Research Article

Natural Therapeutic Agents for Remineralization of Dental Erosion in Primary Teeth: Current Evidence, Digital Monitoring, and Future Pediatric Applications

Sheenam Ayub[1]*, Tanu Nangia[2], Syed Meraj Alam Fatmi[3]

[1]MDS, PhD Scholar, Department of Pediatric and Preventive Dentistry, Manav Rachna Dental College, MRIIRS, Faridabad, Haryana, India, Email: sheenam_ayub25.phd@mriu.ac.in, Orcid id: 0009-0005-4252-7016
[2]MDS, Professor and Head, Department of Pediatric and Preventive Dentistry, Manav Rachna Dental College, MRIIRS, Faridabad, Haryana, India, Email: tanunangia.sds@mrei.ac.in, Orcid id: 0000-0002-5971-2956
[3]PhD Pharmacology, Associate Professor, Department of Pharmacology, FH Medical College and Hospital, Agra, Uttar Pradesh, India, Email: me.syedmeraj@gmail.com, Orcid: 0000-0003-4967-9256

Abstract

Introduction: Dental erosion is a progressive, chemical and non-bacterial loss of dental hard tissues, increasingly associated with acidic foods and beverages among children. Primary teeth are more susceptible to caries due to their thinner enamel and lower mineralization. While fluoride is the best way to protect enamel, safer, less invasive, and kid-friendly alternatives are becoming more popular. This review covers natural remineralizing agents for primary tooth erosion, their mechanism of action, efficacy, and clinical use, as well as digital monitoring and artificial intelligence methods for assessing erosive changes and treatment response in paediatric dentistry. Methods: A literature search was performed to assess the remineralization potential of natural and biomimetic agents used for the management of primary enamel erosion. Results: Natural therapeutic agents can inhibit demineralization and resist acid challenge, supplement mineral ions, guide deposition of scaffolds, and stabilize crystals, thereby promoting remineralization. The most promising results were obtained from calcium phosphate-based systems and biomimetic peptides. Conclusion: Emerging natural and biomimicking remineralizing therapeutic agents are biocompatible and promising for the treatment of dental erosion in primary teeth. In addition, digital technologies may also make it easier to monitor treatment response and objectively assess erosive changes.

Keywords: Dental erosion, Primary teeth, Remineralization, Natural remineralizing agents, Digital dentistry, Artificial intelligence.

1. Introduction

Dental erosion is the permanent loss of dental hard tissue caused by chemical dissolution of the hard tissue by acids, with no involvement of bacteria. In recent years, erosive tooth wear has become more prevalent among children and adolescents due to changes in the consumption of food and beverages, rising consumption of acidic beverages and lifestyle. This condition, if not diagnosed and treated, can lead to loss of tooth structure, dentinal sensitivity, functional problems and aesthetic issues. 1,2 Primary teeth are especially vulnerable to erosive damage since they have thinner enamel, a lower mineral content, higher enamel porosity, and lower enamel microhardness than permanent teeth.

These structural properties cause minerals to be lost to the repeated exposure of intrinsic or extrinsic acids. Moreover, regular intake of fruit juices, carbonated drinks, acidic drugs and lack of oral hygiene worsens the onset and progression of dental erosion. 3,4 Dental erosion is a dynamic process that is controlled by the relationship of demineralization to remineralization. The saliva is rich in calcium and phosphate ions and acts as a buffer to allow the natural repair of the early loss of minerals in physiological circumstances. If the amount of acid exceeds the capacity of saliva to neutralize it, the situation turns in favour of net mineral loss and continued enamel dissolution.

It is therefore important to implement remineralization strategies to restore this balance to maintain the integrity of the primary dentition and to prevent further erosive loss.5 Fluoride treatment has been considered as a standard for minimizing the mineral loss and increasing enamel strength. However, the interest in minimizing the invasiveness of the technique, coupled with the increasing interest in biologically inspired methods, has led to curiosity about other remineralization techniques,6 due to the recent progress in biomimetic dentistry, which has allowed the development of other therapeutic agents from natural sources that can be used to replicate the natural mineralization processes and can support the restoration of enamel.

In recent years, various natural and biomimetic systems for remineralization have been attracting great attention due to their bioactivity, safety, and capacity to re-mineralize demineralized enamel. These systems are calcium phosphate-based, nano-biomaterials, plant polyphenols, herbal products, amino acid-based, salivary protein complexes, naturally occurring biopolymers, calcium-rich biological substances and peptide-driven regenerative technologies. They work in a number of ways, including supplying bioavailable calcium and phosphate ions, reinforcing the protective acquired pellicle, inhibiting the dissolution of minerals, stabilising enamel crystals, and providing scaffolds for biomimetic mineral deposition. 7,8,9 While there have been many in vitro and in situ studies with promising findings, inconsistencies exist in study design, methodology and outcome measures available.

One of the challenges is making an objective assessment of erosive changes and treatment response. Conventional techniques such as visual examination, clinical photographs, and scoring systems may be insensitive to subtle changes or examiner-dependent. The opportunities for digital dentistry, such as standardised photography and sequential three-dimensional scanning, in the area of more objective longitudinal evaluation of morphological changes are even greater, and AI-assisted systems may also aid in the automated detection, severity classification, and monitoring of tooth wear; however, evidence is still scarce in primary teeth and children.

