EUROPEAN JOURNAL OF MATERIALS SCIENCE AND ENGINEERING
Volume 9, Issue 4, 2024: 323-336 | www.ejmse.ro | ISSN: 2537-4338

DOI: 10.36868/ejmse.2024.09.04.323

CURRENT TRENDS ON MATERIALS AND METHODS FOR TEETH WHITENING

Maria Mirabela IANCU[1], Cristiana Ioana TATIA[1], Alina ROBU[1*],
Marius Lucian VASILESCU[1], Iulian ANTONIAC[1], Anca Maria FRATILA[2]

[1] National University of Science and Technology POLITEHNICA Bucharest, Faculty of Material Science and Engineering, Department of Materials Science and Physical Metallurgy, 313 Splaiul Independentei Street, 060042, Bucharest, Romania.
[2]Department of Dental Medicine and Nursing, Faculty of Medicine, Lucian Blaga University of Sibiu, 550169 Sibiu, Romania.

Abstract

The purpose of teeth whitening is the removal of intrinsic or extrinsic discoloration via mechanical or chemical techniques that restore the teeth to their natural shade or lighten it, depending on the chosen method. Both the abrasive particles used in mechanical procedures and the oxidant agents applied in chemical bleaching are effective if they are used according to the stain aetiology, however, the risks associated with these products (e.g. potential tooth wear, sensitivity, damage of the enamel or dentin organic matrix) are not negligible. As a response to these issues, current research in the tooth whitening field is directed towards the development of safer whitening products such as dentifrices with lower abrasive index, natural bleaching agents, or laser-assisted whitening procedures that require shorter exposure time for optimal results. This review aims to provide a description of the currently available teeth whitening techniques and their limitations, as well as the novel alternatives that promise similar or superior results with less potential side effects. For a better understanding of the subject, the structure of the tooth, the causes of teeth discoloration as well as the mechanisms of action and chemistry behind the abrasive agents and peroxide-based whitening processes were also discussed.

Keywords: *whitening materials, gels, hydrogen peroxide, natural ingredients, surface, microscopy, side effects.*

Introduction

Discolored or stained teeth are a significant cosmetic problem, particularly when the anterior teeth are affected, therefore more and more people seek to improve the aesthetics of their smile, as this process boosts their overall self-confidence [1]. As a result, teeth whitening became one of the most requested procedures at dental cabinets, and, recent statistics show that the teeth whitening market will reach an approximate value of 8.94 billion dollars by 2029, with an annual growth rate of 3.75% between 2024 and 2029 [2].

Natural teeth pigmentation is genetically determined and is influenced by the color of the dentine (which can range from yellow to brown), the enamel being relatively translucent and contributing with pink, blue, and green tones. Dental stains are generated by chromogens, highly pigmented organic or metal-containing compounds that accumulate inside the tooth (intrinsic) or stick to the tooth enamel (extrinsic) [3]. Teeth whitening is based on either mechanical removal of the stain via detergents and abrasive agents, physical removal via laser or infrared light, or the

*Corresponding author: alinarobu2021@gmail.com

chemical degradation of the chromogens to lighten the tooth color (~ one or two shades for over-the-counter products or more in the case of professional procedures). Amongst these methods, chemical whitening is considered to be the most effective and safe, especially if natural whitening ingredients are used [4]. According to the growing demand, multiple teeth whitening options were developed. These include several over the counter (OTC) products such as whitening toothpastes, rinses, gums, paint-on varnishes, and strips, or bleaching procedures based on ultrasound, laser or UV light and concentrated hydrogen peroxide or carbamide peroxide gels, usually performed under the dentist supervision [5].

