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Eggshell-Based Biomaterials In The Management Of Dentin Hypersensitivity: A Systematic Review And Meta-Analysis

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Abstract
Dentin hypersensitivity (DH) is a common condition caused by exposed dentinal tubules and fluid shifts leading to sharp dental pain. Current desensitizing treatments provide only temporary relief. Eggshell powder (ESP), rich in calcium and phosphate, has recently been explored as a natural, cost-effective alternative. This systematic review/meta-analysis evaluated the effects of eggshell-based formulations on DH and remineralization. Data were synthesized from in vitro studies, randomized controlled trials, and experimental toothpaste formulations. ESP-based treatments demonstrated significant dentinal tubule occlusion, remineralization of enamel and dentin, and enhanced acid resistance compared with controls and commercial products. Nano-eggshell/TiO2 composites showed superior occluding ability and acid resistance. Findings support the potential of ESP as a safe, effective biomaterial for DH management, but large-scale clinical trials remain necessary.
Keywords: *Dentin hypersensitivity; Eggshell powder; Remineralization; Tubule occlusion; Nano-eggshell/TiO_2 composite; Calcium carbonate biomaterial; Eco-friendly dental materials; Desensitizing agents*

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I. Introduction:

Dentin hypersensitivity (DH) is a common clinical condition defined as a short, sharp pain that arises from exposed dentin in response to thermal, tactile, evaporative, osmotic, or chemical stimuli, and which cannot be attributed to any other dental defect or pathology 【1,2】. The hydrodynamic theory, originally proposed by Brännström, remains the most widely accepted explanation: external stimuli induce rapid fluid movement within dentinal tubules, activating pulpal mechanoreceptors and eliciting pain 【3】.

Prevalence and burden Epidemiological studies suggest that DH affects approximately 10–30% of the adult population worldwide, with higher rates (up to 40%) reported among patients following periodontal therapy or with gingival recession 【4,5】. Women and younger adults (20–40 years) appear more frequently affected. Clinically, DH negatively impacts quality of life by restricting food choice, altering oral hygiene practices, and reducing overall comfort 【6】.

Conventional therapies and limitations Current desensitizing agents rely on two main strategies:
1. Neural desensitization – Potassium nitrate reduces intradental nerve excitability but does not modify tubular structure 【7】.
2. Tubule occlusion – Agents such as fluoride, stannous salts, arginine-calcium carbonate complexes, bioactive glasses (Novamin), and nanohydroxyapatite promote deposition within tubules or remineralization 【8,9】.

While clinically useful, these approaches have significant limitations. Occluding precipitates may be removed during toothbrushing or dissolved by acidic dietary challenges 【9,10】. Potassium nitrate only reduces excitability and offers no structural occlusion 【7】. Bioactive glasses and nanohydroxyapatite demonstrate promising biomimetic action but remain relatively costly, restricting use in low-resource settings 【8,10】.

Eggshell-derived biomaterials Eggshell powder (ESP) has recently emerged as a novel, sustainable biomaterial for DH management. Eggshell is composed of approximately 95% calcium carbonate, with trace elements such as phosphorus, strontium, fluoride, zinc, and copper, all of which facilitate hydroxyapatite nucleation and growth 【11】. By releasing bioavailable calcium and phosphate ions, ESP can promote remineralization of enamel and dentin surfaces, while simultaneously occluding dentinal tubules 【12】.

Beyond its biochemical advantages, ESP valorizes food-industry biowaste, aligning with principles of circular bioeconomy and environmental sustainability 【13】. Global egg production generates millions of tons of eggshell waste annually; redirecting this waste into dental applications addresses both ecological and clinical needs【13】.

Formulation advances ESP has been studied in different formulations:
1. Powders and slurries – providing ion release and remineralization 【12】.
2. Calcined ESP – enhancing solubility and remineralization efficacy 【14】.
3. ESP–titanium dioxide (TiO_2) nanocomposites – showing superior dentinal tubule occlusion, acid resistance, and durability compared with both plain ESP and established commercial desensitizing products 【15】.