Combining digital and AI-powered monitoring with natural remineralising therapies may improve objective assessment of treatment outcomes, but more clinical validation is required. The purpose of this narrative review is to critically summarize the current evidence on natural therapeutic agents with the potential to promote remineralization of dental erosion in primary teeth, investigate their mechanisms of action, efficacy, biological properties, and level of evidence, and discuss the emerging role of digital monitoring and artificial intelligence in objectively assessing erosive changes and treatment-related outcomes. The review also discusses current limitations, research gaps, and future opportunities for combining natural remineralisation strategies with digital technologies in paediatric dentistry.

2. Literature Search

An extensive literature search was carried out to locate relevant research regarding the use of natural therapeutic agents for remineralization and treatment of dental erosion in primary teeth. Electronic databases were used to search articles published up to March 2026: PubMed/MEDLINE, Scopus, Web of Science and Google Scholar. The reference lists of the chosen studies and pertinent review articles were manually screened to identify more articles.

The search terms used included free-text words related to dental erosion and natural remineralizing agents as well as Medical Subject Headings (MeSH). The main search terms consisted of: “dental erosion,” “erosive tooth wear,” “primary teeth,” “deciduous teeth,” “remineralization,” “natural therapeutic agents,” “CPP-ACP,” “CPP-ACFP,” “nano-hydroxyapatite,” “plant-derived polyphenols,” “green tea extract,” “grape seed extract,” “cranberry extract,” “cocoa extract,” “herbal extracts,” “aloe vera,” “neem,” “miswak,” “tulsi,” “licorice,” “eggshell powder,” “arginine,” “salivary proteins,” “gum arabic,” and “chitosan” and “self-assembling peptides.” Inclusion criteria: Clinical trials, observational studies, in vitro and in situ studies, original research articles and relevant review articles published in English were included. Papers with translational and/or mechanistic relevance to primary teeth were also included.

Articles without adequate methodological details, conference abstracts, editorials, and duplicate publications were not included. The literature was critically evaluated and narratively synthesized to provide an overview of the mechanism of action, potential for remineralization and clinical significance of emerging natural therapeutic agents in the management of dental erosion in primary teeth.

2.1. Pathophysiology Of Dental Erosion In Primary Teeth

Dental erosion is an irreversible loss of dental hard tissue in primary teeth caused by the action of chemicals in the form of acids on hard tissues through intrinsic or extrinsic acids without the action of bacteria. Primary teeth have inherently different structure and composition from permanent teeth, including but not limited to thinner enamel, lower mineral content, higher porosity, higher organic matrix content and lower microhardness, which makes them more susceptible to erosive challenges.

These differences permit acid penetration and speed up the dissolution of the minerals. (Table 1) Pathogenesis of dental erosion begins with repetitive exposure to acid, which dissolves hydroxyapatite crystals and leads to the

subsequent mineral loss from the enamel surface. Dental hard tissues are not recoverable, and the surface begins to soften with each cycle of demineralization as long as the amount of demineralization exceeds the remineralization that can occur in saliva. (Figure 1)

2.2. Natural Therapeutic Agents :

The natural therapeutics used in the management of dental erosion in primary teeth could be categorized into calcium and phosphate based systems, polyphenols of natural origin, herbal extracts, natural biomolecules, natural polysaccharides, biomimetic peptides and calcium rich natural material systems. These agents are different in mechanism of action, scientific evidence and clinical use. (Table 2) lists the currently available natural remineralizing agents, their main mechanisms, the level of evidence and possible application in primary teeth.

2.3. Calcium And Phosphate-Based Remineralising Agents (CPP-ACP, CPP-ACFP, Nano-hydroxyapatite)

Calcium and phosphate-based agents are essential to the prevention of dental erosion as bioavailable reservoirs to maintain the mineral saturation at the tooth/saliva junction. Casein phosphopeptide (CPP), a bioactive phosphoprotein derived from milk, acts as a vehicle for calcium and phosphate ions, greatly increasing their solubility and stabilising them in amorphous calcium phosphate.18,11 This complex can inhibit demineralisation and promote subsurface remineralisation due to high local calcium and phosphate concentrations. During an acid challenge, the complex dissociates to buffer pH drops and promote mineral precipitation into the enamel .19 Fluoride is incorporated into this complex to form Casein Phosphopeptide-Amorphous Calcium Fluoride Phosphate.

The synergy between fluoride and calcium phosphate in CPP-ACFP offers a greater acid resistance than CPP-ACP alone, especially in highly acidic environments.20,11 Moreover, nanohydroxyapatite (nHA) acts as a biomimetic agent, which can deeply immerse in eroded dental tissues and has the ability to restore the structural integrity of the surface of the enamel by promoting mineral deposition and sealing the dentinal tubules. 21

3. Plant-Derived Polyphenols

3.1. Green Tea Extract

Polyphenols in green tea extract, especially epigallocatechin-3-gallate, are potent inhibitors of host proteases.22 Green tea polyphenols have been shown to act as non-specific inhibitors of cysteine cathepsins and matrix metalloproteinases, especially MMP-2, -8 and -9 in dental erosion.23 In acidic challenges, the extract prevents the degradation of the dentin organic matrix by the inactivation of these endogenous enzymes. Research has indicated that green tea solutions can be effective in protecting the tooth surface from structural breakdown by minimising dentin loss caused by the combined action of erosion and abrasion.22