An important step in choosing the appropriate whitening method is the identification of the teeth color alteration cause (e.g. extrinsic, intrinsic, internalized - extrinsic stains entering the dentine through dental flaws on the tooth surface). If the cause is not correctly established the treatment will most likely fail to provide optimal results. Moreover, the incorrect use of hydrogen peroxide or carbamide peroxide-based OTC products, due to the patient's lack of knowledge regarding stain etiology, can also lead to undesirable consequences such as increased tooth sensitivity, excessive wear of dental tissues or alterations in the surface topography of the enamel and dentin [6]. Considering these risks, an increased interest is currently directed towards natural ingredients that are considered a safer option for teeth whitening. For example, fruits, particularly citrics, strawberries, apples, pineapples, and papayas, contain essential oils (e.g. limonene), organic acids (e.g. ascorbic acid, malic acid, lactic acid) and naturally occurring enzymes (e.g. bromelain, papain) that are not only effective whitening agents but may also provide an antibacterial effect [7]. Another natural ingredient that showed excellent results in the teeth whitening field is activated charcoal. Due to its porous texture, this compound has a high plaque and small particle adsorption capacity, thus preventing teeth discoloration [8].

Human teeth present two main segments, the crown (covered by a hard mineral tissue called enamel) and the root (comprised of dentin, pulp, and cementum) [9]. Dental enamel is the hardest tissue in the human body, this being attributed to its high hydroxyapatite (HA) crystal content (~95%). Ideally, the ratio between calcium and phosphate ions in HA should be 1.67 [11], however, it was found that in some areas of the enamel, this ratio can vary between 1.33 and 2.0 due to the presence of defects in the crystalline network such as vacancies clusters or substituted atoms or ions. These areas represent demineralization centers and are usually the starting point of dental stains or cavities, therefore the ratio and concentration of ions as well as their quantitative and qualitative characteristics should be monitored for the early detection of pathological changes in the structure of enamel [12]. Dentin is a permeable tubular structure, located in the inner layer of enamel, lateral wall of the pulp cavity and root canal. It contains approximately 70% hydroxyapatite; therefore, its hardness is lower compared to enamel. Since dentin is naturally yellow to light brown, it is the main tissue that determines the overall tooth color. Pure hydroxyapatite (e.g. without structural defects) is incolor or white, but, throughout time, chemical and mechanical erosion lead to the thinning of enamel, thus making the dentin more visible and consequently the overall tooth color darker [13, 14, 15]. Tooth color can also be influenced by the optical characteristics of enamel (e.g. scattering coefficient, absorption coefficient, light reflectivity, infinite optical thickness, etc.) that influence light transmission [14, 16].

Teeth color is influenced by a variety of factors such as light transmission and reflection characteristics at the surface of the tooth, hydroxyapatite content and thickness of the enamel layer, physiological dentine color and, last but not least, the presence of intrinsic or extrinsic stains (Fig. 1). Also, teeth tend to become darker with age, as a result of gradual wear of the enamel and the accumulation of extrinsic stains [17].

Fig. 1. Aspect of extrinsic (A-C) and intrinsic (D-K) teeth staining [4]

Extrinsic stains are generated via two main mechanisms. The first one is direct staining resulted from the incorporation of the staining compound in the enamel layer, while the second one is indirect via chemical interactions between the chromogens and the tooth surface. Direct staining is often associated with lifestyle habits, tannin-rich foods or drinks, tobacco products or deficitary tooth brushing being some causes. More than that, pigment producing microorganisms found in the oral microflora can cause yellow/orange or even brown/black staining. Direct stains can usually be removed using conventional prophylaxis (e.g. effective toothbrushing, whitening toothpastes) but in advanced cases, professional techniques such as ultrasonic cleaning, rotary polishing with prophylactic toothpaste, or air-jet polishing with abrasive powders is required [18]. Indirect staining is associated with the use of cationic anti-septics (e.g. chlorhexidine) and metal salts (e.g. iron salts) that are usually incolor or have a different chromatic than the resultant stain [19]. Studies showed that the mechanism behind indirect staining is based on the cationic antiseptics or metal salts-governed precipitation of dietary chromogens. Moreover, chlorhexidine-based staining was also found to be related to parachloraniline and metal sulfides generation following chlorhexidine breakdown and non-enzymatic browning, also known as the Maillard reaction [20]. Products containing oxidizing agents (e.g. hydrogen peroxide mouthwash) showed good results in controlling indirect staining associated with chlorhexidine, as they were able to physically remove stains from dental surfaces without affecting the antiplaque activity of the cationic antiseptic [21].

