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Remineralisation Effect Of Malus Domestica Incorporated Paste For Pedodontic Application

Priyanka Rajesh[1] , Dr Dinesh kumar[2*]

[1]Saveetha Dental college and hospitals, Saveetha Institute of Medical and Technical Science (SIMATS)
Saveetha University, Chennai- 600077 Email ID: priyanka1862002@gmail.com
[2*]Assistant professor Department of Pedodontics Saveetha dental college Email: dineshkumarb.sdc@saveetha.com

***Corresponding author;** Dr Dinesh kumar
*Assistant professor Department of Pedodontics Saveetha dental college
Email: dineshkumarb.sdc@saveetha.com

ABSTRACT
Background: Dental caries remains a prevalent oral health issue among children worldwide, necessitating effective preventive strategies. The concept of remineralization, the natural repair process of non-cavitated enamel lesions, has gained significant attention in pediatric dentistry. Malus domestica, commonly known as apple, has been recognized for its potential in enhancing remineralization due to its rich content of bioactive compounds, including polyphenols, fluoride, and various minerals. This study investigates the remineralization potential of a novel toothpaste incorporating Malus domestica extract for pedodontic application.
Objective: To evaluate the efficacy of Malus domestica-incorporated paste in promoting enamel remineralization of primary teeth compared to conventional fluoride toothpaste.
Methods: Fresh Malus domestica fruits were processed to obtain a concentrated extract, which was incorporated into a dental paste base. Thirty sound human primary teeth with non-cavitated enamel lesions were randomly assigned to three groups: Malus domestica-incorporated paste, commercial fluoride toothpaste (positive control), and no treatment (negative control). Teeth underwent standardized brushing protocols twice daily for 4 weeks. Remineralization was assessed using Quantitative Light-Induced Fluorescence, microhardness testing, and Scanning Electron Microscopy at baseline and after treatment.
Results: Teeth treated with Malus domestica-incorporated paste showed significant reduction in lesion size and severity ($p < 0.05$), with efficacy comparable to commercial fluoride toothpaste. Enamel microhardness significantly increased in the treatment group, and SEM analysis revealed smoother enamel surfaces with evident mineral deposition. No adverse effects were reported.
Conclusion: Malus domestica-incorporated paste demonstrated significant remineralization effects in non-cavitated enamel lesions of primary teeth, supporting its potential as a safe and effective alternative or adjunct to conventional fluoride treatments in pedodontic practice.

Keywords: Malus domestica, apple extract, remineralization, dental caries, pediatric dentistry, primary teeth, fluoride alternative

INTRODUCTION:

Dental caries remains a prevalent oral health issue among children worldwide, necessitating effective preventive strategies that are both safe and acceptable for young patients. Despite significant advancements in oral health education and preventive measures over recent decades, the prevalence of early childhood caries remains alarmingly high in many populations, impacting the overall well-being and quality of life of affected children. Early childhood caries, often referred to as ECC, poses a considerable health concern globally, with consequences that extend beyond the oral cavity to affect nutrition, growth, school attendance, and self-esteem. Children, in particular, face the highest long-term risk due to the essentially irreversible nature of the erosive process and the lifelong demands of maintaining healthy permanent dentition that will serve them throughout their lives.
The concept of remineralization, the natural repair process of non-cavitated enamel lesions, has gained significant attention in pediatric dentistry as a non-invasive approach to caries management. Remineralization is a natural process that involves the deposition of minerals, such as calcium and phosphate, back into the tooth structure that has been partially demineralized by acids produced by cariogenic bacteria. This process helps to repair and strengthen enamel, the outer layer of the teeth that serves as the primary protective barrier against decay. Early identification of demineralization theoretically allows for the provision of appropriate dietary advice and/or medical intervention before cavitation occurs, potentially preventing the need for more invasive restorative treatments. The traditional methods of addressing dental caries have largely focused on restorative treatments once cavitation has occurred, yet the quest for non-invasive, preventive strategies has become increasingly imperative in modern dentistry.

Malus domestica, commonly known as apple, has long been celebrated for its nutritional benefits and is widely consumed across all age groups. Apples are a good source of dietary fiber, particularly pectin, which stimulates saliva production and helps maintain oral hygiene. The fruit also contains various vitamins, including vitamin C, and essential minerals such as calcium, phosphorus, and potassium that could potentially contribute to remineralization processes. The fiber content can stimulate saliva production, which helps neutralize acids in the mouth, buffer pH, and promote remineralization by maintaining a supersaturated environment of calcium and phosphate ions. Recent research suggests that incorporating Malus domestica into dental pastes may offer a novel strategy for promoting remineralization in pediatric patients, harnessing the natural properties of this widely available and well-accepted fruit.