3.2. Grape Seed Extract (Gse)

Proanthocyanidins, which are highly potent and effective natural collagen cross-linkers, are abundant in grape seed extract. GSE mainly has two functions in the management of primary tooth erosion:

- Matrix Stabilization: Proanthocyanidins (PAs) reinforce the organic dentin scaffold by strengthening the cross-links in the matrix and bonding to the collagen cleavage sites to inhibit matrix collapse and enzymatic proteolysis. The robust scaffolding structures are then used as a template for additional mineral deposition.
- Remineralisation: GSE makes it easier for insoluble calcium-PA complexes to form, which serve as hydroxyapatite crystal nucleation sites.24

Studies focusing on primary teeth have demonstrated that dentifrices containing the combination of these two ingredients (CPP-ACP and GSE) had a more favourable remineralisation potential than either fluoride or CPP-ACP. Scanning electron microscopy (SME) confirmed the formation of a dense, uniform, globular surface--which was similar to sound enamel--and Vickers enamel microhardness testing showed that recovery of mean microhardness was greatest after GSE treatment.25

4. Cranberry Extract

Cranberry extracts are effective in dental erosion prevention through altering the oral environment and cariogenic biofilms. A systematic review indicates that cranberry polyphenols show positive effects on dental biofilms, significantly decreasing biovolume and biomass. These extracts have been reported to raise the pH of biofilms, which is necessary to prevent erosion. Cranberry extracts help prevent pH drops that cause primary tooth enamel and dentin to chemically dissolve by preserving a more alkaline environment at the tooth-biofilm interface.26

4.1. Cocoa Bean Extract

Cocoa bean extract primarily contains theobromine (1,3,7-dimethylxanthine), an effective, safe and cost-effective alternative to fluoride in pediatric dental care, which is water-soluble. Theobromine was found to increase the deposition of minerals and the microhardness of the surface to remineralize the demineralized enamel. Systematic evaluation indicates that the remineralization ability of such agents based on cocoa powder is similar to that of conventional fluoridated agents. They are particularly effective and have low toxicity, which makes them useful for the control of early childhood caries and the prevention of erosive progression in primary dentition. 27,28

4.2. Herbal Extracts

Aloe Vera:

Although promising remineralizing properties of Aloe vera have been demonstrated, available evidence is mostly based on studies of caries-related enamel demineralization rather than dental erosion in primary teeth. Experimental studies have shown the remineralization effect of Aloe vera gel comparable to that of 1,450 ppm fluoride toothpaste by promoting mineral deposition and increasing microhardness of enamel. It is a great source of bioactive polysaccharides, amino acids, antioxidants and anti-inflammatory phytochemicals and is believed to help repair enamel and prevent further mineral loss. Energy-dispersive X-ray spectroscopy has shown increased calcium and phosphate deposition in demineralized enamel after Aloe vera application, and Vickers microhardness analysis has confirmed significant improvements in enamel hardness.29–31However, there is a lack of direct evidence evaluating the use of Aloe vera for the prevention or remineralization of erosive lesions in primary teeth.

Therefore, its application in erosive primary enamel is currently supported solely by indirect evidence and well-designed in vitro and clinical studies concerning dental erosion in the primary dentition are necessary.

Neem (Azadirachta Indica)

The anti-cariogenic and anti-inflammatory properties of neem make it a herbal panacea in dentistry. It contains powerful antibacterial phytochemicals such as nimbidin, azadirachtin and nimbinin, which help account for its strong antibacterial properties against the oral pathogens.32 Dentin wear is considerably decreased for the formulations with neem in the context of dental erosion. One of the most important mechanisms of neem is the modulation of the oral environment, wherein studies conducted on the paediatric population have demonstrated that chewing the neem leaves can restore the oral pH to the baseline level retroactively to the acidic and/or cariogenic stimulus within 60 minutes, thereby providing an environment favourable for remineralization.33

Miswak (Salvadora Persica)

Miswak (Salvadora persica) has a wide range of antimicrobial activity and restores minerals; thus, it is a good natural alternative for fluoride-based treatments. Its pharmacological profile consists of 76 identified compounds, mainly composed of tannins, resins, isothiocyanates and alkaloids as active ingredients.34 Miswak extract can restore the mineral content to baseline levels and has been shown to be effective in reducing enamel demineralisation under experimental conditions.35 In particular, isothiocyanates improve the oral environment by providing a more stable surface for mineral precipitation.

Tulsi (Ocimum sanctum)

Tulsi or Holy Basil is used in paediatric dentistry for management of caries and mucosal lesions due to its ability to modulate salivary parameters. Clinical trials have established that Tulsi-based mouthwashes can effectively raise salivary pH to normal levels, thereby neutralising the acidic conditions that cause dental erosion. Tulsi leaves like neem have been shown to reverse salivary acidogenicity successfully in children after an acidic challenge.

