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Contemporary endodontic strategies and calcium Silicate–Based sealers: Clinical performance, postoperative outcomes, and periapical healing – A systematic review

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ABSTRACT

Background: Postoperative pain and periapical tissue healing are considered essential parameters for evaluating the success of endodontic treatment. In recent years, advances in obturation techniques, irrigation protocols, and calcium silicate–based sealers have substantially influenced clinical endodontic practice. Despite these innovations, the extent to which these factors affect patient-centered outcomes and long-term periapical repair is still not fully clarified.
Objective: This systematic review aimed to critically assess the available clinical evidence regarding the influence of obturation techniques, endodontic sealers, and irrigation strategies on postoperative pain and periapical healing after root canal therapy.
Methods: An extensive literature search was conducted to identify randomized clinical trials and prospective studies investigating postoperative pain and/or radiographic healing after primary root canal treatment. The selected studies evaluated different obturation techniques, including single-cone obturation, lateral condensation, warm vertical compaction, and thermoplasticized systems, as well as different sealer formulations such as calcium silicate–based and resin-based materials. Variations in irrigation protocols were also considered. The primary outcome was postoperative pain evaluated using validated assessment tools, predominantly the visual analogue scale (VAS). Secondary outcomes included radiographic evidence of periapical healing, obturation quality, incidence of sealer extrusion, flare-up occurrence, and overall treatment success. Risk of bias and methodological variability among the included studies were qualitatively analyzed.
Results: The analyzed evidence indicates that postoperative pain following root canal treatment is usually mild to moderate and progressively decreases during the first postoperative days, regardless of the obturation technique used. Studies comparing calcium silicate–based sealers with resin-based sealers reported similar short-term postoperative symptoms, although some investigations suggested improved biological behavior associated with calcium silicate materials. Differences among obturation techniques appeared to have minimal impact on early postoperative discomfort. Furthermore, long-term radiographic evaluations demonstrated comparable periapical healing among the investigated treatment protocols. Nevertheless, variability in study design, follow-up duration, and outcome reporting limited the possibility of direct quantitative comparison between studies.
Conclusions: Current evidence suggests that contemporary obturation techniques and modern endodontic sealers provide similar short- and medium-term clinical outcomes in terms of postoperative pain and periapical healing.

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Postoperative discomfort appears to depend on multiple factors and cannot be related exclusively to the obturation technique or sealer type. Additional well-designed long-term clinical studies using standardized methodologies are required to strengthen the evidence supporting clinical decision-making in endodontics.

1. Introduction

Endodontic therapy has progressively evolved from a predominantly mechanical and infection-centered discipline toward a biologically oriented and patient-centered approach [1–3]. Contemporary endodontics increasingly emphasizes the preservation of tooth structure, the maintenance of pulp vitality when possible, and the promotion of periapical healing through bioactive materials and minimally invasive techniques [4–6]. Within this paradigm shift, calcium silicate–based materials, commonly referred to as bioceramics, have gained widespread attention and acceptance due to their unique physicochemical and biological properties [7–9]– (see Table 1).

Bioceramic materials are characterized by their hydrophilic nature, alkaline pH, antimicrobial activity, and capacity to release calcium ions, which contribute to hydroxyapatite formation and the stimulation of mineralized tissue deposition [10–12]. These properties underpin the excellent biocompatibility of calcium silicate–based materials [13–15]. They also contribute to their ability to support favorable interactions with both pulpal and periapical tissues [16–18]. In this context, their biological behavior plays a crucial role in promoting tissue healing and regeneration[19–21].

As a result, calcium silicate–based materials have been increasingly utilized across a broad spectrum of endodontic procedures [22–24]. These applications include root canal obturation, vital pulp therapy, apexification, perforation repair, and regenerative endodontic treatments [25–28]. Their versatility across different clinical scenarios further highlights their growing relevance in contemporary endodontics [29–32].

A key distinguishing feature of hydraulic calcium silicate–based sealers is their hydration-dependent setting reaction [33–36]. This characteristic differentiates them significantly from traditional resin-based sealers [37–39]. The latter require strict canal desiccation to ensure optimal adhesion and sealing ability. In contrast, bioceramic sealers can tolerate the presence of residual moisture within the root canal system [40–42].

Importantly, in some cases, they may even benefit from controlled levels of residual moisture [43–45]. This property challenges long-standing clinical protocols that advocate complete drying of the canal prior to obturation [46–48]. Consequently, it introduces a more nuanced understanding of the role of moisture in endodontic procedures [49–52].

Controlled residual moisture may enhance sealer penetration into dentinal tubules. It may also improve adaptation to canal walls and reduce void formation [53–55]. Together, these effects contribute to a more effective and durable seal [56–58].

