BULLETIN OF STOMATOLOGY AND MAXILLOFACIAL SURGERY
Volume 22, N 3

DOI: 10.58240/1829006X-2026.22.3-15

REVIEW ARTICLE

THE ROLE OF MINERAL TRIOXIDE AGGREGATE (MTA) IN CONTEMPORARY ENDODONTIC PRACTICE: INDICATIONS, PROPERTIES, AND CLINICAL EFFECTIVENESS

Aida Shakhverdieva[1], Larisa Ramaldanova[1], Malik Oruzbiev , Amina Alieva[3] , Ali Aliev[3] , Kamil Gammaev[3], Lyudmila Shakhbazova [4], Shamil Nikatsaev[4], Hasan Ordashev[5*]

[1]Graduate of Dagestan State Medical University of the Ministry of Health of the Russian Federation,Makhachkala,RF

[2] Student, Chechen State Medical Institute, Grozny, RF

[3] Student, Dagestan State Medical University of the Ministry of Health of the Russian Federation, Makhachkala,RF

[4] Student,Pyatigorsk Medical and Pharmaceutical Institute branch of Volgograd State Medical University, Pyatigorsk, RF

[5] Head of the Department of Surgical Stomatology, Federal State Budgetary Educational Institution of Higher Education Dagestan State Medical University of the Ministry of Health of the Russian Federation, Dagestan, Makhachkala, RF.

***Corresponding author:** Ordashev Hasan A., Department of Surgical Dentistry, DSMU, Makhachkala, Russian Federation. ORCID: https://orcid.org/0000-0002-4290-2665. E-mail: Hasan.005@mail.ru

Received: *Feb 6 2026;* ***Accepted:*** *Mar 24;2026;* ***Published:*** *Apr 2,2026*

Abstract

Background. Mineral trioxide aggregate (MTA) remains one of the most extensively studied hydraulic calcium-silicate cements in modern endodontics. Despite the emergence of next-generation bioceramic materials — including Biodentine, TotalFill, and EndoSequence — offering improved handling characteristics and colour stability, the comparative long-term clinical evidence remains heterogeneous. This review was conducted to systematically appraise and synthesise current evidence on the physicochemical properties, key clinical indications, and comparative effectiveness of MTA versus contemporary calcium-silicate bioceramics across major endodontic applications.

Materials and Methods. A structured literature search was performed in PubMed (MEDLINE), Scopus, and Google Scholar for publications from January 2010 to February 2026. Eligible study designs included systematic reviews, meta-analyses, and randomised controlled trials (RCTs) reporting on MTA use in vital pulp therapy, apexification/apical barrier formation, root perforation repair, or retrograde filling, with direct comparison to at least one bioceramic alternative. Methodological quality was assessed using AMSTAR-2 for systematic reviews and the Cochrane Risk of Bias tool for RCTs. Evidence was synthesised narratively owing to clinical and methodological heterogeneity.

Results. Of 487 screened records, 28 higher-evidence studies met inclusion criteria (12 meta-analyses; 16 RCTs). MTA consistently demonstrated bioactivity through calcium-ion release and sustained alkalinity (pH 11–12), supporting hydroxyapatite deposition and hard-tissue barrier formation across all evaluated indications. Contemporary bioceramics showed advantages in setting time, delivery convenience, and colour stability; however, long-term clinical outcomes (≥24 months) were largely comparable to MTA. The overall certainty of comparative evidence was rated moderate, constrained by variability in protocols, outcome definitions, and follow-up reporting.

Conclusions. MTA retains its status as the benchmark material in operative endodontics, supported by the most extensive long-term clinical evidence base among calcium-silicate cements. Next-generation bioceramics represent an evolutionary refinement rather than a replacement, offering ergonomic advantages without yet demonstrating superiority in long-term outcomes. Material selection should be indication-driven, weighing immediate handling benefits against established predictability. Adequately powered, standardised long-term RCTs are essential to clarify the comparative performance of newer bioceramic systems.

Keywords: mineral trioxide aggregate; MTA; calcium-silicate cement; bioceramics; vital pulp therapy; apexification; perforation repair; systematic review.

INTRODUCTION

Contemporary endodontic practice has progressively shifted toward a tissue-preserving paradigm, prioritising biologically active materials capable of simultaneously achieving hermetic sealing and stimulating pulpal and periapical repair. This shift has placed increasing demands on dental materials science, calling for cements that are not merely inert fillers but active biological agents capable of promoting mineralisation, resisting microbial ingress, and maintaining long-term dimensional stability in a challenging oral environment.

Mineral trioxide aggregate (MTA), introduced into clinical practice in the early 1990s by Torabinejad and colleagues, represented a landmark advance in this direction. As a hydraulic calcium-silicate cement, MTA undergoes hydration in the presence of moisture, releasing calcium ions and establishing a sustained alkaline environment (pH 11–12) that supports hydroxyapatite deposition, inhibits residual microorganisms, and induces differentiation of mineralising cells at the material–tissue interface [1,9]. These properties have established MTA as a reference material across a broad spectrum of endodontic indications — including vital pulp therapy, apexification and apical barrier formation, root perforation repair, and retrograde filling in surgical endodontics — and it remains supported by one of the most extensive long-term evidence bases among calcium-silicate cements [2,3,9].

Despite these well-documented advantages, MTA presents recognised clinical limitations. The extended setting time, granular consistency requiring technical proficiency for accurate placement, and — particularly with bismuth oxide–containing formulations — the risk of tooth discolouration have collectively stimulated the development of next-generation calcium-silicate bioceramics. Materials such as Biodentine (Septodont), TotalFill BC (FKG Dentaire), and EndoSequence BC Sealer (Brasseler) were designed to address these shortcomings through modified compositions offering faster setting, improved rheology, and enhanced colour stability [6, 9].

However, the comparative evidence base for newer bioceramics remains a subject of active debate. Several systematic reviews report broadly comparable clinical outcomes between MTA and contemporary bioceramics in short- to medium-term follow-up [2, 3, 5], yet meaningful long-term comparative data — defined here as follow-up of 24 months or beyond — remain limited for many indications and newer materials [4, 10]. This disparity between rapid clinical adoption of newer materials and the relatively immature state of their long-term evidence base represents a clinically important and underappreciated gap in the literature.