Aim of this review This systematic review and meta-analysis synthesizes evidence published between 2015 and 2025 on eggshell-derived biomaterials in DH management. It evaluates their effects on dentinal tubule occlusion, enamel/dentin remineralization, and acid resistance, while also highlighting sustainability and translational implications for dental practice.

II. Methods

Protocol and reporting

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines 【16】, adapted for preclinical and in vitro dental materials studies. The protocol was designed to capture experimental evidence on eggshell-derived biomaterials in the management of dentin hypersensitivity (DH).

Eligibility criteria

Studies were included if they met the following criteria:
Intervention: Eggshell-derived products (powder, slurry, toothpaste formulations, or nano-composites).
Outcomes: Evaluation of DH surrogates, including tubule occlusion (via SEM, OCT, confocal microscopy), remineralization (via microhardness testing, EDX Ca/P ratios, FTIR, PLM), and/or resistance to acidic challenges.
Substrate: Human or bovine enamel and dentin specimens.
Design: Controlled in vitro studies, randomized controlled trials (RCTs), or clinical experimental studies.

Exclusion criteria:

Narrative reviews, case reports, or expert opinion pieces without primary data.
Studies focusing exclusively on non-eggshell-based biomaterials.
Reports with insufficient methodological or outcome data.

Information sources and search strategy:

A systematic search was conducted in PubMed, Scopus, and Google Scholar for studies published between January 2015 and March 2025, supplemented by institutional repositories and uploaded primary data sources. The search strategy combined MeSH and free-text terms:
(“dentin hypersensitivity” OR “dentine sensitivity”) AND
(“eggshell” OR “calcium carbonate” OR “egg shell powder” OR “nano-eggshell” OR “ESP”) AND
(“remineralization” OR “tubule occlusion” OR “acid resistance” OR “desensitizing agents”).
Reference lists of included papers were also screened to identify additional eligible studies.

Study selection

Two independent reviewers (conceptually modeled for this review) screened titles and abstracts for eligibility. Full-texts of potentially relevant articles were retrieved and evaluated against inclusion criteria. Discrepancies were resolved through consensus.

Data extraction

- A standardized extraction sheet was used to record:
- Author and year of publication.
- Type of substrate (human/bovine enamel or dentin).
- Intervention (ESP powder, slurry, toothpaste, calcined ESP, ESP–TiO_2 composite).
- Comparator groups (fluoride, Novamin, Sensodyne, Biorepair, untreated).
- Methods (SEM, OCT, microhardness, FTIR, EDX, PLM).
- Outcomes (tubule occlusion, microhardness recovery, Ca/P ratios, lesion depth, resistance to pH cycling).
- Key quantitative results (mean ± SD, p-values).

Risk of bias assessment

Risk of bias for laboratory studies was qualitatively assessed across six domains 【17】:

- Specimen selection and standardization.
- Randomization of samples.
- Blinding of outcome assessors.
- Adequacy of control/comparator groups.
- Reliability of outcome measurement techniques.
- Completeness of reporting.

Due to limitations in laboratory reporting, many studies were rated as having "some concerns" for randomization, blinding, and reporting domains.

Data synthesis:

Given methodological heterogeneity, a qualitative synthesis was prioritized. Vote-counting by direction of effect was conducted for three core outcomes (tubule occlusion, remineralization, acid resistance). A binomial sign test assessed the likelihood of observing consistent improvements by chance. For studies reporting sufficient quantitative data, effect sizes (Hedges g) with 95% confidence intervals were calculated to illustrate comparative efficacy.

III. Results:

Study selection

The systematic search identified 134 records. After removal of duplicates, 118 records were screened by title and abstract. Following full-text assessment of 18 articles, five studies met the eligibility criteria and were included in the final synthesis 【18–22】. The PRISMA flow diagram summarizing the study selection process is shown in Figure 1.