However, excessive moisture may adversely affect the material's flow characteristics [59–61]. It may also increase porosity, thereby potentially compromising obturation quality [62–64]. These contrasting effects emphasize the need for careful moisture control during clinical procedures [64–66].

Overall, these considerations highlight the importance of balancing material chemistry with clinical technique [67–69]. This balance is essential to optimize the performance of bioceramic materials and achieve predictable treatment outcomes [70–73].

In parallel with advancements in material science, there has been a growing interest in simplifying endodontic procedures to improve efficiency and reproducibility [74–76]. Techniques such as the single-cone obturation method have gained popularity, particularly when used in conjunction with bioceramic sealers [77–80]. Emerging evidence suggests that, when appropriate protocols are followed, simplified techniques can achieve clinical and radiographic outcomes comparable to more complex condensation methods [81–83]. This has significant implications for clinical practice, as it may reduce technique sensitivity, chair time, and operator variability while maintaining high standards of care [64,84–86].

Beyond obturation, the application of bioceramic materials in vital pulp therapy represents a major advancement in conservative dentistry [87–89]. Traditionally, irreversible pulpitis in both primary and permanent teeth was managed with complete root canal treatment [90–92]. However, the bioactive properties of calcium silicate–based materials have enabled a shift toward less invasive approaches, such as pulpotomy and pulp capping, even in cases that were previously considered unsuitable for vital pulp preservation [93–95]. These materials promote the formation of reparative dentin, support pulpal healing, and maintain long-term tooth vitality [96,97] [Fig. 1]. Their effectiveness has been demonstrated in diverse clinical scenarios, including pediatric patients, immature teeth with open apices, and mature permanent teeth, thereby expanding the therapeutic options available to clinicians [90,98,99].

In addition, premixed bioceramic formulations have addressed some of the practical limitations associated with earlier materials, such as mineral trioxide aggregate (MTA) [100–102]. These ready-to-use materials offer improved handling properties, reduced setting variability, and lower technique sensitivity, making them particularly suitable for complex procedures such as apexification and pediatric endodontics [103–106]. Their ability to form a stable apical barrier and promote periapical healing has been associated with high clinical success rates, even in anatomically challenging cases [107–110].

Despite these advantages, the clinical performance of bioceramic materials is influenced by a range of procedural and environmental factors [111–114]. Variables such as obturation technique, the amount of sealer used, and the force applied during compaction may affect the risk of apical extrusion and, consequently, postoperative outcomes [115–117]. While extrusion of bioceramic materials may occur, their high biocompatibility generally results in minimal inflammatory response and low levels of postoperative pain. Nevertheless, careful control of clinical procedures remains essential to minimize potential complications and optimize patient comfort.

Environmental conditions within the root canal system and periapical tissues also play a critical role in determining material behavior. For instance, acidic conditions associated with periapical inflammation may interfere with the hydration process of calcium silicate–based materials, alter their microstructure, and increase their solubility. Such changes may compromise mechanical stability and sealing ability, potentially affecting long-term treatment success. Moreover, anatomical variations, including canal sclerosis, calcifications, and open apices, further complicate treatment and require materials that can perform reliably under diverse conditions [118,119].

Importantly, the success of endodontic procedures involving bioceramic materials is not solely dependent on the intrinsic properties of the materials themselves. Clinical factors such as accurate diagnosis, appropriate case selection, effective hemostasis, proper canal disinfection, and operator expertise play a fundamental role in determining treatment outcomes. This underscores the complex interplay between material science and clinical execution, highlighting the need for standardized protocols and evidence-based guidelines.

Although a substantial body of research has investigated the properties and applications of calcium silicate–based materials, the available evidence is heterogeneous and includes in vivo and clinical studies with varying methodologies, sample sizes, and follow-up durations. While in vitro and ex vivo studies provide valuable mechanistic insights into

Table 1
Risk of Bias assessment.

Authors (year)	D1	D2	D3	D4	D5	D6	D7	Overall
Nawar et al., 2024	+	-	+	+	+	-	-	-
Abada et al., 2025	+	-	+	+	-	-	-	-
Sobh Y.T.M., Ahmed M.R.A., 2024	+	-	-	+	-	+	+	+
Yan Yang et al., 2023	-	-	+	+	-	-	+	+
Turkyilmaz A. et al., 2023	-	-	+	+	+	+	+	+
Dong M., Wang X., Ma J., 2025	-	-	-	+	+	-	+	-
Ghaly et al., 2025	-	+	-	-	-	-	+	-
Nathani et al., 2024	-	+	-	+	+	+	+	+
Alnassar et al., 2023	-	+	-	+	-	+	+	+
Suresh et al., 2025	+	+	-	+	+	+	+	+
Zhang L. et al., 2024	-	+	-	+	-	+	-	+

Domains: D1: Bias due to confounding. D2: Bias arising from measurement of the exposure. D3: Bias in selection of participants into the study (or into the analysis). D4: Bias due to post-exposure interventions. D5: Bias due to missing data. D6: Bias arising from measurement of the outcome. D7:Bias in selection of the reported result.