Intrinsic tooth discoloration is caused by structural or compositional changes of dental tissues due to genetic reasons (e.g. amelogenesis imperfect, dentinogenesis imperfect), use of certain medications, particularly tetracycline, excessive intake of fluoride, aging or dental trauma [22]. Tetracyclines are broad-spectrum antibiotics that have the ability to chelate calcium ions and incorporate them into dental tissues, thus causing yellow, gray or brown discoloration depending on the dosage, exposure time, and stage of tooth mineralization [23]. First-degree tetracycline stains (yellow to gray) can be successfully managed with OTC whitening products; however, more severe staining (brown, black) requires professional microabrasion and bleaching [24]. Overexposure to fluoride or fluorosis, is characterized by white or brown patches on the tooth surface. This disorder usually starts in the early stages of teeth development, the clinical manifestation being more obvious in permanent dentition. Therefore, to prevent this type of staining, children under the age of 6 shouldn't use toothpastes with fluoride concentrations higher than 600 ppm or 1000 ppm if they have a high risk of developing cavities [25]. Trauma-related intrinsic stains were found to be associated with calcification or necrosis of the dental pulp or pulp extirpation procedures which cause dentine hemorrhages that are followed by the deposition of chromogenic blood degradation products (e.g. hemosiderin, hemine) on the tooth surface [26]. Special abrasion techniques (e.g. hydrochloric acid microabrasion, macroabrasion), hydrogen peroxide bleaching and ceramic or resin-composite veneering produce the best outcomes in the removal of intrinsic stains, with the mention that the use of combinatorial treatments can extend their overall range of effectiveness [27].

Recently, the term of internalized discoloration was introduced to describe extrinsic stains that are incorporated into the enamel or dentine through a developmental defect or as a result of a traumatic event [28]. For example, amelogenesis imperfect and dentinogenesis imperfect are congenital illnesses that cause a disturbance in the formation and mineralization of the enamel or dentin, thus decreasing the mechanical resistance of the teeth and making them more susceptible to rapid wear, breakage, and loss and the areas affected by these conditions are particularly predisposed to the uptake of dietary chromogens. Additionally, dental bridge restorations, or partially skeletonized prosthetics, may affect the adjacent teeth's color [29-34]. Acquired defects caused by caries, gingival recession, or the use of restorative materials (e.g. amalgam restorations) are also areas with increased porosity and tendency to stain [35,36]. Implants are fixed straight into the jawbone, in contrast to traditional bridges, which need the neighboring teeth to be prepared in order to support the repair. This indicates that throughout the implant insertion procedure, neighboring teeth are neither harmed or impaired [37-40]. Considering the diversity of causes for internalized discoloration, professional evaluation and determination of the etiologic factor causing the stain plays an essential role in planning a specific prophylactic method and has an important impact on the related outcome.

This review aims to describe the currently available teeth whitening techniques and their limitations, as well as the novel alternatives that promise similar or superior results with less potential side effects. For a better understanding of the subject, the structure of the tooth, the causes of teeth discoloration as well as the mechanisms of action and chemistry behind the abrasive agents and peroxide-based whitening processes were also discussed.

Teeth whitening methods

As mentioned before, the determination of the stain aetiology and type of teeth discoloration is an important aspect in choosing the optimal teeth whitening method. Superficial or extrinsic stains respond well to less invasive OTC products while intrinsic stains may require professional treatments for best results [41]. Even if these terms are often used interchangeably, there is a difference between teeth whitening and teeth bleaching. The first one refers solely to the removal of stains on the teeth' surface maintaining their natural shade, while the concept of bleaching goes a step further and is based on the use of chemical agents that remove stains and also lighten the teeth with one or multiple shades depending on the bleaching agent [42]. Therefore, two major approaches can be distinguished, mechanical whitening via abrasive agents and chemical bleaching, usually performed with hydrogen peroxide-based products (Fig. 2) or safer alternatives based on natural ingredients (Table 1). Recently, laser and ultrasound-assisted whitening were also introduced in this field as novel techniques with promising results [43].