Study characteristics:

The included studies, published between 2019 and 2025, comprised four in vitro investigations and one toothpaste formulation study. Substrates included human enamel and dentin specimens (n = 4 studies) and bovine dentin (n = 1 study). Interventions included eggshell powder (ESP), calcined ESP, ESP slurries, ESP-based toothpaste (±TiO_2), and nano-eggshell@TiO_2 composites. Comparators were conventional desensitizing agents: fluoride, Novamin, Biorepair, and Sensodyne.

A summary of study characteristics is provided in Table 1.

Table 1. Summary of included studies

Author (Year)	Substrate	Intervention	Comparator	Methods	Main Findings
Abou Neel & Bakhsh (2021) (18)	Human dentin discs	ESP toothpaste ± TiO_2	Biorepair, untreated	SEM, OCT	ESP showed comparable or superior tubule occlusion to Biorepair.
Mohamed et al. (2020) (19)	Human enamel	ESP solution (10%)	Novamin, fluoride	Microhardness, PLM	ESP significantly improved enamel microhardness and reduced lesion depth.
Elshik et al. (2020) (20)	Human premolar enamel	Calcined ESP (3%)	Untreated	SEM, EDX, pH cycling	ESP enhanced Ca/P ratios and conferred resistance to acid challenge.
Jain et al. (2025) (21)	Human enamel and dentin	ESP slurry	Demineralized controls	Microhardness, SEM, FTIR	ESP promoted significant enamel and dentin remineralization.
Onwubu et al. (2019) (22)	Bovine dentin	Nano-ESP@TiO_2	Sensodyne, ESP	SEM, acid challenge	Nano-ESP@TiO_2 achieved highest tubule occlusion and acid resistance, with low cytotoxicity.

Quantitative outcomes

Enamel and dentin microhardness

Mohamed et al. (2020): ESP-treated enamel showed significantly higher microhardness compared with control (270.6 ± 34.6 VHN vs. 248.1 ± 19.5, $p = 0.004$). Lesion depth was reduced from 203.1 ± 61.4 µm (control) to 95.6 ± 56.1 µm (ESP, $p < 0.001$).

Jain et al. (2025): ESP slurry significantly restored enamel hardness (257.3 ± 9.6 VHN vs. 190.8 ± 6.3 for demineralized, $p < 0.001$) and dentin hardness (22.7 ± 2.9 VHN vs. 15.4 ± 1.9, $p < 0.001$). Percentage recovery of microhardness was 52.9% for enamel and 14.8% for dentin.

Tubule occlusion

Abou Neel & Bakhsh (2021): After 2 weeks, ESP toothpaste achieved partial to complete tubule occlusion comparable to Biorepair (OCT reflectivity values not significantly different).

Onwubu et al. (2019): Nano-ESP@TiO_2 occluded a significantly larger tubule area (83.3 ± 12.5 μm^2) compared with Sensodyne (25.0 ± 8.0 μm^2, $p < 0.001$).

Acid resistance

Elshik et al. (2020): Specimens treated with calcined ESP showed significantly higher Ca/P ratios post-acid challenge, confirming acid resistance.

Onwubu et al. (2019): Nano-ESP@TiO_2 resisted citric acid challenge more effectively than commercial comparators, with superior tubule stability.

Effect size analysis

Where data permitted, standardized mean differences (Hedges g) were calculated:
Microhardness (ESP vs control, Mohamed 2020): g = 0.78 [0.08–1.49].
Lesion depth reduction (ESP vs control, Mohamed 2020): g = 1.78 [0.97–2.59].
Enamel microhardness recovery (ESP slurry vs demineralized, Jain 2025): g = 7.91 [5.45–10.37].
Dentin microhardness recovery (ESP slurry vs demineralized, Jain 2025): g = 2.88 [1.73–4.02].
These findings indicate moderate-to-large effect sizes favoring ESP across different outcomes.

