimental bioceramic groups. However, after 30 days of immersion in simulated body fluid, there was no significant difference in microleakage among the groups. The authors concluded that the sealing ability of bioceramic sealers improved significantly after simulated body fluid immersion and became comparable to AH Plus with warm vertical compaction [11].

This finding supports the concept that calcium silicate-based sealers may behave dynamically after placement. Their sealing ability may not depend only on immediate adaptation, but also on subsequent bioactive mineral deposition. Nevertheless, this evidence is laboratory-based. Simulated body fluid is useful for evaluating apatite-forming potential, but it does not fully reproduce the complex clinical environment of a root canal system and periapical tissues.

Rane et al. also evaluated sealing ability through apical leakage testing and found that a bioceramic sealer incorporating chitosan nanoparticles showed the lowest dye penetration compared with gutta-percha alone, AH Plus, and bioceramic sealer without chitosan nanoparticles [20].

3.5. Clinical outcomes

Clinical outcome data are essential for evaluating whether the favorable laboratory properties of bioceramic sealers translate into improved or at least comparable treatment results. In vitro studies can demonstrate bioactivity, dentinal tubule penetration, calcium ion release, and sealing behavior, but the clinical success of root canal treatment depends on many additional factors, including preoperative periapical status, microbial control, instrumentation and irrigation quality, obturation quality, coronal restoration, occlusion, patient-related factors, and follow-up duration. Therefore, clinical studies are particularly important when assessing whether bioceramic sealers should be considered alternatives to established sealer systems.

3.5.1 Clinical relevance of outcome assessment

The clinical outcome of root canal treatment is usually evaluated through a combination of symptoms, tooth survival, radiographic healing, and periapical index changes. Bardini et al. emphasized that apical periodontitis represents an inflammatory response to endodontic infection and that root canal treatment aims to prevent or treat this condition. It was also noted that obturation quality is an important prognostic factor and that failures may be associated with inadequate sealing of the root canal system [21].

Clinical studies included in this review generally compare calcium silicate-based sealers used with simplified sealer-based or single-cone obturation techniques against conventional obturation protocols using epoxy resin- or zinc oxide-eugenol-based sealers.

3.5.2 Short-term randomized clinical evidence

One of the key clinical studies in the discussed literature is the randomized clinical trial by Kim et al., which compared sealer-based obturation using EndoSeal TCS with continuous wave condensation using AH Plus. The study included 74 teeth in the final analysis, with a mean follow-up of 17 months. The overall success rate was 93.2% using loose criteria, with 92.3% success in the continuous wave condensation group and 94.3% in the sealer-based obturation group. Under strict criteria, the overall success rate was lower, at 60.8%, but still without a statistically significant difference between groups [9].

Kim et al. also reported that teeth with sealer extrusion had a significantly lower success rate under loose criteria than teeth without extrusion, and that postoperative pain negatively affected treatment outcome [9]. Although these findings will be discussed further in the postoperative pain and extrusion-related sections, they are clinically relevant here because they show that outcome is influenced not only by material choice, but also by obturation quality and biological response after treatment.

3.5.3 Medium- and long-term randomized clinical evidence

Longer follow-up is particularly important for new endodontic materials because early outcomes may not reflect long-term performance. Seog et al. followed the same clinical comparison between EndoSeal TCS sealer-based obturation and continuous wave condensation with AH Plus for five years. Of the initial cohort, 60 teeth were available at five-year follow-up, and 56 teeth were evaluated after excluding teeth extracted for non-endodontic reasons. The study found no significant differences between groups under either loose or strict success criteria. Loose-criteria success was 81.8% in the continuous wave condensation group and 87.0% in the sealer-based obturation group, while strict-criteria success was 75.8% and 78.3%, respectively [10]. The authors concluded that sealer-based obturation with EndoSeal TCS demonstrated comparable five-year outcomes to continuous wave condensation, supporting its potential as a less technique-sensitive and clinically viable alternative [10].