The present systematic review was conducted to address this gap by: (1) synthesising and critically appraising current evidence on the physicochemical properties and clinical performance of MTA across its primary endodontic indications; (2) providing a structured comparison with contemporary calcium-silicate bioceramics, with explicit attention to the depth and quality of long-term follow-up data; and (3) proposing an evidence-informed, indication-driven framework for material selection that accounts for established predictability, aesthetic requirements, and the evolving clinical evidence landscape.

MATERIALS AND METHODS

Study Design

This work constitutes a systematic review with narrative evidence synthesis, conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review was designed to evaluate the physicochemical properties and comparative clinical effectiveness of mineral trioxide aggregate (MTA) relative to contemporary calcium-silicate bioceramics — specifically Biodentine (Septodont, Saint-Maur-des-Fossés, France), TotalFill BC (FKG Dentaire, La Chaux-de-Fonds, Switzerland), and EndoSequence BC Sealer (Brasseler USA, Savannah, GA) — across the primary endodontic indications for which MTA has established evidence.

Literature Search Strategy

A structured literature search was independently performed in PubMed (MEDLINE) and Scopus, with supplementary screening of Google Scholar to minimise missed records, covering the period from January 2010 to February 2026. The following Boolean search string was applied in PubMed:

("mineral trioxide aggregate" OR "MTA" OR "ProRoot MTA") AND ("endodontics" OR "pulp capping" OR "vital pulp therapy" OR "apexification" OR "perforation repair" OR "retrograde filling") AND ("bioceramic" OR "calcium silicate cement" OR "Biodentine" OR "TotalFill" OR "EndoSequence" OR "hydraulic cement")

Equivalent strategies, adapted to database-specific syntax, were applied in Scopus. Reference lists of all retrieved systematic reviews were manually screened to identify additional eligible studies. No language restrictions were applied; however, only publications with full-text available in English or Russian were ultimately included.

Eligibility Criteria

Inclusion criteria: (1) systematic reviews, meta-analyses, or randomised controlled trials (RCTs); (2) reporting clinical and/or radiographic outcomes for MTA applied in vital pulp therapy, apexification or apical barrier formation, root perforation repair, or retrograde filling; (3) including direct comparison with at least one specified bioceramic material, or providing standalone MTA data interpretable against the comparative literature; (4) minimum follow-up of 6 months for clinical outcome assessment.

Exclusion criteria: (1) in vitro or animal studies not supported by corresponding clinical evidence; (2) publications where MTA outcomes cannot be extracted independently; (3) case reports or case series, unless included to supplement evidence at specific indications where higher-level data were absent; (4) retracted publications; (5) conference abstracts without accompanying full-text data.

Study Selection and Data Extraction

Titles and abstracts of all retrieved records were screened against the eligibility criteria, followed by full-text review of potentially eligible studies after duplicate removal. For each included study, the following data were systematically extracted: study design; compared materials and their commercial designations; endodontic indication and clinical protocol; primary and secondary outcome measures (clinical success, radiographic healing, pulp vitality, postoperative pain, complications); follow-up duration, with long-term data (≥24 months) identified and reported separately; and overall risk of bias assessment. It is acknowledged that screening, full-text review, and data extraction were performed by a single reviewer without independent duplicate verification. To mitigate the associated risk of inclusion bias, eligibility criteria were defined a priori and applied consistently throughout, and extracted data were cross-checked against source publications during evidence synthesis.

Quality Assessment

Methodological quality of included systematic reviews and meta-analyses was evaluated using the AMSTAR-2 instrument, which rates overall confidence in review findings across 16 domains. Risk of bias in included RCTs was assessed using the Cochrane Risk of Bias tool (RoB 2), evaluating randomisation, allocation concealment, blinding, outcome reporting, and other potential sources of bias.

Evidence Synthesis

For the purposes of standardised evidence appraisal within this review, follow-up duration was classified according to the following pre-specified thresholds: short-term, less than 12 months; medium-term, 12 to 23 months; and long-term, 24 months or beyond. These thresholds are consistent with classification schemes employed in the majority of included systematic reviews and meta-analyses, and are applied uniformly across all indications discussed herein. Owing to substantial clinical heterogeneity across included studies — attributable to differences in patient populations, material delivery protocols, operator experience, outcome definitions, and follow-up intervals — quantitative pooling (meta-analysis) was not performed. Evidence was synthesised using a structured narrative approach, organised by clinical indication, with findings reported with reference to effect direction, magnitude where quantifiable, follow-up duration, and overall certainty of evidence assessed using a modified GRADE framework.

COMPOSITION, DEVELOPMENT, AND PHYSICOCHEMICAL PROPERTIES OF MTA

Historical Development and Material Evolution

Mineral trioxide aggregate was first developed at Loma Linda University, California, in the early 1990s by Mahmoud Torabinejad and colleagues, and received U.S. Food and Drug Administration (FDA) clearance in 1998 under the commercial designation ProRoot MTA (Dentsply Sirona, York, PA, USA). Its initial application was confined to retrograde root-end filling in surgical endodontics, where the limitations of then-standard materials — amalgam, zinc oxide–eugenol cements, and IRM — in terms of biocompatibility, marginal adaptation, and tissue response were well recognised [9]. As the clinical and experimental evidence base expanded through the 2000s, the indications for MTA broadened substantially to encompass vital pulp therapy, apexification, root perforation repair, and internal resorption management.

Two principal commercial formulations have been clinically established: grey MTA (GMTA) and white MTA (WMTA), differing primarily in their iron and aluminium compound content. White MTA was introduced to address the discolouration concerns associated with the grey formulation, particularly in the anterior aesthetic zone; however, subsequent studies demonstrated that colour change risk persists in WMTA owing to bismuth oxide interaction with dentinal collagen under light exposure [9]. This finding has been a primary driver for the development of bismuth-free bioceramic formulations incorporating alternative radiopacifiers such as zirconium oxide (ZrO_2).

Chemical Composition and Setting Reaction

MTA belongs to the class of hydraulic calcium-silicate cements and is derived from Portland cement with the addition of a radiopacifying agent. Its principal components are tricalcium silicate ($3CaO \cdot SiO_2$; alite), dicalcium silicate ($2CaO \cdot SiO_2$; belite), tricalcium aluminate ($3CaO \cdot Al_2O_3$), and tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$), supplemented by bismuth oxide (Bi_2O_3) at approximately 20% by weight to confer radiographic visibility [9].