! Very high.

X High.

- Some concerns.

Low.

No information.

material behavior, their direct translation to clinical practice is limited by the inability to fully replicate the biological environment. Conversely, clinical studies offer more relevant outcome data but may be influenced by confounding variables and methodological differences. Therefore, a comprehensive and systematic evaluation of the existing literature is necessary to integrate these findings and provide a clear understanding of the clinical implications [120–122].

In light of these considerations, the present systematic review aims to critically analyze and synthesize the current evidence on bioceramic calcium silicate–based materials in endodontics. Specifically, it seeks to evaluate their clinical effectiveness, biocompatibility, and impact on patient-centered outcomes, as well as to identify key procedural and environmental factors that influence their performance. By consolidating the available data, this review aims to provide clinicians and researchers with a robust evidence base to support the rational and effective use of bioceramic materials in contemporary endodontic practice, ultimately contributing to more predictable, conservative, and patient-oriented treatment strategies [123,124].

2. Materials and methods

2.1. search strategy

The present systematic review was conducted in accordance with the PRISMA guidelines and registered in the International Prospective Register of Systematic Reviews (PROSPERO ID 1346813).

A comprehensive literature search was performed to identify relevant studies evaluating postoperative pain and periapical healing following root canal treatment. The following electronic databases were screened: PubMed, Web of Science, and Scopus. The search focused on clinical studies, including randomized and prospective trials, without restriction to a single obturation technique or material type.

The search strategy was developed by combining keywords related to the topic of interest. Boolean operators were used to integrate the main terms, including:

("root canal treatment" OR "endodontic therapy") AND ("postoperative pain") AND ("obturation technique" OR "single-cone" OR "lateral compaction" OR "warm vertical compaction") AND ("bioceramic sealer" OR "calcium silicate-based sealer") AND ("periapical healing").

2.2. inclusion and exclusion criteria

Studies were selected according to predefined inclusion and exclusion criteria.

Inclusion criteria.

- Randomized clinical trials and prospective clinical studies;
- Studies evaluating postoperative pain and/or periapical healing after primary root canal treatment;
- Studies comparing different obturation techniques, endodontic sealers (bioceramic vs. resin-based), or irrigation protocols;
- Studies conducted on human subjects.

Exclusion criteria.

- In vitro and based on animal samples;
- Case reports, case series, reviews, and letters to the editor;
- Studies lacking relevant clinical outcomes or adequate follow-up.

2.2.1. PICO question

The review addressed the following PICO question:

"In patients undergoing primary root canal treatment, how do different obturation techniques, endodontic sealers, and irrigation protocols influence postoperative pain and periapical healing?"

- Population: patients undergoing primary root canal treatment;
- Intervention: different obturation techniques (e.g., single-cone, lateral compaction, warm vertical compaction), bioceramic sealers, and irrigation protocols;
- Comparison: alternative obturation techniques, resin-based sealers, or different irrigation strategies;
- Outcome: postoperative pain (commonly assessed using Visual Analogue Scale) and periapical healing evaluated radiographically.

2.3. data extraction and quality assessment

The selection process was carried out by multiple independent reviewers. Studies were screened based on titles and abstracts, followed by full-text evaluation according to the inclusion and exclusion criteria.

The primary outcome was postoperative pain, predominantly measured using validated scales such as the Visual Analogue Scale (VAS), while secondary outcomes included periapical healing, obturation quality, sealer extrusion, flare-up incidence, and overall clinical success.

The methodological quality and risk of bias of the included studies were qualitatively assessed, taking into account factors such as study design, heterogeneity, outcome reporting, and follow-up duration. Any disagreements among reviewers were resolved through discussion and consensus.

3. Results

3.1. Characteristics of included articles

Fig. 2 shows the flow diagram of a systematic review carried out using the PRISMA reporting criteria. The diagram describes the search strategy, inclusion and exclusion of publications at each stage of detection.

A total of 531 publications were identified in three databases, including PubMed (176), Web of Science (121), and Scopus (234), obtaining 289 records after the duplicates were deleted (242). The title and abstract analysis resulted in the exclusion of 226 articles because they were off-topic. The remaining 63 records were read deleting 52 articles that did not fill the inclusion criteria. The evaluation includes a total of 11 publications for qualitative analysis.