The tulsi supports the natural remineralisation process with a reduction in the chemical dissolution of the primary enamel by maintaining a more alkaline salivary pH.36,37

Licorice (Glycyrrhiza glabra)

The high content of flavonoids and glycyrrhizin, the main component of licorice, is responsible for the remineralizing properties of the plant. Glycyrrhizin has a stimulatory effect on mineral recovery because it increases the local remineralization rates and stimulates salivation. In addition, it has been demonstrated that adding glycyrrhizic acid to casein phosphopeptide-amorphous calcium phosphate (CPP-ACP) results in higher surface microhardness values in enamel of primary teeth than CPP-ACP alone.38 Together with calcium-phosphate therapy, this indicates a synergistic effect of glycyrrhizic acid.39

4.3. Natural Biomolecules

L-Arginine

L-arginine is now known to be a potent prebiotic that can effectively prevent and treat caries and dental erosion in the primary dentition. The principal biochemical mechanism is the action of arginolytic commensal bacteria (Streptococcus sanguinis and Streptococcus gordonii) that alter the oral biofilm. These microbes can break down L-arginine to generate ammonia, which will raise the pH of the biofilm and help to maintain the pH within an acceptable range.40
L-arginine has anti-biofilm effects beyond the pH effects, which is very significant, as it disrupts multi-species microbial communities and inhibits the adhesion of acidogenic pathogens, including Streptococcus mutans. L-arginine and fluoride are particularly clinically important for pediatric dentistry. A study showed that a 600-ppm NaF child-formula dentifrice, when supplemented with 2% arginine, is much more effective in remineralizing than a 600-ppm NaF child-formula dentifrice, and as effective as an 1100-ppm NaF adult-formula dentifrice. This combination has also proven successful, according to quantitative light-induced fluorescence after bacterial pH cycling, to remineralise demineralised primary dentin.41,42

Salivary Proteins and Derivatives

The proteins of the acquired enamel pellicle, a barrier to diffusion of acids, include statherin, proline-rich proteins, histatins, and mucins. This pellicle decreases the direct contact between the acids and the enamel, and thus the loss of minerals. Furthermore, proteins in saliva bind to the phosphate and calcium ions, maintaining a supersaturated environment that favours remineralization. Casein phosphopeptides (CPP) and other protein derivatives enhance mineral deposition into early erosive lesions and the stabilisation of amorphous calcium phosphate. These proteins provide additional protection by slowing the formation of lesions in primary teeth with less-mineralized and thinner enamel. The peptides in saliva are also bioactive and help repair and grow enamel. Thus, the role of salivary proteins and their derivatives in the integrity of enamel in primary dentition and in preventing dental erosion is of great importance.43,44

4.4. Natural Polysaccharides

Gum Arabic (Acacia senegal)

Hydroxyapatite, the chief mineral in enamel, has a more difficult time dissolving when gum arabic, a food-grade hydrocolloid, is present. Related research shows that food-approved polymers, such as condensed phosphates, can decrease the rate of hydroxyapatite dissolution by 35-64% in citric acid conditions (as seen in many of the soft drinks that are highly erosive). Beyer showed that the enamel hardness loss in citric acid solutions was significantly decreased when gum Arabic was added, and suggested that the mechanism of protection was the formation of an adsorbed polymer–hydroxyapatite layer on the surface of the enamel, which acts as a physical diffusion barrier to acid penetration.

A significant increase in the surface microhardness of demineralized dental specimens has been found when treated topically with a Gum Arabic gel, with the highest increase after 96 minutes of exposure. This particle-polymer interaction would thus create the protective effect, reducing the loss of the nanomechanical properties when challenged with an acid.45,46

Chitosan and Nanochitosan

Chitosan is a linear polysaccharide obtained from chitin, which has a cationic character and can bind to negatively charged surfaces, such as dental biofilms and enamel. The bioadhesive property is crucial for the anti-erosive

mechanism because the amino groups in chitosan are positively charged and have the ability to absorb hydrogen ions from the oral fluids, creating a buffer region that helps to stop organic acids from penetrating the tooth structure. In primary teeth, chitosan acts as a biological matrix that helps transport and stabilize calcium and phosphate ions required for subsurface remineralisation. It is interesting to note that the microhardness of enamel could be substantially improved by application of varnishes containing chitosan, which is more effective than the use of the conventional applications of 5 % sodium fluoride.

Furthermore, the use of nanochitosan is a great advancement in biomimetic remineralization as it increases the surface area-to-volume ratio of nanochitosan, which increases the penetration of minerals into primary tooth structures. Nanochitosan suspensions are especially effective in creating a uniform and well-mineralised organic protection layer, which reduces the dentin loss during erosive challenges. Clinical evaluations of primary molars have demonstrated that the nanochitosan can reverse the demineralisation significantly and reform the enamel surface morphology to a condition similar to sound enamel.47,48

4.5. Biomimetic Peptides

Self-Assembling Peptides

P11-4 is a β-sheet-forming peptide that is the most widely studied self-assembling peptide in today's pediatric dentistry. The pH-responsive self-assembly behaviour of P11-4 controls its biochemical activity, with the monomers transitioning from individual particles to tapes, ribbons, fibrils and fibres upon application to the demineralised lesion, the subsurface body of which has a pH below 7.5.49 Diffusion of monomeric P11-4 into the subsurface body of the lesion, where it forms a three-dimensional bioactive fibrillar scaffold. The elastomeric nematic matrix is used as a template for de novo nucleation of hydroxyapatite. The affinity of the peptide scaffold to calcium ions is profound and forms a high concentration of calcium ions, which attracts phosphate ions and leads to the precipitation of new hydroxyapatite nanocrystals within the lesion volume.