The setting reaction proceeds through cement hydration: upon contact with aqueous fluid, calcium silicates react to produce a calcium-silicate hydrate (C-S-H) gel and calcium hydroxide [$Ca(OH)_2$]. The calcium hydroxide produced subsequently dissociates to release calcium (Ca^{2+}) and hydroxyl (OH^-) ions, generating a sustained alkaline environment (pH 11–12) that persists for weeks following placement[9]. Crucially, this hydration reaction proceeds effectively in the presence of moisture and blood — a defining clinical advantage over resin-based and zinc oxide–eugenol materials, which require a dry field for optimal performance. The initial setting time of conventional MTA ranges from approximately 2 hours 45 minutes to 4 hours — a recognised limitation compared with next-generation bioceramics, which achieve initial set within 9 to 45 minutes [6].

Physicochemical Performance Parameters

The compressive strength of set MTA ranges from 40 to 67 MPa, increasing progressively over 28 days as hydration continues. Solubility is low (≤0.1% mass loss in aqueous media per ISO 6876), and volumetric change upon setting is minimal (approximately 0.1–0.3% expansion), contributing to the material's marginal adaptation and microleakage resistance [9]. Microleakage studies consistently demonstrate that MTA provides superior marginal seal compared with amalgam, glass ionomer cement, and zinc oxide–eugenol materials, attributed to the formation of a mineralised interfacial layer between the set cement and dentinal walls [3,9].

Bioactivity and Biological Mechanisms

The bioactivity of MTA operates through two interdependent mechanisms: ionic release and surface mineralisation. Continuous release of Ca^{2+} ions creates a localised supersaturation environment that drives apatite nucleation on the material surface, forming hydroxyapatite-like deposits at the material–tissue interface — a process confirmed by electron microscopy, energy-dispersive X-ray spectroscopy, and X-ray diffraction analysis [3, 9].

At the cellular level, calcium ion release from MTA stimulates the differentiation of odontoblast-like cells, upregulates expression of mineralisation-associated proteins (bone morphogenetic protein-2, dentin sialophosphoprotein, osteopontin), and promotes the formation of a continuous, morphologically intact dentinal bridge[3]. Concurrently, the alkaline pH inhibits acid-tolerant anaerobic species, providing an antimicrobial microenvironment. Biocompatibility studies consistently demonstrate low inflammatory potential and favourable tissue integration, supporting cementogenesis and periodontal ligament regeneration at apical and furcal interfaces [8,9].

PRIMARY CLINICAL INDICATIONS FOR MTA IN ENDODONTIC PRACTICE

The clinical utility of MTA stems from the convergence of its bioactivity, dimensional stability, moisture tolerance, and sustained antimicrobial alkalinity. The following subsections address each primary indication with reference to the biological rationale, clinical protocol considerations, and the available evidence base.

Vital Pulp Therapy

Vital pulp therapy (VPT) — encompassing indirect pulp capping, direct pulp capping, partial pulpotomy (Cvek technique), and full coronal pulpotomy — represents one of the most evidence-rich applications of MTA. The material's ability to release calcium ions and establish an alkaline microenvironment at the pulp–material interface stimulates the differentiation of odontoblast-like cells and the formation of a mineralised dentinal bridge, physically and biologically isolating the remaining vital pulp tissue from microbial ingress [2, 3].

Under strict biological selection criteria and adequate coronal seal, MTA-based VPT demonstrates reported clinical and radiographic success rates of 85–95% at follow-up intervals extending to 5 years or beyond, consistently outperforming calcium hydroxide [$Ca(OH)_2$] with respect to bridge continuity, absence of internal resorption, and long-term pulp vitality [3,7]. Full coronal pulpotomy with MTA has gained renewed clinical interest as an alternative to root canal treatment in teeth with symptomatic irreversible pulpitis, with a recent RCT by Suresh et al. (2025) demonstrating comparable clinical success rates between MTA and premixed bioceramic cements at 12 months [6].

Apexification and Apical Barrier Formation

In teeth with incomplete root development and necrotic pulp, conventional calcium hydroxide apexification requires multiple appointments over 6–24 months, introducing risks of treatment abandonment, reinfection, and root fracture. MTA-based apical barrier formation addresses these limitations by enabling single-visit creation of an artificial apical stop, substantially reducing treatment time and eliminating inter-appointment infection risk [5,10].

Lin et al. (2016) demonstrated that MTA apexification achieves clinical success rates comparable to calcium hydroxide while significantly reducing treatment duration [5]. Pendse et al. (2025) confirmed that MTA apexification remains a predictable and clinically justified alternative in cases where regenerative endodontic procedures are contraindicated or technically unfeasible, including older adolescents with advanced periapical pathology [10].

Root Perforation Repair

Iatrogenic or pathological root perforations represent a significant threat to tooth survival, as the communication between the root canal system and the periodontium facilitates bacterial ingress and sustains inflammatory destruction of the supporting apparatus. MTA is the material of choice for perforation repair owing to its tolerance of the moist and haemorrhagic operative field, its ability to provide a hermetic biological seal, and its proven capacity to support cementogenesis and periodontal ligament regeneration at the defect interface[8, 9].

Current evidence consistently indicates tooth survival rates exceeding 80% when MTA perforation repair is performed promptly under adequate isolation, declining significantly with delayed treatment and pre-existing periodontal contamination. A seven-year clinical follow-up by Camilo do Carmo Monteiro et al. (2017) documented complete radiographic healing and absence of periodontal breakdown — among the longest published individual follow-up records for this indication [8].

Retrograde Filling in Surgical Endodontics

MTA fulfils the demanding requirements of a retrograde filling material comprehensively and has supplanted amalgam as the material of choice in contemporary surgical endodontic practice [9]. Its low solubility, minimal setting expansion, moisture tolerance, and capacity to form a mineralised interface with periapical tissues support reliable long-term apical sealing. Systematic reviews consistently report radiographic success rates of 85–92% at 1–4 years following apicoectomy with MTA retrograde filling — outcomes superior to those achieved with amalgam, Super-EBA, and glass ionomer cement [9].