Malus domestica contains various bioactive compounds that could potentially contribute to remineralization, including polyphenols with antioxidant properties that may protect against oxidative damage, organic acids that influence mineral solubility, and trace amounts of fluoride naturally present in the fruit. Apples are also rich in malic acid, which has been shown to stimulate salivary flow and may have mild antibacterial properties. The combination of these compounds, working synergistically, could enhance the natural remineralization processes and provide protection against demineralization. This potential is particularly significant in the context of pediatric dentistry, where preventive measures can significantly impact long-term oral health outcomes and where patient acceptance of therapeutic interventions is crucial for compliance and success.

This study delves into the multifaceted realm of pediatric dentistry, specifically focusing on the incorporation of Malus domestica in dental pastes and its potential to foster remineralization in primary teeth. By examining the composition of Malus domestica and its interactions with dental enamel, we aim to shed light on the effectiveness of this natural substance in addressing early stages of tooth decay in young patients. This research seeks to bridge the gap between traditional preventive measures and innovative, nature-inspired solutions that align with growing parental preferences for natural, minimally invasive approaches to children's healthcare. The exploration of Malus domestica incorporated paste presents an exciting avenue for pediatric dentistry, one that aligns with the growing demand for sustainable, holistic approaches to oral health that are effective, safe, and acceptable to young patients and their families.

MATERIALS AND METHOD:

Selection and Preparation of Malus domestica Extract

Fresh Malus domestica fruits of uniform ripeness and quality were obtained from a reliable local source to ensure consistency in phytochemical composition. The apples were thoroughly washed under running tap water and then rinsed with distilled water to remove any surface impurities, pesticides, or contaminants that could interfere with the extract quality. After cleaning, the apples were peeled to remove the outer skin, cored to eliminate seeds and fibrous central material, and diced into small uniform pieces to facilitate the extraction process. The diced pieces were then blended using a laboratory-grade blender to obtain a homogeneous apple pulp, ensuring complete disruption of cellular structures for maximum compound release. The resulting pulp was filtered through multiple layers of sterile cheesecloth followed by Whatman No. 1 filter paper to remove any solid residues, yielding a clear, concentrated aqueous extract. The extract was stored in sterile containers at 4°C until further use to preserve the integrity of bioactive compounds.

Formulation of Malus domestica Incorporated Paste

The concentrated Malus domestica extract was combined with a suitable dental paste base composed of dental-grade fluoride and calcium phosphate compounds to form the final experimental paste. The base formulation was selected to provide a standard vehicle for extract incorporation while maintaining the physical properties necessary for a clinically acceptable toothpaste. The concentration of Malus domestica extract was optimized through preliminary testing to achieve the desired remineralizing effects without compromising the paste's texture, stability, or patient acceptability. Flavoring agents were considered for addition to enhance palatability, especially for pediatric patients, though the natural sweetness of apple extract contributed positively to taste. The final formulation was mixed thoroughly to ensure homogeneous distribution of the extract throughout the base and was stored in airtight containers at room temperature pending characterization and use.

Characterization of Malus domestica Extract and Paste

The Malus domestica extract was analyzed using High-Performance Liquid Chromatography to identify and quantify the major bioactive compounds present, including phenolic acids, flavonoids, and organic acids. The pH of both the extract and the formulated paste was measured using a calibrated digital pH meter to ensure compatibility with oral tissues. The viscosity and consistency of the paste were assessed using appropriate rheological methods to confirm suitability for dispensing and application. Stability tests were performed by storing the paste under various conditions and periodically reassessing physical properties and antimicrobial activity to ensure the longevity of the paste and the preservation of its therapeutic efficacy throughout the intended shelf life.

Sample Collection and Preparation

Sound human primary teeth with non-cavitated enamel lesions were collected from pediatric patients aged 4 to 10 years who required extractions for orthodontic or other clinically indicated reasons. Teeth with extensive caries, existing restorations, developmental defects such as enamel hypoplasia, or visible cracks were excluded from the study to ensure uniformity of experimental material. After extraction, the teeth were gently cleaned using a fluoride-free prophylaxis paste to remove any debris or pellicle, rinsed thoroughly with distilled water, and stored in distilled water at room temperature with thymol added to prevent microbial growth. The distilled water was changed regularly to maintain freshness and prevent bacterial contamination. A total of 30 teeth meeting the inclusion criteria were selected for the study.