The change in mineral density in the subsurface enamel in this process mimics that of natural odontogenesis and allows for a significant gain in net mineral density in P11-4 to be achieved via a safe, noninvasive, and efficient therapeutic approach to early caries and erosive issues in primary dentition.50 Interestingly, the randomized clinical trial results showed that P11-4 was more effective than fluoride varnishes in remineralizing the white spot lesions, suggesting it has a more specific mechanism of action for early caries reversal in the prisms of enamel. P11-4 is added as a scaffold to pH-responsive ion-release systems and biofilm-suppressing agents, creating a new paradigm of multimodal biomimetic therapeutics that will produce a minimally invasive restoration of dental mineral integrity, while significantly minimizing the risk of subsequent primary dentition caries.51

4.6. Natural Calcium And Phosphate-Rich Sources

Eggshell-Derived Calcium and Hydroxyapatite

Eggshell powder is a very good precursor for hydroxyapatite as it is mainly composed of calcium carbonate ($CaCO_3$).52 The production of bioavailable calcium normally involves a calcination process, where eggshells are heated to around 900°C for the process of thermal decomposition, converting it into calcium oxide and releasing carbon dioxide. This material obtained from the eggshell can be used subsequently for the synthesis of biogenic nanohydroxyapatite, thus offering a biomimetic approach to restore the mineral density of primary teeth.53 These biogenic agents allow for the closure of demineralised spaces in the primary dentition by the deposition of new mineral phases.

The remodelling efficacy of eggshell-derived materials is governed by both particle- and ion-mediated pathways. In the presence of erosive or carious lesions, the material releases bioavailable calcium and phosphate ions into the local environment, creating a supersaturated condition that provides the driving force for mineral precipitation into the crystal voids of the enamel.54 Particle size is critical to the restoration of enamel integrity.

Micro-eggshell powder mainly affects the surface layer and acts as a reservoir of ions but has a limited ability to penetrate deep subsurface lesions. Nano-eggshell powder CES nHAp penetrates the subsurface body of the lesion with particles in the range of 20–40 nm, similar to the natural building blocks of human enamel, leading to a uniform mineral gain and effective restoration of the mechanical properties of the enamel matrix.55

4.7. Digital Monitoring and AI-Assisted Assessment of Dental Erosion

Early diagnosis and longitudinal monitoring of erosive tooth wear are important to prevent progressive loss of dental hard tissue. Traditional clinical evaluation is based on visual diagnosis, clinical photographs and the Basic Erosive Wear Examination (BEWE) score. These methods are helpful for clinical evaluation, but small variations in tooth form may not be discernible and measurable, especially at early stages of erosive tooth wear. With the growing use of digital technologies, a new opportunity has arisen to combine the traditional clinical evaluation with objective and reproducible documentation of alterations in tooth surface morphology.68,69

4.8. Digital Photography and Intraoral Documentation

Standardized intraoral photography allows for a simple, non-invasive technique to document the clinical appearance and/or progression of erosive tooth wear. The changes in the morphology and surface appearance of the teeth, as well as their severity, can be compared over time by using serial photographs. Digital images can also help to communicate with the clinician and caregiver and help track progress in treatment. Photographic assessment is, however, affected by image quality, illumination, camera positioning, examiner interpretation and should not be used as a sole method of quantitative assessment, but rather combined with other methods where possible.70,71

4.9. Intraoral Scanning and Three-Dimensional Monitoring

Intraoral scanners (IOS) are a promising quantitative monitoring tool of tooth wear. Sequential digital scans can be overlaid on a baseline scan for the assessment of changes in the three-dimensional surface of the tooth with time. Vertical loss of tooth substance, loss of surface area and volumetric changes are potential measures of tooth wear that can give objective data regarding its evolution. Intraoral scanning has been shown to be feasible in experimental studies to identify and monitor erosive changes.

Using 3D intraoral scans and specific software, Michou et al. were able to identify changes related to higher acid exposures and have proposed the possibility of monitoring early erosive tooth wear. The variation in measurements, however, should be taken with caution because of measurement error and because the reference surface used is difficult to define. Likewise, there are other experimental studies showing that changes in depth, area and volume after erosive challenges can also be quantified using digital scans.72

Digital monitoring might then be especially useful for monitoring over time. A baseline scan taken prior to preventive or remineralizing intervention could be compared to future scans to determine if tooth surface loss has increased, stayed the same or improved with intervention. This can, in the long run, go hand in hand with traditional clinical parameters and offer quantitative data on morphologic changes, which are not easily appreciated visually.70 However, this is an important limitation of digital scanning for very early or mild erosive changes. Previous studies have shown that intraoral scanning was able to detect some subvisual changes, but with limited accuracy and precision, it was not capable of detecting very small levels of wear with reliability. So, at this moment, digital measures should be used in conjunction with clinical data, and not as a substitute for clinical examination.

4.10. Artificial Intelligence-Assisted Assessment

Artificial Intelligence (AI) is another advancement in digital dental evaluation. A computer-based system with artificial intelligence may be able to interpret digital images or 3-D scan data to detect patterns linked to tooth wear, categorize the severity level, and help track tooth wear over time. Automated analysis can minimize examiner variation and aid in the examination of many surfaces of teeth.68,70 For instance, research in recent years has focused on tooth wear progression monitoring through the use of AI and intra-oral scans.