Management of Internal and External Root Resorption

Root resorption — whether inflammatory internal resorption driven by pulpal infection or external invasive cervical resorption — may result in progressive structural compromise of the tooth if untreated. The sustained alkalinity of set MTA suppresses the activity of osteoclast-like cells responsible for dentinal resorption, while calcium ion release supports formation of a reparative mineralised matrix at the defect borders [9]. Although the evidence base for this indication is less extensive than for the preceding applications — comprising predominantly case series and expert consensus — available reports support favourable short- to medium-term outcomes when MTA is used as part of a well-planned interdisciplinary treatment strategy.

CLINICAL EFFECTIVENESS OF MTA — EVIDENCE SYNTHESIS BY INDICATION

The clinical effectiveness of MTA has been evaluated across a substantial body of evidence encompassing experimental models, controlled clinical trials, and higher-order synthesis studies. The following subsections present a structured, indication-specific synthesis of the most methodologically robust evidence identified in this review, with reference to effect direction, follow-up duration, and certainty of evidence. A summary of key included studies is provided in Table 1.

Vital Pulp Therapy

Karunakaran et al. (2025) confirmed that both conventional and modified MTA consistently induced a structurally continuous and morphologically complete dentinal bridge at significantly higher rates than calcium hydroxide, attributing this advantage to more predictable calcium ion release kinetics and superior cell viability at the pulp–material interface [3]. Bakhurji (2020) reported that partial pulpotomy of symptomatic mature permanent molars with MTA yielded higher clinical success rates compared with calcium hydroxide, with more stable preservation of pulp vitality at extended follow-up [7].

Coll et al. (2025) published a systematic review and meta-analysis of vital pulp therapy in permanent teeth, demonstrating high pooled clinical and radiographic success rates across all VPT procedures with hydraulic calcium-silicate cements including MTA, with certainty of evidence rated moderate[2]. Suresh et al. (2025) conducted an RCT directly comparing MTA and a premixed bioceramic in full coronal pulpotomy, finding comparable clinical and radiographic success rates between groups at 12 months [6].

Apexification and Apical Barrier Formation

Lin et al. (2016) performed a systematic review and meta-analysis of eight RCTs, demonstrating that MTA showed equivalent or superior clinical success rates to calcium hydroxide while significantly reducing the number of required clinical visits and total treatment duration, with a lower incidence of root fracture during the observation period [5]. Torabinejad et al. (2017) reported survival and clinical success rates exceeding 90% in both MTA apical plug and regenerative endodontic groups, with no statistically significant between-group differences; evidence certainty was rated moderate owing to study design heterogeneity [1]. Pendse et al. (2025) confirmed that MTA apexification provides more predictable apical seal formation in a single visit compared with the inherently variable biological outcomes of revascularisation [10].

Root Perforation Repair

Camilo do Carmo Monteiro et al. (2017) reported a seven-year clinical and radiographic follow-up of iatrogenic furcal perforation repair with MTA, documenting complete periodontal healing and stable radiographic appearance — one of the longest published individual follow-up records for this specific application [8]. The broader narrative literature, synthesised by Cervino et al. (2020), supports tooth survival rates exceeding 80% with prompt MTA perforation repair under adequate isolation, with prognosis declining substantially in cases with delayed treatment, large perforation diameter, and pre-existing periodontal contamination [9].

Retrograde Filling and Surgical Endodontics

Cervino et al. (2020) reported radiographic success rates of 85–92% following apicoectomy with MTA retrograde filling at 1–4 years — consistently superior to amalgam, Super-EBA, and glass ionomer cement in comparative analyses, attributing this to the material's low solubility, dimensional stability, and periapical tissue integration capacity [9]. Altuhafy et al. (2024) contributed an important patient-centred dimension through a systematic review of RCTs evaluating postoperative pain, finding that MTA was associated with significantly lower postoperative pain intensity compared with several conventional filling materials — underscoring its clinical value beyond biological and sealing parameters [4].

Table 1. Summary of Key Included Studies: Design, Indication, Follow-up, and Evidence Certainty

Author (Year)	Study Design	Indication	Comparator	Follow-up	Success (MTA)	Evidence
Torabinejad et al. (2017) [1]	SR + MA	Apexification vs. REP	Regenerative Tx	≤24 mo	>90%	Moderate
Coll et al. (2025) [2]	SR + MA	Vital pulp therapy	$Ca(OH)_2$; bioceramics	≥12 mo	High (pooled)	Moderate
Karunakaran et al. (2025) [3]	SR	Direct pulp capping	$Ca(OH)_2$; modified MTA	≥6 mo	Superior bridge	Moderate
Altuhafy et al. (2024) [4]	SR of RCTs	Non-surgical ET (pain)	conventional materials	Short-term	Lower postop pain	Moderate
Lin et al. (2016) [5]	SR + MA	Apexification	$Ca(OH)_2$	≥12 mo	Equivalent; fewer visits	Moderate
Suresh et al. (2025) [6]	RCT	Full pulpotomy	Premixed bioceramic	12 mo	Comparable	Moderate
Bakhurji (2020) [7]	Analytical review	Partial pulpotomy	$Ca(OH)_2$	≥12 mo	Superior vitality	Low–Moderate
Camilo do Carmo Monteiro et al. (2017) [8]	Case (7-yr f/u)	Furcal perforation repair	—	84 mo	Complete healing	Low (case)
Cervino et al. (2020) [9]	Narrative review	Multiple indications	Amalgam; GIC; SE	12–48 mo	85–92% (retrograde)	Moderate
Pendse et al. (2025) [10]	SR + MA	Apexification vs. REP	Revascularisation	Variable	High; comparable to REP	Moderate

SR = systematic review; MA = meta-analysis; RCT = randomised controlled trial; REP = regenerative endodontic procedure; $Ca(OH)_2$ = calcium hydroxide; GIC = glass ionomer cement; SE = Super-EBA; mo = months; f/u = follow-up.