3.2. Quality assessment and risk of bias of included articles

3.2.1. Risk of bias assessment

3.2.1.1. Nawar et al. (2024). This ex vivo investigation presents a moderate risk of bias, primarily related to limitations in external validity. Although the study design allowed for strict control of experimental variables, the artificial laboratory conditions do not fully reproduce the complex biological and clinical environment of the root canal system. Consequently, factors such as tissue response, moisture variability, and host-related conditions are not adequately represented. While selection and measurement procedures appear consistent and well-defined, the absence of in vivo validation reduces the direct applicability of the findings to clinical practice, thus justifying a moderate overall risk classification.

3.2.1.2. Abada et al. (2025). This randomized clinical trial demonstrates a moderate risk of bias, despite adopting a prospective design and standardized clinical protocols. The study provides clinically relevant outcomes; however, insufficient detail regarding allocation concealment and blinding procedures may introduce potential performance and detection bias. Additionally, although postoperative outcomes were systematically assessed, the duration of follow-up may not be sufficient to fully capture long-term healing dynamics. These methodological limitations slightly reduce the internal validity of the study, even though the overall design remains robust.

3.2.1.3. Sobh Y.T.M. And ahmed M.R.A. (2024). This clinical study shows an overall low risk of bias, supported by a structured methodology and clinically applicable outcomes. The procedures appear to be well standardized, and outcome measures are clearly defined. Although some degree of operator dependency—particularly in procedures such as hemostasis and dentin conditioning—cannot be excluded, these factors are inherent to clinical practice and do not substantially compromise the study's validity. The consistency between methodology and reported results supports the reliability of the findings.

3.2.1.4. Yan Yang et al. (2023). This study presents a low risk of bias, as the experimental procedures are clearly defined and consistently applied across all material groups and subgroups. While the study may not fully implement randomization or blinding, the specimen preparation, microhardness testing, and SEM/EDS analyses are rigorously described, and the measurement outcomes are transparently reported, minimizing the likelihood that potential biases would substantially affect the overall conclusions.

3.2.1.5. Turkyilmaz A., Durust Bbris S., Hhncerliogullari D., and Eedemir A. (2023). This study shows a low risk of bias, supported by a randomized, single-blind design and adherence to CONSORT guidelines. Sample size calculation and standardized outcome assessment enhance methodological reliability. Minor limitations related to partial blinding are unlikely to affect the overall validity of the results.

3.2.1.6. Dong M., Wwng X., and Mm J. (2025). This randomized clinical study presents a moderate risk of bias, primarily due to factors such as limited sample size and potential attrition during follow-up. Although the study design is methodologically appropriate and includes clinically relevant endpoints, the relatively small population may reduce statistical power and increase variability. Furthermore, the inclusion of specific patient groups, such as older individuals with complex canal anatomy, may introduce confounding variables that are difficult to fully control. These elements justify a moderate risk classification despite the overall quality of the study.

3.2.1.7. Ghaly et al. (2025). This prospective clinical study shows a moderate risk of bias, mainly associated with sample size limitations and potential constraints in follow-up duration. While the clinical protocol appears standardized and the outcomes are relevant, the lack of extended longitudinal data may limit the assessment of long-term success and stability. Additionally, incomplete reporting of certain methodological aspects may affect reproducibility. Nevertheless, the study provides meaningful clinical insights, although with some limitations in robustness.

3.2.1.8. Nathani et al. (2024). This randomized controlled trial demonstrates a low risk of bias, supported by a well-structured study design and clearly defined outcome measures. The methodology appears consistent, and the assessment of postoperative pain and healing outcomes is performed using validated criteria. Although minor limitations related to blinding or follow-up duration may exist, these do not significantly impact the overall validity of the findings, which can be considered reliable and clinically relevant.

3.2.1.9. Alnassar et al. (2023). This randomized clinical trial presents a low risk of bias, with strong methodological consistency and appropriate standardization of clinical procedures. Outcome measures are clearly reported, and the study design minimizes potential confounding factors. While minor methodological limitations, such as sample size or partial blinding, may be present, they do not substantially affect the credibility or applicability of the results.

3.2.1.10. Suresh et al. (2025). This study demonstrates a low risk of bias, owing to its randomized design and adherence to standardized clinical protocols. Outcome evaluation appears systematic and reliable, and the study provides clinically meaningful data. Although complete blinding of outcome assessors is not always explicitly detailed, the overall methodological rigor supports the validity of the findings.