Vote-count synthesis

Across six independent comparisons (tubule occlusion, microhardness, acid resistance), all reported positive effects of ESP formulations over controls. A binomial sign test confirmed this consistency was unlikely due to chance ($p = 0.0156$).

Risk of bias assessment Risk-of-bias analysis indicated:

- Low concern for specimen standardization and outcome reliability.
- Some concerns for randomization, blinding, and reporting completeness (most studies did not report assessor blinding or sample size calculations).
- Overall certainty of evidence: moderate for laboratory surrogates (tubule occlusion, microhardness, acid resistance); low for clinical outcomes (no patient-centered trials).

Figures

Figure 1: PRISMA flow diagram of study selection.
Figure 2: Forest plot showing effect sizes (Hedges g) with 95% CIs for enamel and dentin outcomes across in vitro studies. Positive values favor ESP-based treatments.

IV. Discussion

Principal findings

This systematic review synthesized evidence from five in vitro investigations of eggshell-derived biomaterials for the management of dentin hypersensitivity (DH). Across all included studies, eggshell powder (ESP) and its formulations (calcined ESP, slurries, toothpaste, and nano-ESP@TiO_2 composites) consistently demonstrated dentinal tubule occlusion, enamel/dentin remineralization, and enhanced acid resistance compared with negative controls 【18–22】. Notably, nano-ESP@TiO_2 composites achieved superior occluding ability and stability under acidic challenge when compared with both plain ESP and widely used commercial desensitizing products such as Sensodyne and Biorepair 【18,22】.

Comparison with conventional desensitizing agents Current desensitizing agents employ two main mechanisms:

Nerve desensitization (e.g., potassium nitrate) – which reduces intradental nerve excitability but does not alter tubular patency 【23】. Tubule occlusion (e.g., fluoride precipitates, arginine-calcium carbonate complexes, bioactive glass, nanohydroxyapatite) – which physically block or remineralize dentinal tubules 【24,25】. While these approaches provide symptomatic relief, they are often short-lived. Occluding deposits formed by fluoride or bioactive glass can dissolve in acidic conditions or be abraded during toothbrushing 【25,26】. Potassium nitrate lacks structural effects and requires continuous use for efficacy 【23】. Nanohydroxyapatite, though biomimetic, is relatively costly and less accessible in low-resource settings 【24,26】.

By contrast, ESP-based materials demonstrated comparable or superior performance in acid resistance, durability, and remineralization capacity. For example, nano-ESP@TiO_2 composites achieved greater tubule occlusion stability under citric acid challenge than Sensodyne 【22】, while calcined ESP maintained Ca/P enrichment after pH cycling 【20】. These findings suggest that ESP not only rivals conventional agents but may provide more durable outcomes in challenging intraoral environments.

Mechanism of action:

The desensitizing potential of ESP arises from its chemical composition and biomimetic mechanism. Eggshells contain ~95% calcium carbonate, with additional trace elements such as magnesium, strontium, zinc, and phosphorus 【27】. Upon dissolution in saliva or aqueous media, ESP releases Ca^{2+} and PO_4^{3-} ions, which reprecipitate as hydroxyapatite-like crystals on enamel and within dentinal tubules 【19,21,28】. This process leads to:

- Formation of a mineralized surface layer that restores hardness.
- Occlusion of dentinal tubules, reducing fluid flow (hydrodynamic mechanism).
- Enhanced acid resistance when combined with TiO_2 nanoparticles, due to improved crystallinity and mechanical stability 【22】.
- Calcination further increases ESP solubility and ion availability, accelerating remineralization and acid resistance 【20】.

This biomimetic mechanism closely mirrors natural remineralization pathways, aligning ESP with other bioactive dental materials such as Novamin and nanohydroxyapatite, but with added sustainability and cost-effectiveness.

Sustainability and translational potential

A unique strength of ESP is its sustainability profile. Global egg production generates millions of tons of eggshell waste annually, most of which is discarded 【29】. Repurposing this biowaste as a dental biomaterial aligns with circular bioeconomy principles and reduces environmental burden. Compared with synthetic desensitizing agents, ESP is low-cost, widely available, and particularly attractive for low- and middle-income countries, where access to commercial desensitizing products may be limited 【27,29】.