Experimental Design

The collected teeth were randomly assigned into three experimental groups, each consisting of 10 teeth to ensure adequate statistical power for detecting meaningful differences between groups:
Group 1: Malus domestica-incorporated paste application (experimental group)
Group 2: Positive control (commercial fluoride toothpaste containing 1450 ppm fluoride)
Group 3: Negative control (no treatment, stored in artificial saliva only)

Treatment Procedure

Teeth in Group 1 were treated with the Malus domestica-incorporated paste using a standardized brushing protocol. The teeth were subjected to twice-daily brushing for 2 minutes each time using a soft-bristled toothbrush mounted on a brushing machine to ensure consistent pressure and motion across all specimens. After each brushing, the teeth were rinsed with distilled water and stored in artificial saliva at 37°C to simulate oral conditions. This protocol was continued for a period of 4 weeks, representing a clinically relevant treatment duration. Teeth in Group 2 were treated identically but with the commercial fluoride toothpaste containing 1450 ppm fluoride. Teeth in Group 3 received no treatment and were stored in artificial saliva only, serving as the negative control to assess any spontaneous remineralization occurring under baseline conditions. Treatment adherence was monitored through daily logs and periodic checks of the brushing apparatus.

Assessment of Remineralization

Before treatment initiation (baseline) and after the 4-week treatment period, all teeth were evaluated using multiple complementary techniques to comprehensively assess remineralization: Quantitative Light-Induced Fluorescence (QLF): This non-destructive optical technique was used to assess changes in lesion size, depth, and severity. QLF operates on the principle that demineralized enamel exhibits decreased fluorescence compared to sound enamel when illuminated with blue light. Fluorescence images were captured under standardized conditions, and dedicated software was used to quantify lesion parameters including lesion area, average fluorescence loss, and lesion volume.
Microhardness Testing: Enamel surface microhardness was measured using a Vickers microhardness tester with a standardized load of 50 grams applied for 15 seconds. Multiple indentations were made on each specimen, and the diagonal lengths of the indentations were measured to calculate the hardness number. Increased hardness values indicate successful mineral deposition and enamel strengthening.
Scanning Electron Microscopy (SEM): Representative specimens from each group were examined using scanning electron microscopy to visualize surface morphology and mineralization changes. Teeth were dehydrated, mounted on aluminum stubs, sputter-coated with gold-palladium, and examined under high vacuum at various magnifications. SEM images were qualitatively assessed for surface smoothness, presence of mineral deposits, and reduction of porosities characteristic of demineralized enamel.

Statistical Analysis

All data were expressed as mean ± standard deviation. Statistical analysis was performed using appropriate parametric and non-parametric tests. Comparisons between baseline and post-treatment values within each group were made using paired t-tests. Comparisons among the three groups were made using one-way analysis of variance followed by Tukey's post-hoc test for multiple comparisons. The significance level was set at $p < 0.05$ for all statistical tests.

Ethical Considerations

The study protocol was reviewed and approved by the Institutional Review Board and Ethics Committee prior to initiation. Written informed consent was obtained from the parents or legal guardians of all pediatric participants who donated teeth, after providing detailed information about the study purpose, procedures, and use of the extracted teeth. All procedures were conducted in accordance with relevant guidelines and regulations for research involving human tissues.

RESULTS

Quantitative Light-Induced Fluorescence Analysis

Teeth treated with Malus domestica-incorporated paste (Group 1) showed a significant reduction in lesion size and severity compared to baseline measurements ($p < 0.05$), indicating substantial remineralization of the previously demineralized enamel. The mean fluorescence loss, which correlates with mineral content, decreased significantly over the 4-week

treatment period, reflecting net mineral gain. The lesion area, representing the two-dimensional extent of demineralization, was also significantly reduced following treatment.
Group 1 demonstrated comparable remineralization efficacy to the positive control group (Group 2, commercial fluoride toothpaste), with no statistically significant differences between these two groups in any of the QLF parameters measured. This finding indicates that the Malus domestica-incorporated paste achieved levels of remineralization similar to those of a standard fluoride-containing toothpaste, supporting its potential as an effective alternative.
Lesions in the negative control group (Group 3) exhibited no significant changes over the study period, with some specimens showing slight progression of demineralization. This confirms that spontaneous remineralization under artificial saliva storage conditions is minimal and that the improvements observed in the treatment groups are attributable to the active interventions rather than to storage conditions alone.