3.2.1.11. Zhang L. et al. (2024). This randomized study shows a low risk of bias, despite the presence of potential clinical confounding factors such as operator variability, preoperative pulp status, and procedural differences. These elements are intrinsic to clinical research and are difficult to eliminate entirely. However, the study design, data analysis, and outcome reporting are sufficiently robust to ensure reliable conclusions, supporting a low overall risk classification.

4. Discussion

Nawar Naguib Nawar and colleagues provide foundational evidence regarding the influence of canal moisture on the performance of hydraulic calcium silicate–based sealers. Their ex vivo study highlights that, unlike conventional resin-based sealers that require complete canal drying, bioceramic sealers benefit from slight residual moisture due to their hydration-dependent setting reaction. The authors demonstrated

Fig. 1. Obturation of 4.5 with bioceramic sealer.

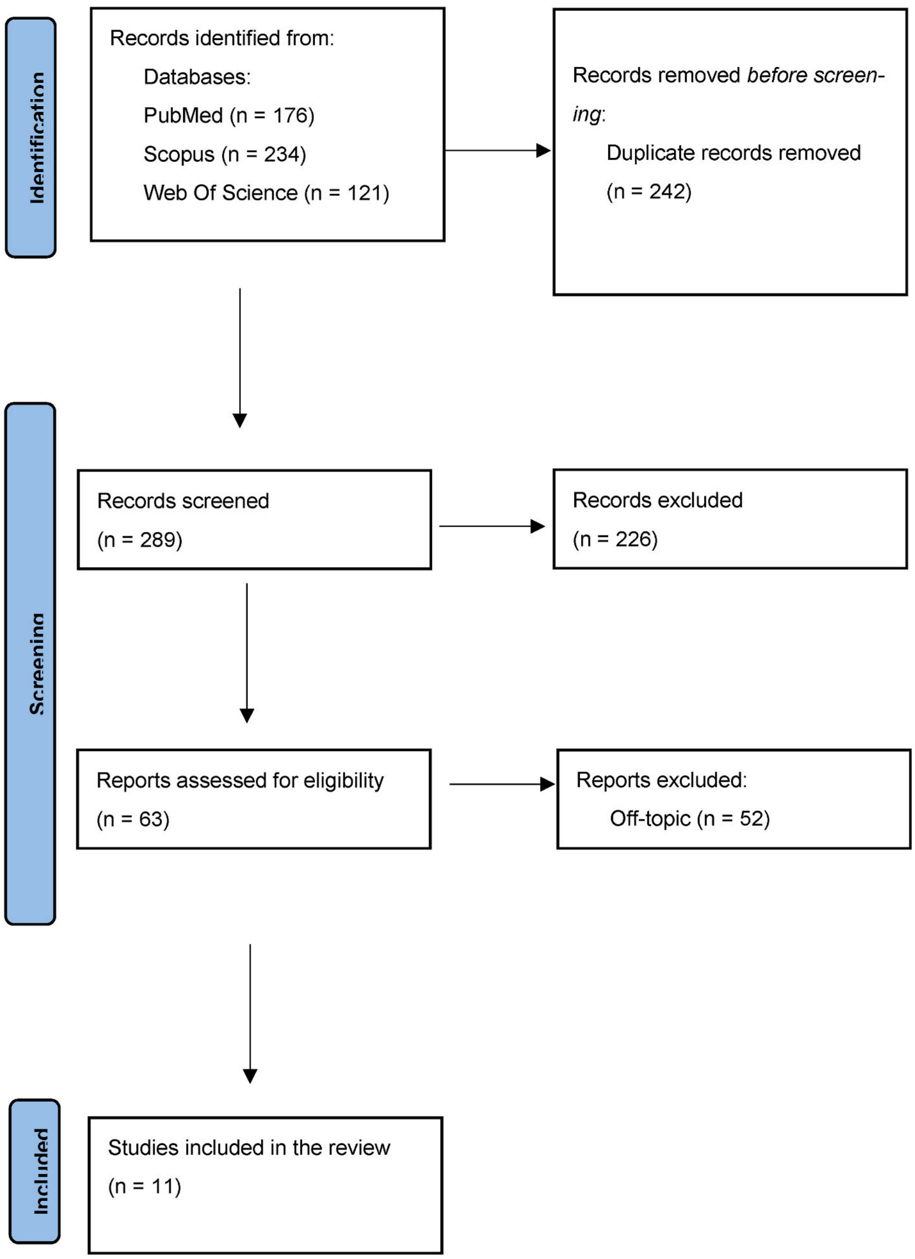

Fig. 2. Prisma flowchart.

that minimal moisture improves the sealer's adaptation to dentinal walls, reducing void formation and potentially enhancing the long-term seal [115,125,126]. Conversely, excessive canal wetness may compromise obturation quality by increasing porosity and affecting sealer flow. Notably, the study suggests that simplified obturation techniques such as the single-cone method can achieve outcomes comparable to more complex condensation techniques, provided the canal moisture is appropriately controlled. Clinically, this challenges traditional protocols, suggesting that dentists may adopt a more nuanced approach to canal drying when using hydraulic sealers, balancing sufficient moisture for material hydration without compromising obturation quality. While the ex vivo design limits the direct translation to in vivo scenarios, the study provides mechanistic insight into the interaction between canal moisture, material chemistry, and obturation technique [127,128].