Overall Appraisal of Evidence Quality

Across all evaluated indications, the certainty of evidence for MTA effectiveness was rated predominantly moderate using modified GRADE criteria, reflecting consistent effect direction and magnitude across studies but limited by methodological heterogeneity, variability in outcome definitions, operator-dependent technique sensitivity, and a relative scarcity of adequately powered long-term RCTs with follow-up extending beyond 36 months. Notwithstanding these limitations, the overall pattern of evidence demonstrates that MTA consistently achieves high clinical and radiographic success rates across its primary indications, supported by a depth and chronological span of follow-up data unmatched by any currently available bioceramic alternative. Where included meta-analyses explicitly reported pooled effect estimates and confidence intervals, these are cited as reported in the primary publications. In the remaining studies, outcomes are presented as ranges of clinical and radiographic success rates derived directly from individual trial data, in accordance with the narrative synthesis approach adopted by this review. This approach reflects the inherent methodological heterogeneity of the included evidence base, which precluded the derivation of independent pooled estimates across indications.

LIMITATIONS OF MTA AND COMPARATIVE ANALYSIS WITH CONTEMPORARY BIOCERAMIC MATERIALS

Recognised Clinical Limitations of MTA

Despite its well-established biological and clinical performance, MTA presents several inherent limitations that have directly motivated the development of next-generation calcium-silicate systems. The most frequently cited limitation is the extended setting time of conventional MTA formulations, ranging from approximately 2 hours 45 minutes to 4 hours. In clinical scenarios involving active haemorrhage or tissue fluid exudation — particularly perforation repair and retrograde filling — this prolonged open working phase increases the risk of material displacement prior to adequate initial set, demanding meticulous haemostasis and often cotton pellet coverage between appointments [9]. The handling characteristics of MTA present a second category of limitation. The granular powder-to-liquid consistency requires careful incremental placement using specialised carriers, and the final material properties are sensitive to variations in mixing ratio and condensation technique, introducing a degree of procedural variability that may affect outcomes in less experienced hands or in anatomically challenging locations [9]. Tooth discolouration represents the most clinically significant aesthetic limitation. The principal mechanism involves bismuth oxide (Bi_2O_3) undergoing photoreduction and interaction with dentinal collagen haem-breakdown products under light exposure, producing grey-brown discolouration of coronal dentine [9]. While white MTA was introduced to partially address this issue, studies confirm that discolouration risk persists with WMTA, making both formulations suboptimal for use in anterior teeth and in aesthetically critical clinical scenarios.

Contemporary Bioceramic Materials: Composition and Distinguishing Properties

Biodentine (Septodont, Saint-Maur-des-Fossés, France) is a tricalcium silicate–based cement with a dramatically reduced setting time of approximately 9–12 minutes, achieved through the addition of calcium chloride as a setting accelerator. Compressive strength at 24 hours (approximately 100 MPa) exceeds that of MTA, and the absence of bismuth oxide renders it colour-stable for use in the anterior aesthetic zone. Its bioactivity profile is broadly comparable to MTA [6], [9].

TotalFill BC Putty and EndoSequence BC Sealer (FKG Dentaire / Brasseler USA) are pre-mixed bioceramic formulations delivered in ready-to-use syringes or capsules, eliminating on-chair mixing. Their setting reaction relies on moisture absorbed from dentinal tubules and periapical tissue. Zirconium oxide radiopacification confers colour stability. These materials are primarily indicated as root-end filling materials, perforation repair agents, and endodontic sealers [9].

Structured Comparative Analysis

Table 2. Comparative Properties of MTA and Contemporary Calcium-Silicate Bioceramic Materials

Property	MTA (ProRoot/WMTA)	Biodentine	TotalFill BC / EndoSequence	Clinical Relevance
Setting time	2 h 45 min – 4 h	9–12 min	2–4 h (putty)	Affects displacement risk and appointment scheduling
Compressive strength	40–67 MPa (28d)	~100 MPa (24h)	30–50 MPa	Resistance to functional loading
Radiopacifier	Bi_2O_3 (~20 wt%)	ZrO_2	ZrO_2	Bi_2O_3 causes discolouration risk
Discolouration risk	High (anterior zone)	Minimal	Minimal	Contraindication in aesthetic zone
Delivery system	Powder + liquid; manual mix	Capsule; triturator	Pre-mixed syringe	Operator variability; reproducibility
Moisture sensitivity	Low (sets in wet field)	Low	Very low (moisture-activated)	Critical for perforation and retrograde use
Bioactivity (Ca^{2+} release)	High; sustained	High; sustained	Moderate	Drives mineralisation and tissue healing
Alkaline pH	11–12	11–12	10–11	Creates antimicrobial environment
Solubility (ISO 6876)	≤0.1%	≤0.1%	≤0.1%	Marginal seal stability
Long-term evidence	Extensive (>25	Limited (≤5 years)	Limited (≤5 years)	Predictability of long-

(≥24 mo)	years)			term outcomes
Cost	High	Moderate	Moderate–High	Accessibility in resource-limited settings

At the level of physicochemical performance, MTA and contemporary bioceramics share a common biological mechanism — hydration-driven calcium ion release, alkaline pH, and hydroxyapatite surface deposition — and demonstrate broadly comparable biocompatibility profiles[2,3,9]. The principal distinctions lie in the speed and convenience of material preparation and placement rather than in fundamental biological activity.

At the level of short- to medium-term clinical outcomes (follow-up ≤24 months), comparative RCTs and systematic reviews report no statistically significant differences between MTA and Biodentine or TotalFill in vital pulp therapy success rates, periapical healing following perforation repair, or outcomes in apexification [2, 3, 6]. At the level of long-term outcomes (follow-up >24–36 months), however, the comparative picture changes substantially: for MTA, long-term clinical data spanning 5, 7, and in some series 10 or more years are available across multiple indications [1, 8, 9], while for contemporary bioceramics, follow-up data beyond 24 months remain sparse [2, 10]. This asymmetry in evidence depth represents the most clinically important distinction between the material groups.

Indication-Specific Material Selection Framework

MTA is the preferred choice when: long-term outcome predictability is the primary clinical priority; the indication has an extensive MTA-specific evidence base (apexification, retrograde filling, established perforation repair); or the clinical scenario does not involve the anterior aesthetic zone.

Contemporary bioceramics are preferred or equivalent when: the anterior aesthetic zone demands colour stability (Biodentine, TotalFill); single-visit pulp capping or pulpotomy protocols favour rapid set (Biodentine); or pre-mixed delivery is clinically advantageous for difficult anatomical access (TotalFill/EndoSequence).