These methods illustrate how AI can detect and measure tooth shape changes over time and offer a more convenient and consistent monitoring method compared to human inspection. Digital or AI-supported screening for erosive tooth wear was evaluated in adults recently in a clinical study with promising diagnostic performance and repeatability, but not in children.68,69 In a pediatric setting, AI-guided surveillance may be able to aid in early identification of erosive features, severity grading, comparing serial digital images, and treatment outcome assessment. These applications are still in their infancy, however. Most evidence available in the form of digital imaging and AI evidence is from general tooth-wear populations or experimental populations and not from primary teeth. Therefore, the direct use of these technologies in the pediatric erosive tooth wear has yet to be determined.69,70

4.11.Future Applications in Pediatric Dentistry

Natural therapeutic agents may be useful adjuncts in the prevention and management of dental erosion in children. Child-friendly formulations such as toothpastes, gels, varnishes and mouthrinses can contain calcium- and phosphate-based materials, plant-derived polyphenols, herbal extracts, natural biomolecules, polysaccharides and biomimetic peptides. These approaches may offer additional protection against an acid challenge and may aid in remineralization of early erosive lesions.73,74

Safety and acceptance by children are important for paediatric use. Compliance may be influenced by taste, texture and method of application, especially for herbal preparations which may be bitter or astringent. Therefore, future developments will have to focus on appropriate concentration, agreeable sensory properties, ease of use and long-term safety. Standardized formulations are also necessary because the concentration and frequency of application of many natural agents differ substantially between studies.1,75

Natural therapeutic agents may play a particular role in preventive care in children at increased risk of erosive tooth wear. Dietary counselling, identification of frequent acidic exposure and appropriate topical preventive measures may be combined with natural remineralising therapies to prevent further mineral loss. Early intervention may help to preserve the thin and relatively vulnerable enamel of primary teeth.76

Digital technologies can be used to further enhance monitoring of erosive tooth wear. Intraoral pictures and digital scans in a standardized format can document the morphology of teeth, with the capability of being compared at subsequent appointments. The changes in surface morphology of the teeth may be monitored over time using three-dimensional superimposition of scans. These techniques may be used in addition to the traditional clinical examination to give a more objective evaluation of disease activity and response to treatment. Artificial intelligence (AI) could help identify and measure erosive tooth wear using digital photographs or 3-D scan data in the future. AI systems could be used to potentially help identify early changes, classify the severity of erosive wear, and compare sequential changes. At present, there is still limited evidence of the use of AI to assess primary teeth, and datasets and clinical validation are required to enable its use on a routine basis in pediatrics.68,70

An area where development may be possible is the merging of natural therapeutic agents with digital monitoring. Baseline digital records may be made prior to any preventive or remineralizing treatment, and then compared to other records made over time to determine whether changes have occurred. This could facilitate more personalized prevention practices and enable clinicians to spot children who need more attention. In summary, the management of dental erosion in primary teeth in the future may be going towards the combination of risk assessment, natural preventive or remineralizing therapy and the use of digital monitoring, all in the interests of a minimally invasive and individual approach. Additional, well-designed clinical trials in children are required to demonstrate efficacy, safety, proper concentrations and long-term effects of these methods. (Table 3, Figure 2)

5. CONCLUSION:

Although these agents have shown encouraging in vitro and preliminary clinical results, several issues need to be resolved before they can be incorporated into standard pediatric care. First, standardized clinical protocols for the ideal concentrations and application frequencies for biomineralization are severely lacking. Second, large-scale, carefully planned randomized controlled trials are needed to verify the long-term effectiveness and safety of these natural agents in the dynamic oral environment, even though the laboratory results are strong. Finally, child-specific compliance factors, such as the unpleasant organoleptic qualities (bitter or astringent taste) of some herbal extracts and the high production and formulation costs of biomimetic nanoparticles, impede practical implementation.

Digital photography, intraoral scanning, monitoring of treatment response in 3D dimensions and artificial intelligence could offer alternative means for objective assessment of erosive changes and monitoring of treatment response. These methods, however, have not been substantiated in primary teeth until now, and they need to be validated in children. In perspective, the integration of natural remineralizing agents with the new monitoring technologies, which are digital, could be part of the set of minimally invasive interventions for the management of dental erosion in the primary dentition that are based on a biological approach.

Future treatments could target mineral recovery and the structural and mechanical properties of primary enamel using the synergistic potential of natural bioactive molecules and biogenic minerals.