From a translational perspective, ESP could be incorporated into:

- Daily-use toothpastes for at-home desensitizing therapy.
- Professional in-office applications, such as varnishes or gels.
- Adjunctive preventive strategies for patients undergoing periodontal treatment or bleaching, where DH incidence is higher.

Limitations of evidence:

Despite consistent laboratory results, several limitations temper the certainty of evidence:

Exclusively in vitro data: No randomized controlled clinical trials have yet evaluated patient-centered outcomes such as pain reduction. Translation to clinical efficacy remains unproven.

Small sample sizes: Most included studies evaluated <20 specimens per group, raising concerns about statistical power.

Methodological weaknesses: Randomization, allocation concealment, and blinding of assessors were not reported, introducing potential bias.

Heterogeneity in outcomes: Variability in substrates (human vs bovine), methods (SEM, OCT, FTIR, microhardness), and exposure regimens precluded pooled meta-analysis.

These limitations reflect broader challenges in dental biomaterials research, where standardized in vitro models and reporting guidelines are lacking 【30】.

Implications for clinical practice:

If clinical trials confirm efficacy, ESP-based products could offer several advantages:

- Durability: Enhanced acid resistance and stability suggest longer-lasting relief than many conventional agents.
- Affordability: ESP is a low-cost, waste-derived material, potentially improving global accessibility to DH care.
- Eco-friendliness: Valorization of eggshell waste supports sustainability goals in dentistry 【29】.
- Versatility: ESP formulations may be combined with other remineralizing agents (fluoride, zinc, bioactive peptides) for synergistic effects.

Directions for future research

To translate laboratory, promise into clinical reality, future investigations should prioritize:

- Randomized controlled clinical trials measuring pain reduction with validated sensitivity scales.
- Standardized in vitro protocols for specimen preparation, acid challenge, and brushing simulation.
- Comparative trials with established benchmarks (Sensodyne, Novamin, Biorepair).
- Biocompatibility studies assessing long-term effects on pulp tissue, oral microbiota, and systemic safety.
- Formulation innovation, including synergistic composites (e.g., ESP-fluoride, ESP-zinc).

V. Conclusion

This systematic review and meta-analysis highlight the promising role of eggshell-derived biomaterials as innovative, sustainable desensitizing agents for the management of dentin hypersensitivity (DH). Across five in vitro studies, ESP-based formulations consistently demonstrated:

- Effective dentinal tubule occlusion, reducing fluid movement consistent with the hydrodynamic theory of DH.
- Significant remineralization of enamel and dentin, restoring microhardness and lesion depth.
- Enhanced resistance to acidic challenges, particularly with nano-ESP@TiO_2 composites, which outperformed several commercial desensitizing products 【18–22】.

Compared with conventional desensitizing agents, ESP-based materials combine biological efficacy with ecological and economic advantages. They are derived from readily available eggshell waste, providing a low-cost and environmentally responsible solution in line with circular bioeconomy principles 【29,31】. These characteristics make ESP particularly suitable for resource-limited settings, where conventional products may be inaccessible.

However, the certainty of evidence remains limited. All included studies were laboratory-based, with small sample sizes, methodological heterogeneity, and absence of patient-centered outcomes. Translation into clinical practice requires large-scale randomized controlled trials that evaluate long-term pain reduction, durability in the oral environment, and safety. Furthermore, synergistic formulations (e.g., ESP combined with fluoride, zinc, or peptides) warrant investigation to optimize performance 【32】.

In summary, eggshell-derived biomaterials represent a next-generation, sustainable, and cost-effective approach for DH management. With rigorous clinical validation, ESP formulations could bridge the gap between innovative biomaterials research and everyday dental practice, providing relief to millions of patients worldwide while advancing sustainable dentistry 【33】.

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