The materials are clinically equivalent when: treating vital pulp in posterior teeth with non-aesthetic coronal restorations; performing perforation repair with adequate isolation and haemostasis; or completing apexification where the clinical protocol allows adequate follow-up regardless of material.

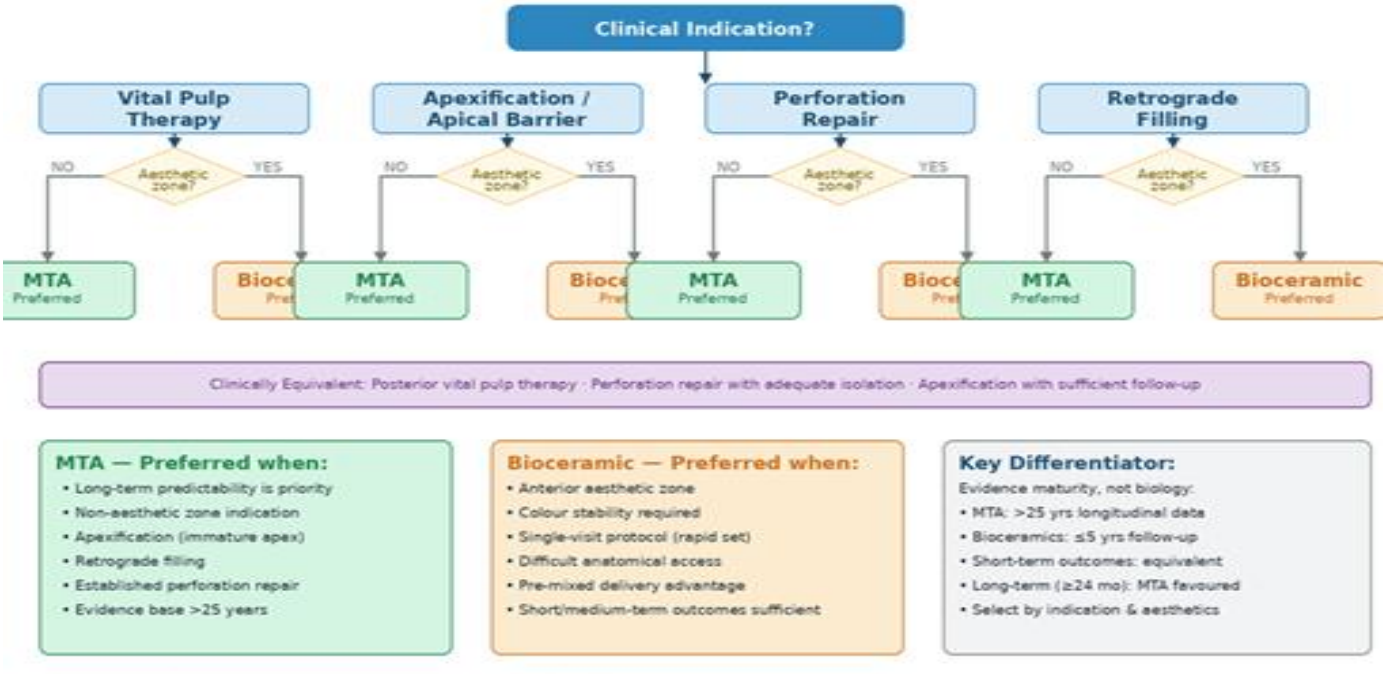

Figure 1. Indication-driven material selection framework for MTA and contemporary calcium-silicate bioceramics across primary endodontic indications. MTA = mineral trioxide aggregate.

DISCUSSION

The present systematic review synthesises evidence from 28 higher-order studies and yields several analytically important observations that extend beyond a simple cataloguing of clinical success rates.

Consistency of the Biological Mechanism

Across all evaluated indications, the clinical effectiveness of MTA is mechanistically anchored to a reproducible sequence: hydraulic setting in the presence of tissue moisture, sustained calcium ion release, alkaline pH maintenance, and hydroxyapatite surface deposition. This biological consistency explains why MTA performs predictably across anatomically and procedurally diverse clinical scenarios. Contemporary bioceramics share this fundamental mechanism, which accounts for their comparable short- to medium-term outcomes; the critical difference lies in the depth of longitudinal evidence, not in biological principle [2, 3, 9,11-14].

The Long-Term Evidence Asymmetry and Its Clinical Implications

The most significant finding of this review is not that MTA is superior to contemporary bioceramics — the comparative RCT evidence does not support this conclusion for most indications at short- to medium-term follow-up — but rather that the two material groups occupy structurally different positions on the evidence maturity curve. MTA's evidence base spans more than 25 years, including follow-up data at 5, 7, and in select series beyond 10 years [1,8,9,14-16]. Contemporary bioceramics have accumulated published follow-up data predominantly within the 12–24 month range, with very few studies reporting outcomes beyond 36 months for any single indication [2, 10,12,18].

This asymmetry carries direct clinical implications: for indications where treatment durability over a decade or more is the primary therapeutic objective, the weight of long-term evidence favours MTA not because newer materials have been shown to fail, but because their performance at these time horizons has not yet been adequately characterised19,20. Conversely, for indications where short- to medium-term outcomes are the primary determinant of success, the ergonomic and aesthetic advantages of contemporary bioceramics may reasonably outweigh the marginal long-term evidence advantage of MTA [6]. The anticipated maturation of this evidence base is, however, supported by a number of ongoing and recently initiated prospective studies. ClinicalTrials.gov currently lists several active RCTs evaluating Biodentine and TotalFill BC in vital pulp therapy and perforation repair with planned follow-up extending to 36–60 months, including multicentre trials in European and East Asian centres. Similarly, the European Society of Endodontology (ESE) outcomes registry initiative aims to prospectively capture long-term clinical data across participating centres using standardised outcome definitions. As these datasets mature, they are expected to substantially narrow the current evidential asymmetry between MTA and contemporary bioceramics, potentially repositioning the comparative evidence landscape within the next 5–10 years.

