International Journal of Pharmaceutical research and Applications
Volume 11, Issue 3, May-June 2026, pp:71-78 www.ijprajournal.com ISSN: 2456-4494

Reviving Enamel: A Comprehensive Review on Tooth Remineralization

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Date of Submission: 23-04-2026 Date of Acceptance: 03-05-2026

Abstract
Tooth remineralization plays a significant role in protecting and managing early stages of dental caries by restoring minerals lost from the enamel. This review focuses the potential of chemical dentifrice formulations along with coconut derived products in promoting enamel remineralization under simulated oral conditions. Demineralization happens when calcium and phosphate ions are lost from the enamel, causesformation of white spot lesions and reduction in its hardness; however, this process can be reversed by using suitable remineralizing agents.
Various formulations, including calcium-based systems and coconut-derived compounds such as coconut milk, studied using in vitro models. The experimental procedures involved forming artificial enamel lesions, carrying out pH cycling to simulate oral conditions, and applying toothpaste slurries. The effectiveness of these treatments tested using techniques such as surface microhardness testing, contact angle measurement, mineral content analysis, and microscopic examination. This review explained that remineralization significantly enhnaced both enamel hardness and mineral content than demineralized samples. Coconut milk showed better contact with the enamel surface. Calcium-based biomimetic materials also showed strong potential due to their similarity to natural hydroxyapatite.We had reviewed various research and review articles in different platforms like Research gate, Pubmed, Elsevier, Scopus and Science direct.

Key words: Tooth remineralization, Coconut derived products, Hydroxyapatite, Dental caries, Enamel microhardness, pH cycling, Lyophilized coconut extract, Coconut milk, Calcium-phosphate systems, Dentifrice formulations.

Abbreviations

1. HA – Hydroxyapatite
2. ACP – Amorphous Calcium Phosphate
3. CPP-ACP – Casein Phosphopeptide–Amorphous Calcium Phosphate
4. APF – Acidulated Phosphate Fluoride
5. RCT – Randomized Controlled Trial
6. MTT – 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide assay
7. WSLs – White Spot Lesions
8. ANOVA – Analysis of Variance
9. SPSS – Statistical Package for the Social Sciences
10. SD – Standard Deviation
11. pH – Potential of Hydrogen
12. HV – Vickers Hardness Value
13. µL – Microlitre
14. kg/cm^2 – Kilograms per square centimeter

I. Introduction :

The concept of tooth remineralization has become primary focus in preventing the dental problems, as it offers a non progressive approach to managing early stages of dental caries. Tooth enamel is mostly made up of hydroxyapatite crystals, and its mineral content is highly influenced by daily changes in the oral environment. When acids produced by oral bacteria or acidic foods reduces the pH in the mouth, minerals like calcium and phosphate are lost from the enamel a process known as demineralization. If this continues, it can leads formation of early carious lesions. However, this damage is not always permanent. Under suitable conditions, lost minerals can be restored into the enamel structure through remineralisation, helping restore its strength and resistance.[1]Saliva plays a crucial natural role in this repair process by offer minerals and buffering acids. Building on this natural defence, recent research has focused on enhancing remineralization using therapeutic agents and specially formulated dental formulations.[2] Fluoride has long been considered as most beneficial agent, as it strengthens enamel by forming acid resistant crystals. In addition to other materials such as casein phosphopeptide amorphous calcium phosphate (CPP ACP), calcium-phosphate systems, preparations, coconutderived products, and advanced tooth creams have been examined. These methods aim to supply bioavailable minerals or create conditions that improve mineral redeposit ion on the tooth surface.[3]

Studies also stated that remineralizing agents can help prevent or reverse prior enamel changes, including white spot lesions generally seen during orthodontic treatment. This highlights how modern dentistry is moving towardsmore patient friendly approach that focuses on prevention and conservation. Instead of immediately going for fillings or other painful invasive treatments, the priority is now to protect and restore the natural tooth structure whenever it is possible.Variousexperimental works has further explored natural and bioactive alternatives, representing promising results, although their effectiveness based on formulation design, mineral availability, and clinical conditions.[4]

All inclusive remineralization represents a modern preventive strategy centred on restoring the natural mineral balance of teeth other than removing damaged tissue. This notion continues to guide the improvement of innovative dentifrice formulations and therapeutic oral-care products, strengthen its importance in both clinical practice and research.[5]