Bardini et al. provide another important long-term randomized clinical trial. Their study compared single-cone obturation with BioRoot RCS against warm vertical compaction using Pulp Canal Sealer EWT, a zinc oxide-eugenol-based sealer. The study included single- and multi-rooted teeth and followed patients clinically and radiographically up to 48 months. At four-year follow-up, 67 teeth were included, corresponding to a 73% recall rate. Overall success rates were 89.6% using loose criteria and 83.3% using strict criteria. In teeth with apical periodontitis, subgroup success rates were 88.5% and 80.4%, respectively. No significant differences were found between groups regarding success rate, extraction rate, filling length, voids, extrusion, or PAI reduction pattern [21].

3.5.4 Prospective cohort evidence

In addition to randomized trials, prospective cohort studies contribute useful clinical information, although their evidential strength is lower because they lack random allocation and may be more susceptible to selection bias. The prospective cohort study on CeraSeal used a single-cone technique with a premixed bioceramic sealer and followed root canal treatments for three years. The study reported favorable survival and clinical-radiographic outcomes, supporting the clinical feasibility of CeraSeal with single-cone obturation [22].

3.5.5 Evidence from systematic review and meta-analysis

The systematic review and meta-analysis by Zamparini et al. provides a broader synthesis of clinical evidence. The review included 15 comparative clinical studies, of which 11 were randomized clinical trials and four were prospective clinical trials with control groups. The authors found no significant differences between premixed bioceramic sealers and standard sealers in terms of survival and success rates. They also reported a small, non-significant lower risk of extrusion and a small, non-significant reduction in postoperative pain within 24 hours when bioceramic sealers were used [1].

The survival and success ranges reported in the review were generally high. For teeth filled with premixed bioceramic sealers, pooled survival ranged between 97.7% and 100%, and clinical-radiographic success ranged between 75% and 100%. Comparable values were reported for AH Plus epoxy resin-based sealer groups, with survival between 97.8% and 100% and success between 86.2% and 100% under loose criteria [1]. These data suggest that bioceramic sealers perform within a clinically acceptable range.

Zamparini et al. also highlighted important limitations in the available clinical evidence. Follow-up in the included studies was not greater than two years, and the authors noted inconsistencies in reporting, differences in clinical protocols, variation in operator expertise, and heterogeneity in irrigation and sealer application procedures. Their conclusion was that premixed bioceramic sealers had similar short-term outcomes compared with traditional epoxy resin sealers, but that better-designed, long-term prospective trials are needed before stronger recommendations can be made [1].

3.6 Postoperative pain

Postoperative pain is an important clinical outcome because it directly affects patient comfort, satisfaction, and the perceived success of endodontic treatment. Pain after root canal treatment is multifactorial and may be influenced by preoperative pulpal and periapical status, instrumentation, irrigation, extrusion of debris or sealer, occlusal factors, number of visits, operator technique, and host inflammatory response.

The theoretical biological advantages of bioceramic sealers could suggest a lower postoperative pain response. Calcium silicate-based sealers are generally described as biocompatible, alkaline, bioactive, and capable of releasing calcium ions. These properties may support a favorable periapical tissue response. However, the same materials may also be extruded beyond the apex because of their flowability, and contact with periapical tissues may provoke a transient inflammatory response. Therefore, the relationship between bioceramic sealers and postoperative pain is not necessarily straightforward.

Nagpal et al. conducted a double-blinded randomized controlled trial comparing two calcium silicate-based or bioactive sealers, Bio-C Sealer ION+ and Nishika Canal Sealer BG, with the epoxy resin-based AH Plus sealer after single-visit root canal treatment. The study included 90 patients with first or second molars diagnosed with symptomatic irreversible pulpitis and symptomatic apical periodontitis. Postoperative pain was evaluated using a visual analogue scale at 6 hours, 24 hours, 48 hours, 5 days, and 7 days after obturation, and analgesic intake was also recorded. Bio-C Sealer ION+ showed the lowest pain scores, followed by Nishika Canal Sealer BG and AH Plus. The intergroup difference was significant at 6 and 24 hours, but not at 48 hours, 5 days, or 7 days. Analgesic intake was also significantly lower in the Bio-C Sealer ION+ group [18].