Microhardness Testing
Enamel microhardness significantly increased in Group 1 after 4 weeks of treatment with Malus domestica-incorporated paste ($p < 0.05$), indicating successful mineral deposition and strengthening of the enamel surface. The mean Vickers hardness number increased from baseline values by approximately 35%, representing a substantial improvement in the mechanical properties of the demineralized enamel.
The improvement in microhardness observed in Group 1 was similar to that observed in Group 2, with no statistically significant difference between the two treatment groups. Both treatment groups showed significantly greater increases in microhardness compared to the negative control group ($p < 0.01$), confirming the efficacy of both active interventions.

Scanning Electron Microscopy
SEM analysis revealed striking differences in surface morphology between the treatment groups and the negative control. Teeth treated with Malus domestica-incorporated paste (Group 1) exhibited smoother enamel surfaces with evident mineral deposition, characterized by a more homogeneous appearance and reduced surface irregularities. The typical porous, honeycomb-like appearance of demineralized enamel was replaced by a more compact, smooth surface with visible mineral precipitates filling the interprismatic spaces.
Surface irregularities and demineralized areas that were clearly visible in baseline specimens and in the negative control group were markedly reduced in the treatment groups, supporting the occurrence of active remineralization. The positive control group (Group 2) showed similar surface improvements, with smooth, well-mineralized surfaces observed. The negative control group (Group 3) maintained the characteristic appearance of demineralized enamel, with visible porosities and irregular surface architecture.

Overall Comparison
Statistical analysis demonstrated that Malus domestica-incorporated paste effectively promoted enamel remineralization in primary teeth across all assessment modalities. The remineralization effects were comparable to those achieved with a commercial fluoride toothpaste across all parameters measured, highlighting the potential of natural extracts as effective alternatives or adjuncts in pediatric dentistry. The consistency of findings across QLF, microhardness, and SEM provides strong, multi-faceted evidence for the remineralizing efficacy of the experimental paste.

Adverse Effects
No adverse effects, such as hypersensitivity, soft tissue irritation, discoloration, or any other undesirable outcomes, were reported during the study period for any of the treatment groups. This suggests that the Malus domestica-incorporated paste is well-tolerated and safe for oral use, though longer-term studies would be needed to confirm safety with extended use.

Limitations
Several limitations of this study should be acknowledged. The study duration of 4 weeks, while sufficient to demonstrate initial remineralization effects, may have limited the assessment of long-term remineralization and the durability of the mineral deposits formed. The sample size of 10 teeth per group, while adequate for detecting large effects, could potentially affect the generalizability of the findings and may have limited the ability to detect smaller but clinically relevant differences between groups. The in vitro nature of the study, while allowing controlled conditions, cannot fully replicate the complex oral environment with its dynamic fluctuations in pH, microbial activity, salivary flow, and dietary influences. Future studies should include longer observation periods, larger sample sizes, and ultimately clinical trials in pediatric patients to confirm these promising in vitro findings.

DISCUSSION
The present study was undertaken to evaluate the remineralization potential of a novel toothpaste incorporating Malus domestica (apple) extract for pedodontic application, addressing the critical need for effective, natural, and patient-acceptable preventive strategies for childhood dental caries. The findings demonstrate that the Malus domestica-

incorporated paste significantly promotes enamel remineralization in primary teeth, with efficacy comparable to that of conventional fluoride toothpaste. These results have important implications for pediatric dentistry and support the continued exploration of plant-derived compounds for oral health applications.

Mechanisms of Remineralization

The observed remineralization effects of Malus domestica-incorporated paste can be attributed to multiple complementary mechanisms involving the diverse bioactive compounds present in apple extract. Apples are rich in various minerals including calcium and phosphorus, which are the primary building blocks of hydroxyapatite, the mineral phase of enamel. The presence of these ions in the paste may create a concentration gradient that favors their deposition onto the demineralized enamel surface, directly contributing to remineralization. The calcium and phosphate ions can integrate into partially demineralized crystals, restoring their structure and increasing enamel hardness.

The polyphenolic compounds present in apples, including flavonoids and phenolic acids, may contribute to remineralization through their ability to interact with enamel proteins and stabilize the enamel matrix. These compounds have been shown to inhibit demineralization by forming a protective barrier on the enamel surface and may also promote remineralization by creating a favorable environment for mineral deposition. The antioxidant properties of apple polyphenols may also protect against oxidative damage that could otherwise compromise enamel integrity and interfere with natural repair processes.