II. Materials:

Table-2.1: Commonly used materials for development of dental formulation.[6]

1. Calcium carbonate
2. Dicalcium phosphate
3. Sodium lauryl sulphate (SLS)
4. Glycerine
5. Methyl paraben
6. Propyl paraben
7. Water
8. Carboxy methyl cellulose
9. Peppermint oil
10. Coconut extract
11. Sorbitol

III. Method of Preparation

3.1 Preparation of Dentifrice Formulations

Tooth cream formulations prepared using a simple mixing and homogenization process to ensure that all ingredients mixed thoroughly. At the starting, powdered ingredients such as abrasives and ingredients accurately weighed and passed through a sieve to obtain uniform particle size. The thickening agent or binder initially dispersed in purified water or mixed with humectants like glycerin or sorbitol to form a uniform base. After the base prepared, abrasive materials incorporated slowly while stirring continuously to prevent the formation of lumps. Surfactants, preservatives, and sweetening agents then added one after another to enhance foaming and product stability. Flavoring agents incorporated at the final stage to prevent loss of their volatile components. The mixture mixed properly until a smooth and uniform paste obtained and then transferred into suitable containers for further evaluation.[7]

3.2 Formulation of Toothpaste or Tooth Cream Base by Wet Dispersion

To prepare the toothpaste gel, gel-forming agents like cellulose derivatives initially dispersed in purified water with continuous stirring to ensure appropriate hydration. After complete dispersion, humectants added to retain moisture and improves the consistency of the preparation. Abrasives and active ingredients then added slowly into the base with constant mixing to obtain uniform distribution. Surfactantsdissolved separately in water and incorporated carefully to the mixture to decrease excessive foaming during formulation. The pH of the formulation adjusted when required; moreover the mixturehomogenized to get the suitable viscosity. Finally, the prepared base transferred into containers for stability and evaluation.[7]

3.3 Laboratory Formulation of Experimental Remineralizing Tooth Creams

Remineralizing tooth creamsare formulated in the laboratory to assess their biological effectiveness, a semisolid base with aqueous ingredients and stabilizing agentsformulated. Measured quantities of remineralizing agentsthen added into this base while mixing gradually to ensure proper distribution. Mixing continued until the formulation attained a smooth and uniform consistency.[8]The prepared samples then exposed to standardization tests like viscosity and stability testing before being used for biological studies.

3.4 Preparation of Natural Coconut-Derived Treatment Samples

In studies involving natural remineralizing substances, coconut-derived materials like pure coconut oil, coconut extract, and coconut water are used. When necessary, these samples filtered to remove impurities and get clear solutions. Based on the experimental design, the prepared sampleseither used directly or diluted to specific concentrations before administration on enamel specimens.[9]

3.5 Preparation of Activated Carbon from Corn Cob by Chemical Activation

Corn cobs selected as the raw material and initially unsoiled to remove dust and impurities. The unsoiled material dried and compressed into smaller particles to gain uniform precursor. This material then exposed to a chemical activating agent. The treated biomass exposed to high temperature carbonization under suitable conditions to get activated carbon. After the carbonization method, the materialcleaned many times to remove unwanted chemical residues and then dried appropriately beforefurther characterization and can be used in the formulations.[10]

3.6 Preparation of Artificial Demineralized Enamel Lesions

Artificial enamel lesionsprepared to reproduce the initial stages of dental caries for experimental studies. Extracted teeth or enamel blocks first cleaned cautiously to remove debris and remaining soft tissues. The enamel surfaces polished using graded abrasive papers to get a smooth and uniform surface. They then soaked in a demineralizing solution for a specified duration to produce mineral loss similar to early enamel demineralization. After this treatment, the samples were cleaned again and stored properly until subsequent experimentation.[11]

3.7 Preparation of Toothpaste Slurry for Treatment Application

For in vitro experiments, toothpaste samples converted into slurry form to obtain uniform interaction with enamel specimens. A standard quantity of toothpaste measured and mixed with distilled water or artificial saliva in a pre established ratio. The mixture stirred continuously until a uniform suspension obtained. This slurry permits the active ingredients and abrasives to be evenly distributed and provided consistent treatment conditions during experimental procedures like pH cycling.[9]