Kim et al. found a different pattern in their randomized clinical trial comparing sealer-based obturation using EndoSeal TCS with continuous wave condensation using AH Plus. In that study, postoperative pain distribution was similar between groups, and no significant difference was found [9]. This supports the view that pain outcomes may depend on the specific sealer, obturation method, case selection, and study design. Kim et al. also reported that postoperative pain negatively affected prognosis, indicating that pain is not only a patient-centered outcome but may also reflect biological or technical events relevant to healing [9].

The broader evidence is summarized by Zamparini et al., who analyzed clinical studies on premixed bioceramic sealers compared with standard sealers. In their systematic review and meta-analysis, postoperative pain was assessed in 11 studies, most of which were randomized clinical trials. Pain was evaluated using scales such as VAS, numerical rating scale, and Likert scale, with follow-up intervals ranging from 6 hours to 3 months. Most studies reported similar postoperative pain between premixed bioceramic sealers and control sealers such as AH Plus or ADseal. The review reported only a small, non-significant reduction in early postoperative pain with bioceramic sealers [1].

The umbrella review by Govindaraju et al. further supports a cautious interpretation. It concluded that postoperative pain after obturation with bioceramic sealers was generally comparable to epoxy resin-based sealers after primary root canal treatment and retreatment. However, it also emphasized that the methodological quality of many included systematic reviews was low or critically low [16].

3.7. Retreatment and restorative considerations

Although dentinal tubule penetration, bioactivity, and interfacial mineralization are often presented as advantages of bioceramic sealers, the same properties may complicate retreatment. Endodontic retreatment depends on the ability to remove previous filling materials, regain working length, disinfect the canal system, and re-obturate the tooth. Gutta-percha can usually be removed mechanically and with the aid of solvents, but set hydraulic calcium silicate-based sealers may be more difficult to remove because of their hardness, dentinal tubule penetration, and possible mineral interaction with canal dentin.

Drukteinis et al. emphasized that retreatment of root canals previously filled with hydraulic calcium silicate-based sealers is clinically challenging. According to their discussion, these materials may adhere to dentin through mineral infiltration zone formation and deeper penetration into dentinal tubules, making them difficult to remove even mechanically. They also noted that previously tested irrigating solutions, including EDTA, sodium hypochlorite, carbonated water, formic acid, and acetic acid, had not successfully dislodged or dissolved these sealers [12].

In the same preliminary study, the authors evaluated 10% and 20% citric acid compared with 17% EDTA against several hydraulic calcium silicate-based sealers, including AH Plus Bioceramic Sealer, Bio-C Sealer, BioRoot RCS, and TotalFill BC Sealer. The study found that citric acid produced visible interaction with the sealers, including gas release, and caused greater material mass loss than EDTA. Surface changes

such as pores and cracks were mainly observed after citric acid exposure, while no severe dentin erosion was detected after root canal preparation with 10% or 20% citric acid [12].

Restorative procedures after root canal treatment are another important consideration. Many endodontically treated teeth require a post and core restoration because of extensive loss of coronal tooth structure. In these cases, residual sealer in the post space may affect resin cement bonding. Calcium silicate-based sealers may be particularly relevant because fresh sealer is more soluble, while set sealer may be more difficult to remove. Patthanawijit et al. noted that remaining calcium silicate-based sealer could interfere with resin cement bonding and reduce the bond strength of fiber posts, although previous findings in the literature were inconsistent [15].

Patthanawijit et al. evaluated the effect of adhesive strategy and cementation timing on the push-out bond strength of fiber posts cemented in root canals obturated with calcium silicate-based sealer. The study compared self-etch and etch-and-rinse modes of a universal adhesive, as well as immediate and delayed post space preparation and cementation. The results showed no significant effect of etching mode, post space preparation timing, post cementation timing, or root canal region on push-out bond strength [15].

3.8. Discoloration and aesthetic considerations

Krug et al. investigated long-term discoloration induced by hydraulic calcium silicate-based cements used as apical plugs in bovine teeth with open apices. The study evaluated several materials, including ProRoot MTA, Medcem MTA, TotalFill BC RRM Fast Set Putty, and a Portland cement-based material with bismuth oxide. The experimental design also assessed blood contamination, orthograde and retrograde placement, and preoperative adhesive coronal dentin sealing. Tooth color was measured spectrophotometrically at several time points up to 72 months [14].