Hisham Mahmoud Hamdy Abada and colleagues examined the relationship between obturation technique, sealer extrusion, and postoperative pain in a randomized clinical setting. Their findings indicate that techniques exerting higher compaction forces or introducing more sealer into the canal can increase the risk of apical extrusion, potentially causing mild early postoperative discomfort. Importantly, overall pain levels remained low across the study population, highlighting the biocompatibility of calcium silicate–based sealers. This suggests that while extrusion may occur, the biological response to bioceramics is generally favorable, likely due to their alkaline pH, antimicrobial properties, and ability to induce mineral deposition at the sealer–tissue interface. Clinically, the study emphasizes that careful control of obturation force and volume, alongside standardized protocols, can minimize postoperative morbidity while maintaining an adequate apical seal, reinforcing the safety and patient-centered advantages of bioceramic materials [103,129].

Yan Yang and colleagues explored how acidic environments, such as those associated with periapical inflammation, impact the physicochemical properties of hydraulic calcium silicate–based and calcium phosphate silicate–based cements. Their in vivo study revealed that low pH conditions can disrupt the hydration process, alter microstructure, and increase solubility, potentially compromising mechanical stability and sealing ability. Interestingly, differences among material formulations suggest that certain bioceramics may resist acidic degradation more effectively than others. Clinically, this finding is significant because teeth with periapical inflammation may present a mildly acidic environment, which could influence sealer performance. This study provides valuable mechanistic insight, underscoring the need to select bioceramic materials with proven stability under varying environmental conditions [130–132].

Yasmin Tawfik Mohamed Sobh and Mona Rizk Aboelwafa Ahmed investigated the role of contemporary chelating agents in vital pulp therapy procedures performed with bioceramic materials. Their study showed that both tested chelants effectively prepared the dentin surface without compromising the biological performance of the calcium silicate–based pulp-capping material. High rates of clinical and radiographic success were observed, suggesting that careful decontamination and smear layer removal can synergistically enhance the material's bioactivity. This work reinforces the concept that the success of vital pulp therapy is influenced not only by the material used but also by procedural factors such as adequate pulp exposure management, hemostasis, and dentin conditioning, emphasizing that protocol adherence is critical to maximizing the inherent healing potential of bioceramic materials.

Ali Turkyilmaz and colleagues provided clinical data on postoperative pain following obturation with three novel calcium silicate–based sealers. The study consistently found low postoperative pain across all groups, suggesting that these bioceramic sealers are highly biocompatible and induce minimal inflammatory responses. The bioactive nature of the sealers—promoting calcium ion release, hydroxyapatite formation, and favorable tissue interactions—likely contributes to patient comfort. Clinically, this highlights that modern bioceramic sealers not only provide effective sealing but also improve patient-centered outcomes, reinforcing their suitability for routine clinical practice and inclusion in protocols aiming to minimize postoperative discomfort [133,134].

Liping Dong and colleagues focused on the performance of a hydraulic calcium silicate–based sealer, C-root SP, in older patients using different obturation techniques. The study demonstrated that simplified obturation approaches, including the single-cone technique, achieved high clinical and radiographic success, comparable to more complex techniques. Older patients often present with canal sclerosis or calcification, and these findings indicate that bioceramic sealers maintain predictable outcomes even under challenging anatomical conditions. The bioactive properties of C-root SP, including hydroxyapatite deposition and chemical bonding to dentin, likely contribute to these favorable results, supporting their reliability in diverse clinical scenarios and emphasizing the practical advantage of simplified techniques in time- and resource-sensitive settings [135,136].

Mohamed S. Ghaly and colleagues evaluated premixed bioceramic putty as an apical plug in nonvital immature anterior teeth. Their study revealed high rates of periapical healing and clinical success, with reduced technique sensitivity and fewer treatment visits compared to traditional calcium hydroxide apexification. The biological properties of the putty, including biocompatibility, alkaline pH, and mineralized tissue induction, enable the formation of a stable apical barrier, facilitating predictable obturation in teeth with open apices. Clinically, premixed bioceramic putty offers a practical solution for apexification, reducing procedural complexity while supporting periapical healing, an important consideration in young patients where procedural efficiency and success rates are critical [137–139].