3.8 Preparation and Processing of Components

The components used in dentifrice preparations processed before being addedinto the formulation. The plant materials first washed to remove dirt and unwanted impurities. Then, it was then dried to remove excess moisture. After drying, the materials crushed into fine powder for proper mixing in the toothpaste formulation. In some conditions, extracts also formulated and standardized to maintain consistency in the active constituents. These processed ingredients then added into the dentifrice base.[3]

3.9 Post-Preparation Stability Conditioning and Evaluation

After the formulations prepared, stability studies carried out to test their suitability for storage and use. The samples stored under suitable environmental conditions for certain duration of time. During this period, the formulations frequently observed for any alterations in appearance, texture, colour, or phase separation.[7]

3.10 pH Cycling Simulation Method

The pH cycling model implemented to simulate the natural oral environment where teeth undergo constant cycles of demineralization and remineralization. In this process, enamel specimensalternately subjected to acidic demineralizing solutions and demineralizing solutions containing required mineral ions. These cyclesreplicated for many days in order to simulate the daily conditions of the oral cavity. Between each step, the specimens cleaned with distilled water to remove any unwanted solution.[12]

IV. Evaluation Parameters

4.1 Evaluation of Dentifrice Formulations

The prepared toothpaste preparations are tested using several physicochemical and performance tests to check their quality, stability, and suitability for oral use. The pH of the formulations measured using a calibrated digital pH meter and we say can that it is safe for oral tissues and compatible with ingredients. Viscosity is measured using viscometric methods to study the flow of the toothpaste and to validate that the formulation can be easily drawn from the container. Spreadability of the formulation analysed to understand how easily the toothpaste spreads on tooth surfaces while brushing. Foaming abilityis tested by shaking toothpaste suspensions and noting the foam produced. Abrasiveness and cleaning ability was determined by simulated brushing studies. [13]

4.2 Evaluation of Toothpaste or Tooth Cream Base Prepared by Wet Dispersion

Toothpaste bases prepared using the wet dispersion method is tested to ensure uniformity and stability of the formulation. Homogeneity of the base observed visually and by touch to validate that all ingredients are evenly spread. The consistency and texture of the formulation also tested to establish that the base had proper handling properties and a smooth feel. The ability of the formulation to maintain moisture examined during storage. Periodic pH checkingperformed to get chemical stability. [7]

4.3 Evaluation of Experimental Remineralizing Tooth Creams

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Experimental remineralizing tooth creams evaluated to verify both their safety and efficacy. Cytocompatibility studies carried out to observe the response of cells when the formulation is applied. Enamel samples treated with the formulations examined to determine the extent of mineral restoration. Microscopic analysis used to observe any changes on the surface of the enamelMicro hardness testing performed before and after treatment to measure any increase in enamel strength.[5]

4.4 Evaluation of Coconut-Derived Remineralization Samples

Coconut derived samples used in the study analyzed to determine their ability to restore remineralization of enamel. Analytical methods used to check mineral restoration in demineralized enamel samples. Hardness of the surface is tested to measure improvements in enamel strength. Comparative studies also performed to examine the effectiveness of different coconut derived formulations. Microscopic observation of enamel surfaces helped identify structural changes or mineral deposition.[14]

4.5 Evaluation of Activated Carbon Prepared from Corn Cob

physical and functional properties of activated carbon prepared from corncobis evaluated to determine its Surface area analysis performed to understand the adsorption capacity of the material. The pore structure also studied to determine the availability of active sites for adsorption. Moisture content and ash contentdetermined to evaluate purity and structural stability of the material.[11,12]

4.6 Evaluation of Artificial Demineralized Enamel Lesions

After the preparation of artificial enamel lesions, evaluation carried out to know the extent of demineralization. Surface micro hardness testing used to measure the reduction in enamel strength. Scanning electron microscopy used to observe structural changes on the enamel surface. Additional analyses performed to determine the loss of minerals such as calcium and phosphate from the enamel. The depth of the lesion measured.[15]

4.7 Evaluation of the pH Cycling Simulation Method

The pH cycling method used in the study evaluated to ensure that it simulated the conditions of the oral environment. Micro hardness measurements taken after the cycling process to assess the extent of enamel remineralization. Mineral uptake studies also performed to determine the restoration of calcium and phosphate ions in the enamel. Microscopic examination of enamel surfaces helped identify structural improvements after treatment.[16]