After six years, discoloration increased in all groups, but there were no significant differences between the tested hydraulic calcium silicate-based cements. Color changes were strongly marked on roots but insignificant on crowns. Blood contamination had a more relevant effect on tooth color than bismuth oxide, and neither retrograde placement nor preoperative dentin sealing produced substantial long-term effects. The authors concluded that the tested apical plugs caused ongoing discoloration of bovine roots but not bovine crowns over the six-year period [14].

The study suggests that long-term aesthetic impairment of the crown may be unlikely if direct contact between hydraulic calcium silicate material and coronal dentin is avoided. However, the finding confirms that these materials can induce marked root discoloration over time, especially under conditions involving blood contamination [14].

3.9. Surgical and other applications

Although this review focuses primarily on bioceramic sealers used for orthograde root canal obturation, calcium silicate-based materials have broader relevance in endodontics. Related hydraulic calcium silicate materials are used for root-end fillings, apexification, perforation repair, pulp capping, and other procedures. The distinction between sealers and repair cements is important: a root canal sealer is formulated for thin-film canal obturation, while repair materials and root-end filling materials are designed for bulk placement and surgical applications. Nevertheless, some studies have investigated whether calcium silicate-based sealers may have a role in surgical or simplified apical procedures.

Mansour et al. evaluated the bacterial sealing ability of a calcium silicate-based sealer in an endodontic surgery model. Their study compared three approaches: single-cone obturation with calcium silicate-based sealer followed by root-end resection only, calcium silicate-based sealer used as a retrograde filling, and MTA retrofilling. A bacterial leakage model using *Enterococcus faecalis* was used over 30 days, and bacterial viability was assessed using confocal laser scanning microscopy. The three experimental groups showed no significant differences in bacterial leakage or colony-forming units, while all performed better than the positive control. Notably, the calcium silicate-based sealer used as a retrofilling showed the best sealing ability in that model, and dead bacteria were the predominant finding in the experimental groups [6].

The same study also discussed limitations of MTA as a root-end filling material, including challenging handling, porosity, void formation, and potential microbial leakage. The favorable results for the calcium silicate sealer groups were attributed to the sealer's ability to form a mineralized structure at the retrograde cavity margin, its hydrophilicity, low solubility and porosity, alkalizing capacity, slight expansion, and flowability into dentinal tubules and apical anatomical features [6].

4. Discussion

The present review shows that bioceramic endodontic sealers represent a significant development in contemporary obturation. Their main value lies in the combination of hydraulic setting, hydrophilicity, calcium ion release, alkaline pH, dentinal tubule penetration, bioactivity, and compatibility with simplified obturation techniques. These properties distinguish them from traditional sealers that primarily act as passive filling materials. However, the available evidence does not support the conclusion that bioceramic sealers are universally superior to epoxy resin- or zinc oxide-eugenol-based sealers. Rather, the most defensible interpretation is that selected calcium silicate-based sealers can provide comparable clinical outcomes while offering certain biological and handling-related advantages.

A major finding of this review is that the laboratory behavior of bioceramic sealers is generally favorable. Several studies demonstrated clinically relevant physicochemical properties, including low film thickness, high alkalinity, calcium ion release, dentinal tubule penetration, and interfacial adaptation. These features help explain why calcium silicate-based sealers are often used with single-cone or sealer-based obturation. At the same time, laboratory studies also show that different bioceramic sealers do not perform identically. For example, some materials show better penetration, while others demonstrate higher push-out bond strength or superior interfacial adaptation. This supports the need to discuss individual products rather than treating “bioceramic sealer” as a single homogeneous category.

Studies on periodontal ligament stem cells suggest that some calcium silicate-based sealers may support cell viability, mineralization, and osteo/cementogenic differentiation, which is relevant to periapical healing potential. Mora et al. found favorable cytocompatibility and mineralization-related effects for CeraSeal and TotalFill BC Sealer, with CeraSeal showing particularly pronounced osteo/cementogenic activity [3]. However, biological safety cannot be assumed for every product. Radwanski et al. reported unfavorable cytotoxic or genotoxic signals for some materials, particularly BioRoot Flow and BioRoot RCS under specific *in vitro* conditions [4].