Ibrahim Alnassar and colleagues demonstrated that both mineral trioxide aggregate and premixed bioceramic putty achieve high success rates in pulpotomy of primary molars with irreversible pulpitis. Comparable clinical and radiographic outcomes suggest that premixed bioceramic materials are a reliable alternative to MTA, with the added advantages of ready-to-use consistency and ease of handling. These findings reinforce the role of bioactive calcium silicate–based materials in pediatric vital pulp therapy, supporting predictable dentin bridge formation, pulpal healing, and long-term retention of primary teeth without resorting to more invasive procedures [101,135,140,141].

Sarang Suresh and colleagues assessed full pulpotomy in mature permanent teeth with irreversible pulpitis, comparing mineral trioxide aggregate and premixed bioceramic cement. Both materials demonstrated high clinical and radiographic success, indicating that vital pulp therapy is feasible even in mature teeth traditionally managed with complete root canal treatment. The bioactive properties of these materials, including hydroxyapatite formation, antibacterial effects, and promotion of reparative dentin, likely underpin the positive outcomes observed. Clinically, this supports the adoption of conservative, biologically based treatment strategies and highlights the versatility of premixed bioceramics as a reliable alternative to MTA [131,142–145].

Linlin Zhang and colleagues investigated the influence of clinical variables on vital pulp therapy success using two calcium silicate–based materials. Their findings emphasize that factors such as preoperative pulp status, hemostasis control, and operator technique significantly impact outcomes, reinforcing that procedural standardization and careful case selection are critical. While the materials themselves provide a favorable biological environment, their efficacy is maximized when combined with meticulous clinical execution. This highlights the interplay between material properties and procedural quality in achieving predictable results in pulp-preserving therapies.

Finally, Tousif Iqbal Nathani and colleagues compared postoperative pain between resin-based and bioceramic sealers in single-visit root canal treatments. They observed low pain levels and favorable periapical responses with bioceramic sealers, demonstrating their safety and patient-centered advantages. These results further support the adoption of bioceramic materials in modern endodontics, as they combine effective sealing and bioactivity with minimal postoperative morbidity [146–149].

Taken together, these studies collectively demonstrate the versatility, biocompatibility, and clinical reliability of bioceramic materials across multiple endodontic applications, including root canal obturation, vital pulp therapy, apexification, and pediatric treatments. They highlight that bioceramics tolerate variations in canal moisture, perform effectively in anatomically challenging or immature teeth, and maintain predictable outcomes across age groups. Importantly, they underscore the role of clinical variables such as obturation technique, preoperative pulp status, hemostasis, and operator proficiency in optimizing treatment success. Mechanistically, these outcomes are supported by the bioactive properties of calcium silicate–based materials, including hydroxyapatite formation, alkaline pH, antimicrobial effects, and promotion of reparative dentin and periapical healing. While limitations such as sample size and follow-up duration the body of evidence strongly supports the integration of bioceramic materials into contemporary endodontic practice, offering predictable clinical outcomes, enhanced patient comfort, and simplified procedural protocols. These findings are highly relevant for systematic reviews and meta-analyses aiming to evaluate the efficacy, safety, and clinical implications of bioactive endodontic materials, providing a robust evidence base for their widespread adoption [70,150,151].

From a practical clinical perspective, the collective evidence from these studies suggests several actionable insights for clinicians using bioceramic materials. When using hydraulic calcium silicate–based sealers, complete canal desiccation is not strictly necessary; slight residual moisture can optimize the hydration reaction, improve adaptation to dentinal walls, and reduce void formation, especially when combined with simplified obturation techniques such as the single-cone method [14,152]. Clinicians should also consider patient-centered outcomes: postoperative pain following obturation with bioceramic sealers is generally low, and extrusion beyond the apex, while possible, rarely results in significant discomfort due to the material's biocompatibility and bioactivity. In vital pulp therapy and full pulpotomy procedures, the use of contemporary calcium silicate–based materials—whether in mature or immature teeth, or in pediatric cases—consistently leads to high rates of pulp vitality preservation, reparative dentin formation, and periapical healing, provided that proper case selection, hemostasis control, and procedural standardization are ensured [60,77,147]. Additionally, environmental factors, such as acidic conditions in inflamed periapical tissues, may influence the physicochemical behavior of bioceramics, so awareness of local biological conditions and selection of materials with proven stability is important. Across all clinical contexts, premixed bioceramic putties offer practical advantages in terms of ease of handling, reduced technique sensitivity, and consistent clinical performance, making them particularly suitable for apexification and pediatric pulpotomy [27,148].