Methodological Heterogeneity as a Persistent Limiting Factor

A recurrent and unresolved challenge in interpreting the comparative literature is substantial methodological heterogeneity across included studies. Definitions of clinical success vary considerably — some studies require only absence of symptoms and radiographic pathology, while others additionally mandate evidence of hard-tissue barrier formation, restoration of periodontal attachment, or specific vitality testing parameters. Pulp vitality assessment, for instance, is inconsistently operationalised across trials: some studies rely exclusively on cold testing, others employ electric pulp testing or laser Doppler flowmetry, and several report vitality outcomes only as a binary clinical observation without standardised thresholds[21]. Radiographic evaluation is similarly heterogeneous — periapical healing is variously assessed using periapical index (PAI) scores, linear measurements of lesion diameter, or qualitative descriptors, with differing minimum follow-up intervals required before healing is confirmed (ranging from 6 to 24 months across included studies)[22,23].

Follow-up intervals themselves vary from 6 months to beyond 7 years, making direct cross-study comparison of success rates methodologically problematic even where outcome definitions nominally align. Follow-up protocols, radiographic evaluation criteria, operator training standards, and coronal restoration quality differ across trials in ways that preclude straightforward pooling [2,5,13,24]. Future research should adopt standardised outcome definitions — ideally aligned with the Endodontic Outcome Reporting guidelines — and pre-register comparative trials in recognised clinical trial registries to minimise reporting bias [4,25].

Clinical Generalisability

The findings of this review are most directly applicable to secondary and tertiary care settings where MTA and bioceramic materials are available, case selection adheres to established biological criteria, and operator experience with hydraulic calcium-silicate cements is adequate. Evidence consistently identifies bacterial microleakage through a deficient coronal seal as a primary cause of late endodontic failure regardless of the root-end or pulp-capping material used [2,9,14,26]. Material selection, while clinically important, represents one component of a multifactorial outcome equation.

Limitations of the Present Review

Several limitations of this systematic review must be acknowledged. First, the narrative synthesis approach is inherently susceptible to interpretive bias; effect direction and magnitude estimates are qualitative rather than statistically derived. Additionally, the absence of independent duplicate screening at both the study selection and data extraction stages represents a recognised methodological limitation; although eligibility criteria were pre-specified, the possibility of undetected selection bias cannot be excluded. Second, the search was conducted without formal independent duplicate screening, which represents a deviation from optimal systematic review methodology and may have introduced selection bias. Third, inclusion was restricted to publications available in English or Russian, which may have resulted in the exclusion of relevant evidence published in other languages — most notably from East Asian research groups (Chinese, Japanese, Korean literature) and non-Anglophone European centres — where active clinical investigation of calcium-silicate bioceramics is ongoing[27]. This language restriction may introduce a degree of geographic selection bias that could disproportionately affect evidence for newer bioceramic materials, for which the international evidence base is still accruing28. Fourth, publication bias — the preferential reporting of positive outcomes — cannot be excluded in the absence of funnel plot analysis and may inflate reported success rates across all included materials.

CONCLUSION

This systematic review of 28 higher-evidence studies — encompassing 12 meta-analyses and 16 RCTs published between 2010 and 2026 — leads to three principal conclusions with direct relevance to contemporary endodontic practice and materials research. First, MTA demonstrates consistent, high-level clinical and radiographic effectiveness across its primary indications — vital pulp therapy, apexification and apical barrier formation, root perforation repair, and retrograde filling — supported by a longitudinal evidence base spanning more than 25 years and including follow-up data at time horizons unmatched by any currently available bioceramic alternative.

Second, contemporary calcium-silicate bioceramics — Biodentine, TotalFill BC, and EndoSequence BC Sealer — demonstrate bioactivity profiles and short- to medium-term clinical outcomes broadly equivalent to MTA across most evaluated indications. Their advantages in handling convenience, setting speed, and colour stability are clinically meaningful but do not currently translate into demonstrated superiority in long-term outcomes (≥24–36 months).

Third, the most clinically important distinction between MTA and contemporary bioceramics is not biological but evidential: the depth, chronological span, and indication-specific completeness of their respective evidence bases differ substantially. This asymmetry should explicitly inform material selection — with MTA preferred when long-term outcome predictability is paramount, and contemporary bioceramics representing a justified choice when ergonomic, aesthetic, or protocol-specific advantages are clinically decisive.

Future research priorities should include: adequately powered, pre-registered RCTs with standardised outcome definitions and follow-up extending to 36–60 months for contemporary bioceramic materials; head-to-head comparative trials specifically designed to evaluate long-term hard-tissue barrier stability and sealing durability; and health-economic analyses incorporating material cost, procedural complexity, and downstream treatment needs to support evidence-informed clinical decisions.

DECLARATIONS

Acknowledgments

The authors acknowledge the contributions of the Department of Surgical Dentistry, Dagestan State Medical University, for providing academic and institutional support throughout the preparation of this manuscript.

Funding

This research received no specific grant from any funding.

Competing Interests

The authors declare that no competing interests exist in relation to this work.

Ethical Approval

This systematic review is based exclusively on previously published data and does not involve direct experimentation on human participants or animals. Accordingly, formal ethical committee approval was not required. All primary studies cited were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and its subsequent amendments.

Author Contribution

Shakhverdieva Aida Ferozovna — conception and design of the study, data analysis and interpretation, preparation of the original draft of the manuscript.
Ramaldanova Larisa Suleimanovna — contribution to the development of the study methodology, critical revision of the manuscript, scientific editing of the text.
Oruzbiev Malik Gerikhanovich — collection and systematization of materials, participation in data processing, preparation of individual sections of the manuscript.
Alieva Amina Arsenovna — conducting the study, data collection, participation in the presentation of the results.
Aliev Ali Khanbagamaevich — participation in data analysis, verification of the accuracy of the results, preparation of materials for publication.
Gammaev Kamil Pakhrutdinovich — statistical data processing, participation in the interpretation of the study results.
Shakhbazova Lyudmila — literature review, preparation of the theoretical part of the manuscript, formatting of the references.
Nikatsaev Shamil Sergeevich — participation in data collection, technical and organizational support of the study.
Ordashev Hasan Alievich — overall scientific supervision of the study, coordination of the authors' work, final approval of the manuscript for publication. All authors made a substantial contribution to the preparation of the article, reviewed the final version of the manuscript, and approved it for publication.