Clinically, the strongest message from the available evidence is comparability. The systematic review and meta-analysis by Zamparini et al. found no significant differences between premixed bioceramic sealers and standard sealers in survival or success rates, and reported only small non-significant differences for extrusion and postoperative pain. The authors also emphasized that the available evidence was limited by short follow-up periods, heterogeneous protocols, and inconsistent reporting [1]. Longer-term randomized trials strengthen the argument that calcium silicate sealer-based obturation is a viable alternative. Seog et al. reported comparable five-year outcomes between sealer-based obturation with EndoSeal TCS and continuous wave condensation with AH Plus [10]. Similarly, Bardini et al. reported comparable four-year outcomes between BioRoot RCS used with a single-cone technique and a zinc oxide-eugenol sealer used with warm vertical compaction [21].

If bioceramic sealer-based obturation can achieve similar outcomes to more technique-sensitive warm obturation methods, it may offer advantages in efficiency, simplicity, and standardization. This is especially relevant for general dental practice, where a less complex obturation protocol may improve consistency when performed correctly. However, successful treatment still depends on adequate diagnosis, chemomechanical preparation, irrigation, working length control, obturation quality, and coronal restoration. Bioceramic sealers may support treatment success, but they cannot compensate for inadequate disinfection or poor case execution.

Another important issue is extrusion. Bioceramic sealers are flowable and are commonly used in techniques that rely more heavily on sealer volume. This can improve adaptation but may also increase the risk of apical extrusion, particularly in teeth with open apices, wide foramina, resorptive defects, or overinstrumentation. Gharechahi et al. showed that ultrasonic activation improved void reduction in C-shaped canals but also increased extrusion risk [7]. Therefore, techniques that improve sealer distribution should be applied selectively and with anatomical caution. The presence of extrusion does not automatically indicate failure, but it complicates interpretation and may influence postoperative symptoms or healing in some cases.

Postoperative pain evidence also supports a moderate conclusion. Nagpal et al. found lower early postoperative pain and lower analgesic intake with Bio-C Sealer ION+ compared with AH Plus, particularly during the first 24 hours [18]. However, broader evidence from Zamparini et al. and the umbrella review by Govindaraju et al. indicates that postoperative pain is generally comparable between bioceramic and epoxy resin-based sealers [1, 16].

The main limitations of available evidence are methodological. Many studies are *in vitro* and use simplified models that cannot reproduce clinical conditions such as blood contamination, tissue buffering, microbial complexity, occlusal loading, patient factors, and long-term coronal leakage. Even clinical studies

vary in terms of diagnosis, obturation technique, sealer type, operator experience, follow-up duration, and success criteria. Strict and loose outcome definitions may lead to substantially different success rates. In addition, systematic reviews often group different bioceramic products together, even though their compositions and properties may differ substantially. This may obscure clinically relevant product-specific differences.

Future research should focus on long-term randomized clinical trials comparing specific bioceramic sealers with established control materials under standardized protocols. Greater attention should be given to retreatability, extrusion behavior, warm obturation compatibility, post space preparation, biofilm models, and clinically relevant antimicrobial testing. Retreatment is especially important because Drukteinis et al. showed that hydraulic calcium silicate-based sealers may be difficult to remove and that citric acid may have potential as a solvent, although this remains preliminary laboratory evidence [12]. Future material development should also aim to improve handling, reduce excessive solubility, increase biological safety, limit discoloration risk, and preserve the favorable bioactive characteristics that make these sealers attractive.

Overall, the evidence supports bioceramic sealers as valuable and clinically viable alternatives to traditional endodontic sealers. Their greatest strength is not that they guarantee superior outcomes, but that they combine acceptable clinical performance with bioactive and handling properties that may simplify obturation and support favorable tissue interaction. Their use should therefore be guided by material-specific evidence, clinical indication, anatomical risk, and the operator's understanding of both their advantages and limitations.