4.8 Evaluation of Toothpaste Slurry Preparation and Application08

Toothpaste slurries prepared for experimental treatment evaluated to check consistency and reliability during testing. Homogeneity of the slurrymeasured to confirm uniform distribution of toothpaste particles. The pH of the slurry also measured to ensure that it suitable for experimental use. Viscosity and flow properties of the slurryanalyzed. Abrasiveness testing performed. The remineralization effect of the slurryevaluated by measuring mineral recovery or improvement in enamel hardness.[17]

4.9 Evaluation of Processed Components

The materials used in the dentifrice formulations to ensure their quality and consistency. Organoleptic characteristics such as colour, odor, and texture observed. Particle size analysis performed to analyze proper dispersion of powders. Phytochemical screening carried out to identify the presence of active constituents. Moisture content also determined. Compatibility studies done to ensure that the materials did not interact negatively with other formulation ingredients.[18]

4.10 Evaluation of Stability Conditioning

Stability studies provides information whether the formulations retained their quality during storage. Physical observationsdone to detect any changes in appearance, texture, or phase separation. The pH of the formulations monitored periodically. Viscosity measurements also taken over time. Microbial testingperformed to ensure that the preservative system was effective. Accelerated stability studies done at various temperatures to ensure the shelf life of the formulation.[18]

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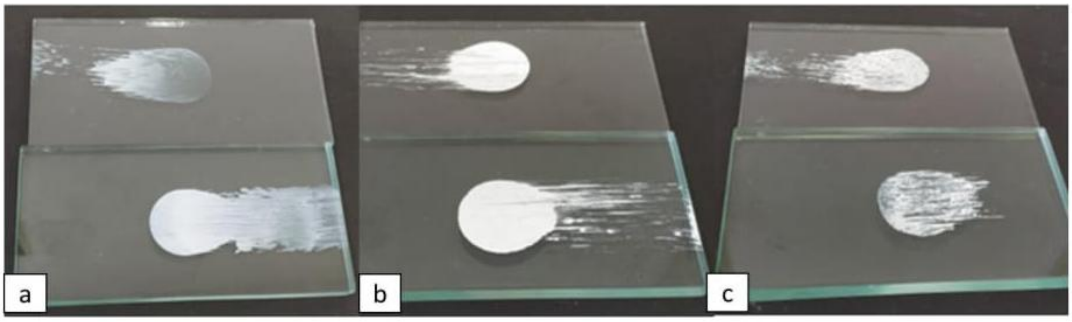

Fig 1: Spreadability testing: a Control, b.Coconut milk tooth paste, and C Lyophilized coconut toothpaste. [19]

4.11 Surface Microhardness Test:
The enamel surface microhardness evaluated using a Vickers Microhardness Tester.A diamond indenter applied with a load of HV 0.3 (2.942 Newtons) for 20 seconds.Indentations observed under 40X magnification, and hardness values recorded in kg/cm². This test assesses the degree of remineralization by measuring the increase in enamel hardness after treatment.[20]

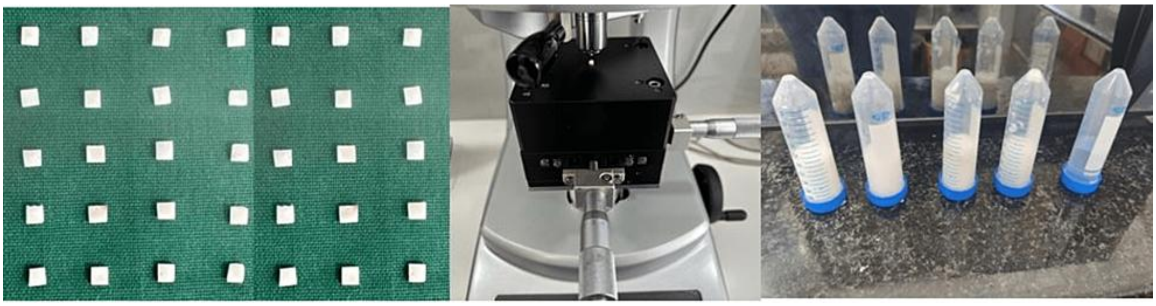

Fig 2:Tooth slab preparation measuring 3*3*1.5 (left), microhardness value assessed using a Vickers Microhardness tester (middle), and sample preparation for remineralization (right).[21]