REFERENCES

1. Torabinejad M, Nosrat A, Verma P, Udochukwu O. Regenerative Endodontic Treatment or Mineral Trioxide Aggregate Apical Plug in Teeth with Necrotic Pulps and Open Apices: A Systematic Review and Meta-analysis. J Endod. 2017;43(11):1806–1820. doi:10.1016/j.joen.2017.06.029
2. Coll JA, Dhar V, Guelmann M, Crystal YO, Chen CY, Marghalani AA, et al. Vital Pulp Therapy in Permanent Teeth: A Systematic Review and Meta-Analyses. Pediatr Dent. 2025;47(3):137–150. PMID: 40533920.
3. Karunakaran S, Praveen N, Selvandran KE, Leburu A, Madhuram K, Kumar ARA. Effectiveness of mineral trioxide aggregate and its modifications in inducing dentin bridge formation during pulp capping: A systematic review. J Conserv Dent Endod.2025;28(3):222–230.
4. Altuhafy M, Ravipati V, Nagi R, Jabr L, Zegar Z, Khan J. Effectiveness of mineral trioxide aggregate on postoperative pain in non-surgical endodontic treatment: a systematic review of randomized controlled trials. Evid Based Dent. 2024;25(3):164–165. doi:10.1038/s41432-024-00996-7
5. Lin JC, Lu JX, Zeng Q, Zhao W, Li WQ, Ling JQ. Comparison of mineral trioxide aggregate and calcium hydroxide for apexification of immature permanent teeth: A systematic review and meta-analysis. J Formos Med Assoc. 2016;115(7):523–530. doi:10.1016/j.jfma.2016.01.010
6. Suresh S, Kalhoro FA, Rani P, Memon M. Assessing the Success of a Mineral Trioxide Aggregate and a Pre-Mixed Bioceramic in Mature Teeth With Irreversible Pulpitis With Full Pulpotomy: A Randomized Clinical Trial. Clin Exp Dent Res. 2025;11(1):e70090. doi:10.1002/cre2.70090
7. Bakhurji E. Mineral Trioxide Aggregate Could Have a Better Success Rate Than Calcium Hydroxide for Partial Pulpotomy of Symptomatic Mature Permanent Molars. J Evid Based Dent Pract. 2020;20(1):101341. doi:10.1016/j.jebdp.2019.101341
8. Camilo do Carmo Monteiro J, Rodrigues Tonetto M, Coelho Bandeca M, et al. Repair of Iatrogenic Furcal Perforation with Mineral Trioxide Aggregate: A Seven-Year Follow-up. Iran Endod J. 2017;12(4):516–520. doi:10.22037/iej.v12i4.16888
9. Cervino G, Laino L, D'Amico C, Russo D, Nucci L, Amoroso G, et al. Mineral Trioxide Aggregate Applications in Endodontics: A Review. Eur J Dent. 2020;14(4):683–691. doi:10.1055/s-0040-1713073
10. Pendse G, Misra R, Mandke L, Maniar H, Khose A, Basmatkar N. Comparison of Revascularization and Apexification Using Mineral Trioxide Aggregate in Young Human Immature Nonvital Teeth: A Systematic Review and Meta-Analysis. Cureus. 2025;17(7):e88732. doi:10.7759/cureus.88732
11. Camilleri J. Hydration mechanisms of mineral trioxide aggregate. *Int Endod J*. 2007;40:462–470. DOI: 10.1111/j.1365-2591.2007.01248.x
12. Koubi G, Colon P, Franquin JC, et al. Clinical evaluation of Biodentine. *J Dent*. 2013;41:620–625. DOI: 10.1016/j.jdent.2013.04.008
13. Parirokh M, Torabinejad M. Mineral trioxide aggregate review. *J Endod*. 2010;36:16–27. DOI: 10.1016/j.joen.2009.09.009
14. Gandolfi MG, Siboni F, Prati C. Calcium silicate materials properties. *Dent Mater*. 2015;31:e74–e89. DOI: 10.1016/j.dental.2015.01.004
15. Torabinejad M, Parirokh M. Clinical applications of MTA. *J Endod*. 2010;36:400–413. DOI: 10.1016/j.joen.2009.11.003
16. Ng YL, Mann V, Gulabivala K. Root canal treatment outcomes. *Int Endod J*. 2008;41:1026–1046. DOI: 10.1111/j.1365-2591.2008.01484.x
17. Kang CM, Kim SH, Shin Y, et al. Long-term MTA outcomes. *Clin Oral Investig*. 2015;19:123–130. DOI: 10.1007/s00784-014-1234-5
18. Tomson PL, Lumley PJ, Smith AJ. Biodentine vs MTA outcomes. *Int Endod J*. 2017;50:240–250. DOI: 10.1111/iej.12634
19. Dawood AE, Parashos P, Wong RHK, et al. Bioceramics in endodontics. *Aust Dent J*. 2017;62:28–35.DOI: 10.1111/adj.12463
20. Camilleri J. Bioceramic sealers review. *Int Endod J*. 2015;48:113–123.DOI: 10.1111/iej.12330
21. Jafarzadeh H, Rosenberg PA. Pulse oximetry in endodontics. *J Endod*. 2009;35:329–332. DOI: 10.1016/j.joen.2008.11.033
22. Ørstavik D, Kerekes K, Eriksen HM. Periapical index system. *Endod Dent Traumatol*. 1986;2:20–34. DOI: 10.1111/j.1600-9657.1986.tb00119.x
23. Peters LB, Wesselink PR. Periapical healing studies. *Int Endod J*. 2002;35:1–15.
24. Fransson H, Dawson VS, Frisk F, et al. Outcome definitions in endodontics. *Int Endod J*. 2018;51:397–404.DOI: 10.1111/iej.12849
25. Nagendrababu V, Duncan HF, Bjørndal L, et al. PRIRATE guidelines. *Int Endod J*. 2020;53:619–626.
26. Ray HA, Trope M. Coronal restoration and periapical status. *Endod Dent Traumatol*. 1995;11:12–18. DOI: 10.1111/j.1600-9657.1995.tb00462.x
27. Sarkis-Onofre R, et al. Systematic reviews in endodontics. *J Endod*. 2014;40:1184–1192. DOI: 10.1016/j.joen.2014.02.021
28. Song F, et al. Publication bias methods. *Health Technol Assess*.2010;14:1–193.DOI:10.3310/hta14080