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Table 1: Comparative Structural Characteristics and Their Role in Dental Erosion

Structural Characteristic	Primary Teeth	Permanent Teeth	Impact on Erosive Susceptibility
Enamel Thickness	Significantly thinner enamel layer (depth of about 1 mm in thickness)	Thicker enamel providing a more robust physical barrier (2-3 mm in thickness)	Thinner enamel provides less material to resist acid dissolution, leading to faster progression of wear and earlier exposure of underlying dentin10,11
Mineral Content	Lower mineral density; approx 81.3–94.2 wt%	Higher mineral density; approx. 97 wt%	Reduced mineral content results in fewer hydroxyapatite crystals available to resist chemical dissolution caused by extrinsic or intrinsic acids12,13
Porosity and Permeability	Increased porosity and higher permeability, characterized by a greater diffusion coefficient.	Lower porosity and reduced permeability to fluids and ions14	Increased porosity and a disordered crystal structure facilitate deeper and more rapid penetration of acids into the tooth structure12,13

Organic Matrix Content	Higher organic content and greater water/carbonate content15,13	Lower organic content, typically around 1 wt% in enamel16	A higher proportion of organic matrix relative to mineral content increases susceptibility to acid-induced mineral dissolution15
Microhardness	Lower baseline surface microhardness; primary teeth are inherently softer17	Higher baseline surface microhardness17	Reduced microhardness results in more rapid surface softening and irreversible mineral loss upon exposure to low-pH substances11,12

Table 2: Overview of Natural Remineralizing Agents for Dental Erosion in Primary Teeth

Therapeutic Agents	**Evidence**	**Main Target Of Action**	**Potential Role In Primary Teeth**	**Current Evidence Status**
Calcium And Phosphate Based Remineralizing Agents				

CPP-AC	Clinical (RCTs)	Mineral replenishment	Promotes mineral replenishment and enhances enamel resistance to erosive challenges56,57	Extensive
CPP-ACFP	Clinical (RCTs)	Mineral replenishment and acid resistance	Provides calcium phosphate and fluoride ions for improved remineralization57	Extensive
Nanohydroxyapatite	Clinical + in situ	Enamel crystal repair	Repairs superficial enamel defects and restores mineral content57,58	Extensive
Plant Derived Polyphenols				
Green Tea Extract	In situ + in vitro	Pellicle enhancement/protection	Enhances acquired pellicle protection and reduces enamel softening59	Moderate
Grape Seed Extract	In vitro + limited clinical	Matrix stabilization	Improves resistance of dental tissues to acid-induced degradation59,25	Moderate
Cranberry Extract	In vitro	Anti-erosive surface protection	Reduces erosive mineral loss and supports enamel protection26	Moderate

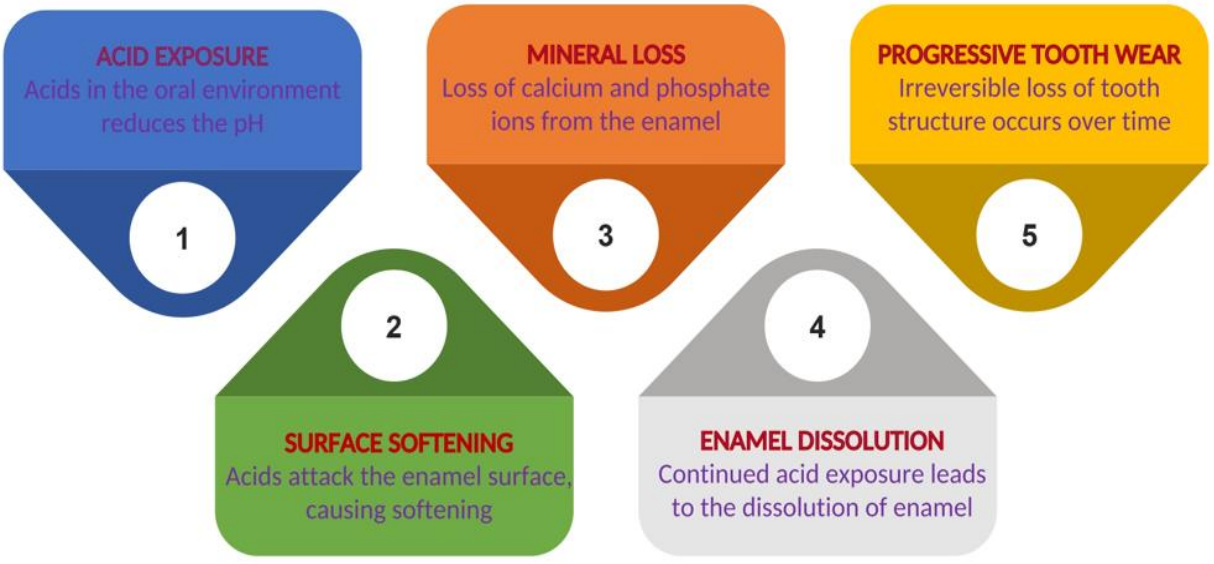
Cocoa Bean Extract	In vitro + limited clinical	Crystal strengthening	Increases enamel hardness and promotes crystal stability60	Mod erate
Herbal Products				
Aloe Vera	In vitro	Surface protection	Provides protective and antioxidant effects on enamel surfaces61	Limit ed
Neem	In vitro	Protective and antioxidant effects	Supports enamel protection against dimeralization 61,62	Limit ed
Miswak	In vitro	Surface protection	Contributes to maintenance of mineral integrity61	Limit ed
Tulsi	In vitro	Anti-oxidant activity	Exhibits antioxidant and protective properties60	Limit ed
Licorice	In vitro + limited clinical	Protective activity	May reduce mineral loss and support enamel preservation6 1,62	Limit ed
Natural Biomolecules				
L-Arginine	Clinical (RCTs)	Mineral deposition support	Enhances mineral deposition and acid resistance63	Mod erate
Salivary Proteins	Experi mental	Pellicle-mediated protection	Strengthens natural pellicle-mediated defense mechanism64	Mod erate