Authors and Year	Type of Study	Study Sample (n)	Gender (M:F)	Follow-up (months)	Age of Sample (years)	Variables
Nawar et al., 2024 [73]	Randomized clinical trial	24 patients	NA	1	18-40	- Dryness protocol, - Obturation technique - Voids - Sealer adaptation
Abada et al., 2025 [153]	Randomized clinical trial	100 patients	NR	6	18-35	- Obturation technique, - Sealer type, - Pain - Sealer extrusion
Sobh Y.T. M., Ahmed M.R.A., 2024 [154]	Randomized controlled clinical trial	40 patients	NR	12	18-50	- Irrigation protocol (17% EDTA vs apple vinegar) - Postoperative pain (VAS) - Clinical success - Radiographic healing
Yan Yang et al., 2023 [125]	Randomized controlled clinical trial	125 specimens	Not applicable	Not applicable	Not applicable	Material type, exposure medium, mechanical and structural properties
Turkyilmaz A. et al., 2023 [99]	Prospective randomized clinical trial	120 patients	NR	up to 7 days for pain assessment	Adult patients	- Type of calcium silicate-based sealer used for root canal obturation - Pulpal status (asymptomatic irreversible pulpitis vs necrotic pulp with apical periodontitis) - Postoperative pain intensity assessed using VAS at multiple time intervals
Dong M., Wang X., Ma J., 2025 [50]	Randomized clinical trial	240 patients	NR	12	18–65	- Obturation technique - Sealer - Pain - Success
Ghaly et al., 2025 [44]	Randomized clinical trial	50 patients	NR	12	8–11	- Material (Well-Root PT vs MTA), - Healing - Bone density
Nathani et al., 2024 [107]	Randomized controlled trial	101 patients	NR	6	NR	Sealer type, postoperative pain
Alnassar et al., 2023 [69]	Randomized controlled trial	40 patients	NR	12	6-8	Material (MTA vs bioceramic) - Success
Suresh et al., 2025 [15]	Randomized clinical trial	60 patiens	NR	6	NR	- MTA vs bioceramic - Success - Pain
Zhang L. et al., 2024 [49]	Randomized clinical trial	115 patients	NR	12	23–26	- Material (TheraCal LC vs iRoot BP Plus) - VPT type (DPC, PP, FP) - Pain - Success rate - Preoperative pain

(continued on next column)

(continued)

5. Conclusion

In conclusion, the collective body of evidence strongly supports the integration of bioceramic materials into contemporary endodontic practice. They demonstrate high biocompatibility, reliable bioactivity, predictable clinical outcomes, and favorable patient-centered results, including low postoperative pain and effective healing in both immature and mature teeth [121]. Bioceramics provide flexibility in obturation techniques, tolerate minor variations in canal moisture, and can simplify procedures without compromising treatment success. [45,64]. While certain clinical factors—such as operator technique, preoperative pulp status, and environmental conditions—remain influential, these materials offer robust performance across diverse clinical scenarios. Overall, bioceramic materials represent a paradigm shift in endodontics, moving toward more biologically conservative, predictable, and patient-friendly therapie [107]. Future research should focus on long-term outcomes, head-to-head comparisons between formulations, and the influence of local tissue conditions to further refine clinical protocols and optimize the use of bioactive materials in both routine and complex endodontic treatments [129–131].

Author contributions

- **Angelo Michele Inchingolo** †: Conceptualization, Methodology, Writing – Original Draft.
- **Grazia Marinelli** †: Data Curation, Formal Analysis, Visualization.
- **Pietro Lauria**: Investigation, Resources, Validation.
- **Pierluigi Marotti**: Formal Analysis, Data Visualization.
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Data availability statement

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

Patietn consent statement

All clinical and radiographic data were anonymized before publication. The manuscript does not contain identifiable patient information.

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Abbreviations

BC	Bioceramic
Ca^{2+}	Calcium ions
CBCT	Cone Beam Computed Tomography
CI	Confidence Interval
CSB	Calcium Silicate-Based
CT	Clinical Trial
EDTA	Ethylenediaminetetraacetic Acid
HA	Hydroxyapatite
IRRCT	Irreversible Pulpitis Root Canal Treatment
LC	Lateral Compaction
MDF	Mean Difference
MMPs	Matrix Metalloproteinases
MTA	Mineral Trioxide Aggregate
NaOCl	Sodium Hypochlorite
PA	Periapical
PBS	Phosphate Buffered Saline
pH	Potential of Hydrogen
PRF	Platelet-Rich Fibrin
RCT	Root Canal Treatment
RCTs	Randomized Controlled Trials
SC	Single-Cone (obturation technique)
VAS	Visual Analogue Scale
VPT	Vital Pulp Therapy

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