4.12 Contact Angle Measurement (Wettability Test):
Contact angle measured using a Goniometer by the sessile drop method. A 5 µL water droplet placed on the sample surface at five different points. The average contact angle in degrees is recorded. This test evaluates surface wettability, indicating hydrophilic or hydrophobic nature, which influences remineralization.[20]

V. Statistical Analysis:

Statistical analysis done evaluate the remineralization potential of thedentifrices and coconut-derived samples on tooth enamel. All experimental procedures, including surface microhardness testing, mineral content analysis, and physicochemical evaluation performed three times to ensure reliability of the results. The data obtained presented as mean ± standard deviation (SD).[22]

To compare the effectiveness of different formulations and testgroups, one-way analysis of variance (ANOVA) used. When significant difference can be identified, post hoc tests conducted to determine specific group differences. A p-value of less than 0.05 ($p < 0.05$) considered statistically significant. This study helped in understanding the effectiveness of every formulation in enhancing remineralization of tooth enamel under simulated pH cycling conditions.Fluoride has high efficiency in the prevention of dental caries, however its ability to reduce white spot lesions (WSLs) is limited, as its action is mainly restricted to the enamel surface.[23]All experimental values (before treatment, after demineralization, and after remineralization). Statistical analysis for microhardness and contact angle test carried out using SPSS software (Version 26.0). Descriptive statistics such as mean and standard deviation used to summarize the data. One-way ANOVA applied to determine the statistical significance betweengroups and post-hoc Tukey test used for multiple group comparisons. A p value less than 0.05 considered statistically significant.[20]

Fig 3: Presence of initial white spot lesions post removal of brackets after completion of orthodontic treatment

VI. Result:

All studies uniformly showed that demineralization significantly reduces mineral content (calcium/phosphate) and enamel hardness, while remineralization leads to a significant improvement in these values [24]

In the coconut-based study:Higher concentrations (2:1) of both coconut milk and lyophilized extract produced greater microhardness values (~322–324 kg/cm²) than the lower concentrations [27]Coconut milk (2:1) showed higher contact angle, while lyophilized extract (2:1) showed lower contact angle, shows different surface interactions.All treatment groups indicatesmore calcium content after remineralization. 20% concentration showed maximum remineralization effect.[24]Evaluation techniques:Micro hardness testing and micro radiographyeffectively identified mineral gain after remineralization[25]

VII. Discussion:

The results concluded that remineralization is concentration-dependent:[26]Higher concentrations of remineralizing agents (coconut extract, calcium compounds) supply more ion availability, leading to better enamel repair.

Coconut based agents:[27]Their effectiveness is due to high calcium, phosphate, and mineral content, which improves enamel repair.Lyophilized extract shows enhance penetration, while coconut milk provides greater surface interaction.

Calcium-based systems (coral calcium, HA, ACP):Theseact as biomimetic materials,attentively resembling natural hydroxyapatite, enabling effective enamel restoration.Optimal concentration (around 20%) is necessary, too low is ineffective, too high may not enhance results further.

Role of remineralization mechanisms:According to modern concepts, calcium + phosphate + fluoride synergy is required for effective enamel repair.Saliva alone provides slow remineralization, hence external agents enhance the process substantially (new approaches to enhance remineralization)[24]

VIII. Conclusion:

All studies detected that remineralization substantially restores enamel structure after demineralization.Higher concentrations of remineralizing agents (coconut extracts, calcium-based materials) show greater efficacy.Coconut-derived products are encouraging natural alternatives for enamel remineralization due to their mineral rich composition.[27]Calcium-based biomimetic materials (e.g., coral calcium, hydroxyapatite) are highly effective in improving mineral deposition.[24]

Effective remineralization depends on appropriate calcium and phosphate availability. Suitable formulation and concentration. Use of sophisticated delivery systems. Overall, remineralization is a non-invasive and efficient strategy for early caries management and enamel repair.

Acknowledgement:
We sincerely thank Dr. M. Ramaiah, Principal of Maharajah's College of Pharmacy, for his encouragement.We also express our heartfelt gratitude to Mr. L. Krishna Raju, guide, for his guidance, support in completion of review article.

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