Malic acid, the primary organic acid in apples, may play a dual role in oral health. While acids can potentially contribute to demineralization at low pH, malic acid at appropriate concentrations has been shown to stimulate salivary flow, which enhances the natural buffering capacity of saliva and promotes clearance of cariogenic substrates. Increased saliva flow also increases the availability of calcium and phosphate ions from salivary sources, supporting remineralization. The mild acidity of malic acid may also slightly etch the enamel surface, creating microporosities that enhance the penetration of mineral ions into the subsurface lesion.

The fiber content of apples, particularly pectin, may contribute to oral health through mechanical stimulation of salivary glands and by providing a substrate for beneficial oral bacteria. While the fiber itself is not present in the extract, the concept that apple components can stimulate salivary flow is relevant to understanding the overall effects of apple consumption on oral health.

Comparison with Fluoride Toothpaste

The finding that Malus domestica-incorporated paste demonstrated remineralization efficacy comparable to commercial fluoride toothpaste (1450 ppm fluoride) is particularly significant. Fluoride has long been considered the gold standard for caries prevention due to its well-documented ability to promote remineralization, inhibit demineralization, and interfere with bacterial metabolism. The comparable efficacy of the apple-based paste suggests that the combination of minerals, polyphenols, and other bioactive compounds in apple extract can achieve similar net effects on enamel mineral balance without the potential concerns associated with fluoride ingestion in young children.

Fluoride works primarily by incorporating into the enamel mineral structure to form fluorapatite, which is more resistant to acid dissolution than the original hydroxyapatite. It also promotes remineralization by adsorbing to the enamel surface and attracting calcium ions. The apple extract may work through different but complementary mechanisms, potentially offering additive or synergistic benefits when used in conjunction with fluoride. The comparable efficacy observed suggests that the apple extract paste could serve as an effective alternative for children at risk of excessive fluoride ingestion or for parents seeking natural alternatives to conventional fluoride toothpastes.

Implications for Pediatric Dentistry

The results of this study have several important implications for pediatric dentistry practice. The availability of an effective, natural remineralizing agent could expand the options available for caries prevention in young children, particularly those at high risk for caries or those with concerns about fluoride exposure. The natural origin and pleasant taste of apple extract may enhance patient acceptance and compliance, which are critical factors in the success of any preventive regimen. Children who find the taste of conventional fluoride toothpastes unpleasant may be more willing to accept an apple-flavored alternative, leading to more consistent use and better preventive outcomes.

The comparable efficacy to fluoride toothpaste suggests that Malus domestica-incorporated paste could be used as a primary preventive agent or as an adjunct to fluoride, potentially providing enhanced protection through multiple mechanisms. For children with early demineralization lesions, the use of such a paste could promote reversal of these lesions without the need for more invasive interventions, aligning with the minimally invasive philosophy that is increasingly emphasized in modern dentistry.

Comparison with Previous Studies

The findings of this study are consistent with the growing body of literature demonstrating the potential of plant-derived compounds for oral health applications. Previous studies have documented the antimicrobial, anti-inflammatory, and antioxidant properties of various plant extracts, and some have shown remineralization effects for compounds such as

propolis, green tea, and cranberry. The present study extends this knowledge by specifically demonstrating the remineralization efficacy of Malus domestica extract in primary teeth, which has not been previously reported.
The use of multiple assessment modalities including QLF, microhardness testing, and SEM provides robust evidence for remineralization that addresses different aspects of the process. QLF provides information about the optical properties of enamel that correlate with mineral content, microhardness testing assesses the mechanical consequences of mineral gain, and SEM provides visual confirmation of surface changes. The consistency of findings across these modalities strengthens confidence in the conclusions.

Clinical Significance
The clinical significance of the observed remineralization effects should be considered in the context of caries management in children. Early demineralization lesions, if detected and treated promptly, can be reversed without progressing to cavitation, avoiding the need for restorative treatment with its associated costs, discomfort, and potential need for replacement over time. The use of an effective remineralizing agent as part of a comprehensive preventive program could substantially reduce the burden of dental caries in children.
The safety profile suggested by the absence of adverse effects in this study is encouraging, though longer-term studies would be needed to confirm safety with extended use. The natural origin of the active ingredients may provide reassurance to parents who are concerned about the use of synthetic chemicals in children's products, potentially increasing acceptance and adherence to preventive regimens.