Natural Polysaccharides				
Gum Arabic	In vitro	Surface coating and mineral stabilization	Forms a protective layer and stabilizes minerals46	Limited
Chitosan And Nanochitosan	Clinical + in situ	Anti-erosive barrier formation and enhanced mineral delivery	Reduces erosive wear by forming a protective barrier and improves mineral delivery65	Moderate
Biomimetic Peptides				
Self - Assembling Peptide (P11-4)	Clinical (RCTs)	Guided mineral regeneration	Facilitates guided enamel regeneration and crystal nucleation66, 57	Moderate
Calcium Rich Natural Materials				
Eggshell-Derived Powder	In vitro + animal	Calcium supplementation	Serves as a bioavailable calcium source for remineralization54,67	Moderate

Table 3: Digital Approaches For Monitoring Erosive Tooth Wear And Their Potential Applications In Pediatric Dentistry

Digital Technology	**Potential Application**	**Potential Pediatric Application**	**Advantages**	**Key Limitation**	**References**
INTRAORAL PHOTOGRAPHY	Documentation of erosive changes and comparison during follow-up	Baseline documentation, follow-up comparison and communication with parents	Simple, non-invasive and inexpensive	Highly dependent on image quality and standardization	[70]

INTRAORAL SCANNING(IOS)	Recording tooth morphology and monitoring surface changes	Baseline digital records and monitoring of tooth-surface changes	Non-invasive and provides digital records	Scanning and registration errors	[72]
3D SCAN SUPERIMPOSITION	Assessment of changes in tooth surface over time	Longitudinal monitoring of progression or treatment response	Objective quantitative measurements	Requires accurate registration and stable reference areas	[76]
DIGITAL SURFACE ANALYSIS	Measurement of depth, area and volume of erosive lesions	Quantification of subtle morphological changes	Provides numerical outcomes	Sensitivity to very small changes remains concern	[77]
AI-ASSISTED ANALYSIS	Detection, grading and monitoring of erosive tooth wear	Potential early detection, severity assessment and longitudinal monitoring	Reduce examiner variability and automated analysis	Limited pediatric datasets clinical validation	[68]



6. Figure 1: Pathogenesis of Dental Erosion in Primary Teeth

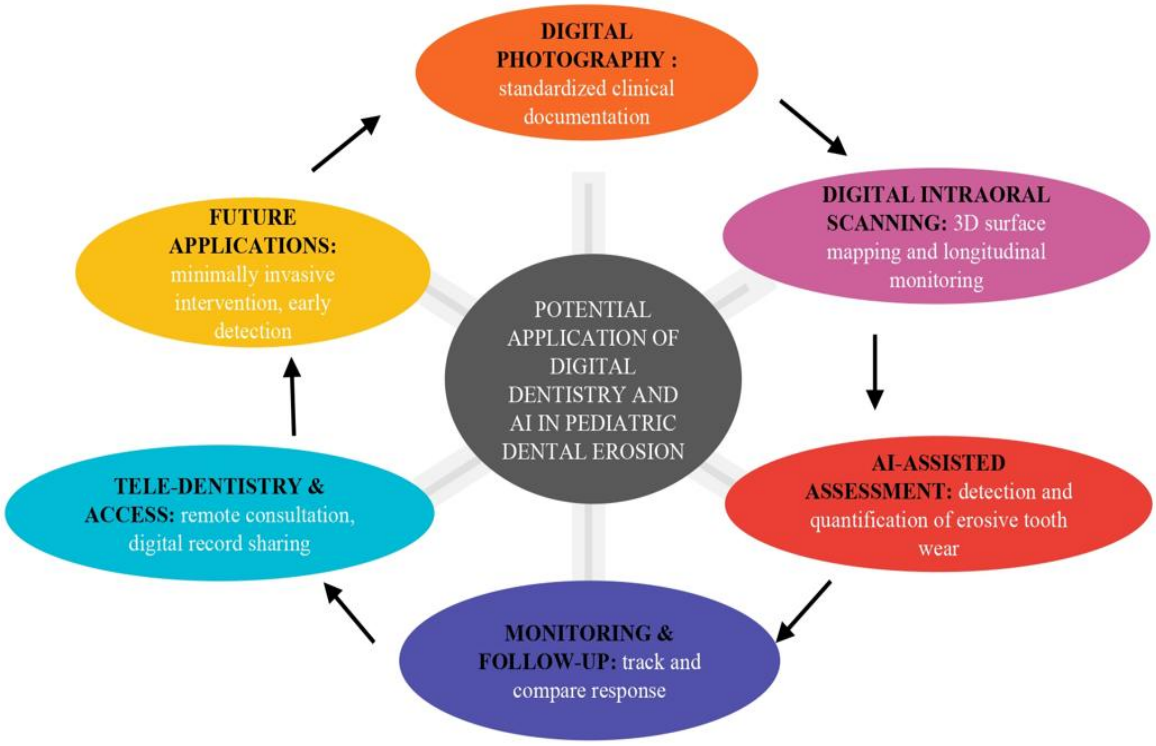


Figure 2: Digital And AI Applications In Pediatric Dental Erosion

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