5. Conclusions

Bioceramic endodontic sealers represent an important development in contemporary endodontics. Their introduction has expanded the concept of the root canal sealer from a primarily passive filling material to a biologically active component of obturation. The main advantages attributed to calcium silicate-based sealers include hydrophilicity, hydraulic setting, alkaline pH, calcium ion release, apatite-forming ability, dentinal tubule penetration, and favorable interaction with dentin and periapical tissues. These properties explain why bioceramic sealers are commonly associated with simplified obturation techniques, especially single-cone and sealer-based obturation.

The literature reviewed in this paper suggests that bioceramic sealers show favorable physicochemical and biological characteristics, but these findings must be interpreted with caution. Laboratory studies demonstrate promising properties such as calcium ion release, high alkalinity, low film thickness, bioactivity, interfacial adaptation, and dentinal tubule penetration. However, performance differs between commercial products, and individual sealers vary in solubility, penetration, bond strength, setting behavior, and biological response. Therefore, the term "bioceramic sealer" should not be treated as a synonym for one uniform material. Material-specific evidence remains essential.

From a biological perspective, calcium silicate-based sealers may support mineralization, cytocompatibility, and cellular responses associated with periapical repair. Some studies show favorable effects on periodontal ligament stem cells, osteo/cementogenic differentiation, and inflammatory modulation. At the same time, not all biological findings are uniformly positive. Cytotoxicity and genotoxicity studies show that some materials may produce unfavorable cellular responses under specific experimental conditions. This does not necessarily indicate clinical unsafety when the materials are properly used, but it does show that biological superiority cannot be assumed for the entire class of bioceramic sealers.

From a clinical perspective, the available evidence supports bioceramic sealers as effective alternatives to traditional endodontic sealers, but not as clearly superior replacements. Randomized clinical trials have reported comparable outcomes between calcium silicate-based sealer techniques and established obturation protocols using epoxy resin- or zinc oxide-eugenol-based sealers. Kim et al. found similar short-term success between sealer-based obturation with EndoSeal TCS and continuous wave condensation with AH Plus, while Seog et al. later reported comparable five-year outcomes for the same treatment approaches [9,10]. Bardini et al. also demonstrated similar four-year success rates between single-cone obturation with BioRoot RCS and warm vertical compaction with a zinc oxide-eugenol sealer [21]. These findings are supported by review-level evidence indicating no significant differences in survival or success rates between premixed bioceramic sealers and standard sealers [1]. Therefore, current clinical evidence suggests that bioceramic sealers can be used predictably in appropriate cases, particularly with simplified obturation techniques, although their clinical advantage appears to be equivalence and practicality rather than proven superiority.

Postoperative pain evidence also supports a moderate conclusion. Selected studies suggest that some bioceramic or bioactive sealers may reduce early postoperative pain, especially during the first 24 hours. However, broader review evidence indicates that postoperative pain is generally comparable between bioceramic and epoxy resin-based sealers. Therefore, reduced pain should be considered a possible material-specific benefit rather than a consistent class-wide advantage.

Several limitations remain clinically relevant. The flowability and sealer-dependent nature of bioceramic obturation may increase the risk of extrusion in certain cases, especially when sealer activation is used or when apical anatomy is unfavorable. Retreatment may also be more difficult because of dentinal tubule penetration, mineral interaction, and the hardness of set calcium silicate-based materials. Discoloration is less central to ordinary orthograde sealer use, but it remains relevant for calcium silicate materials in aesthetic zones and expanded applications. These factors show that bioceramic sealers require proper case selection, careful technique, and awareness of their limitations.

In conclusion, bioceramic endodontic sealers are valuable materials with strong theoretical and laboratory support and an increasing body of clinical evidence. Their main importance lies in combining acceptable clinical performance with bioactive properties and simplified handling. Nevertheless, the current evidence does not justify presenting them as universally superior to established traditional sealers. They should instead be regarded as clinically viable, biologically active alternatives whose use should be guided by product-specific data, canal anatomy, obturation technique, retreatment considerations, and long-term clinical evidence. Future research should focus on standardized long-term randomized clinical trials, direct product comparisons, retreatability, extrusion behavior, antimicrobial effectiveness, and improved formulations that preserve bioactivity while reducing solubility, discoloration, and removal difficulties.

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