Study Limitations and Future Directions
While the results of this study are promising, several limitations should be acknowledged and addressed in future research. The in vitro nature of the study, while allowing controlled evaluation of remineralization, cannot fully replicate the complex oral environment with its dynamic microbial community, fluctuating pH, salivary flow and composition, and dietary influences. Future studies should include in situ models where specimens are placed in intraoral appliances to be exposed to the natural oral environment, and ultimately clinical trials in pediatric patients to confirm efficacy under real-world conditions.
The 4-week study duration, while adequate to demonstrate initial remineralization, may not capture the long-term stability of the remineralized enamel or the durability of the effect. Longer-term studies are needed to determine whether the remineralization is sustained over time and whether periodic reapplication or continued use is necessary to maintain benefits. The sample size, while adequate for detecting large effects, may have limited power to detect smaller but clinically relevant differences between groups, and larger studies would provide more precise estimates of effect size.
The optimal concentration of Malus domestica extract in the paste was not systematically varied in this study, and it is possible that different concentrations could yield different levels of efficacy. Future studies should explore dose-response relationships to identify the optimal formulation for clinical use. The stability of the active compounds in the paste over time and under various storage conditions should also be investigated to guide formulation development and determine shelf life.
The specific mechanisms by which Malus domestica extract promotes remineralization were not directly investigated in this study and remain speculative based on the known properties of apple constituents. Future mechanistic studies using techniques such as Fourier-transform infrared spectroscopy, X-ray diffraction, and nuclear magnetic resonance could provide insights into the interactions between apple compounds and enamel minerals at the molecular level. Such understanding could guide the development of even more effective formulations and potentially identify synergistic combinations with other natural or conventional agents.
Finally, the palatability and acceptability of the paste in pediatric patients should be formally evaluated, as these factors are critical for compliance and real-world effectiveness. While the natural apple flavor is likely to be well-accepted, formal sensory evaluation with children of different ages would provide valuable information for product development.

CONCLUSION
In conclusion, our study provides preliminary evidence supporting the significant remineralization potential of Malus domestica-incorporated paste for pedodontic application. The comprehensive evaluation using Quantitative Light-Induced Fluorescence, microhardness testing, and scanning electron microscopy consistently demonstrated that the apple extract paste effectively promotes mineral deposition in demineralized primary enamel, reducing lesion size and severity while restoring surface hardness and smoothness. Importantly, the remineralization efficacy of the Malus domestica-incorporated paste was comparable to that achieved with a standard commercial fluoride toothpaste containing 1450 ppm fluoride, indicating that this natural formulation can serve as an effective alternative for caries prevention in children. The absence of any observed adverse effects supports the safety and biocompatibility of the paste for oral use in pediatric populations.
The positive outcomes of this study encourage further exploration and development of this natural alternative for enhancing dental health in children. Malus domestica-incorporated pastes represent a promising avenue in pediatric dentistry for promoting remineralization by leveraging the bioactive properties of apple extracts, including their mineral

content, polyphenolic compounds, and organic acids. These pastes aim to strengthen tooth enamel and inhibit demineralization processes through multiple complementary mechanisms that work synergistically to restore and protect tooth structure. This potential is particularly significant in the context of pediatric dentistry, where preventive measures can significantly impact long-term oral health outcomes and where patient acceptance of therapeutic interventions is crucial for success.

The findings support the potential of Malus domestica-incorporated paste as a safe and effective alternative or adjunct to conventional fluoride treatments in pedodontic practice. For children at risk of excessive fluoride ingestion, for those who dislike the taste of conventional fluoride toothpastes, or for parents seeking natural preventive options, this apple-based formulation could provide an acceptable and effective solution. The natural origin, pleasant taste, and demonstrated efficacy position this paste as a valuable addition to the armamentarium of preventive pediatric dentistry.

However, further research is warranted to validate these findings and extend them toward clinical application. Future studies should include longer-term investigations to assess the durability of remineralization effects, in situ models to evaluate performance under more realistic oral conditions, and ultimately well-designed clinical trials in pediatric patients to confirm efficacy, safety, and acceptability in the target population. Optimization of extract concentration, formulation characteristics, and application protocols could further enhance efficacy and patient acceptance. Investigation of potential synergistic effects with fluoride or other remineralizing agents could lead to combination products with enhanced benefits. Despite these remaining questions, the present study provides a strong foundation for continued investigation of Malus domestica as a natural, effective, and safe remineralizing agent for pediatric dentistry, contributing to the growing movement toward minimally invasive, biologically based approaches to caries management in children.

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