Table 1. The chemical composition of OTC and professional whitening products and their method of action [5, 44]

Type of product	Active agents	Method of action
Dentifrices	Abrasive particles: silica calcium phosphates alumina perlite diamond powder	Mechanical polishing of tooth surface, most effective on extrinsic stain.
	Tensioactive compounds: sodium citrate sodium peroxide sodium hexametaphosphate	Reduction of stain deposition on dental tissues.
	Anti-calculus agents: sodium pyrophosphate sodium tripolyphosphate	Reduction of Ca and Mg deposition on enamel.
	Optical dyes: Covarine Blue	Modification of the visual perception of tooth color.
Whitening rinses	Hydrogen peroxide at low concentrations (1–4%), sodium hexametaphosphate	Oxidation of chromogenic molecules, reduction of stain deposition.
Whitening strips	Hydrogen peroxide (5-15%)	Oxidation of chromogenic molecules
Chewing Gums	Sodium metaphosphate or hexametaphosphate	Reduction of stain deposition
Paint-On gels	Any combination of hydrogen or carbamide peroxide in any concentration	Oxidation of chromogenic molecules.
Professional whitening gels	25-40 % carbamide or hydrogen peroxide, gelling agents (cellulosic rubbers, fumed silica), gel stabilizers	Plain chemical or light activated oxidation of chromogenic molecules.
OTC products with natural ingredients	Limonene, caproic acid strawberry juice, weak organic acids (e.g. l-ascorbic acid, citric acid, malic acid) and enzymes (e.g. lactoperoxidase, bromelain, papain, actinidain)	Mild whitening effect by polishing the superficial layer of enamel and reducing plaque formation.

Mechanical whitening can be performed either at home or in dental offices, stain removal being achieved by brushing the teeth with a dentifrice. The term dentifrice is derived from the lLatin “dens” and “fricare” which mean “tooth” and “to rub”. Dentifrices are marketed as toothpastes, gels, or powders and they contain abrasive particles (e.g. hydrated silica, perlite, alumina, calcium carbonate, calcium pyrophosphate, sodium bicarbonate, etc.) that remove microbial plaque and extrinsic stains without inducing significant damage to tooth and gingival tissues. The abrasiveness of dentifrices is influenced by the particle shape, size, hardness, and usually in office used products contain harder abrasives in higher concentrations [47]. Even if they are generally considered safe, incorrect or excessive use of dentifrices can lead to increased teeth sensitivity due to the damaging of enamel or exposed dentin layer [48]. To develop safer products, current studies are directed towards the selection of abrasive agents that provide an optimization of radioactive dentin abrasion (RDA) and pellicle cleaning ratio (PCR) proportion in dentifrices, the most promising results being obtained with silica [49,50] and microfibrilated cellulose [51]-based formulations.

Depending on the type of tooth that the procedure is applied on, chemical bleaching can be divided into vital and non-vital bleaching. The ingredients in bleaching products are variable but most of them contain hydrogen peroxide as active agent, glycerin as a carrier, carbopol as a thickener, and flavoring agents. Vital teeth can be bleached at home using OTC products (e.g. toothpastes, strips, paint-on gels) and custom-fitted mouth guards filled with oxidizing gels (nightguards) or power bleached in an office with professional products. Since in-office bleaching implies higher concentrations of hydrogen peroxide (~25-40%) and, in some cases, activation of the oxidizing agent by curing lights (e.g. halogen, plasma arc, Xe–halogen, metal halide – Zoom, etc.), this method tends to act faster and provide more noticeable results [52]. Non-vital teeth are the ones that no longer receive blood flow, usually as a result of nerve damage or death. The primary indicators that a tooth became non-vital are discoloration (dull, gray color), pain, and sensitivity.

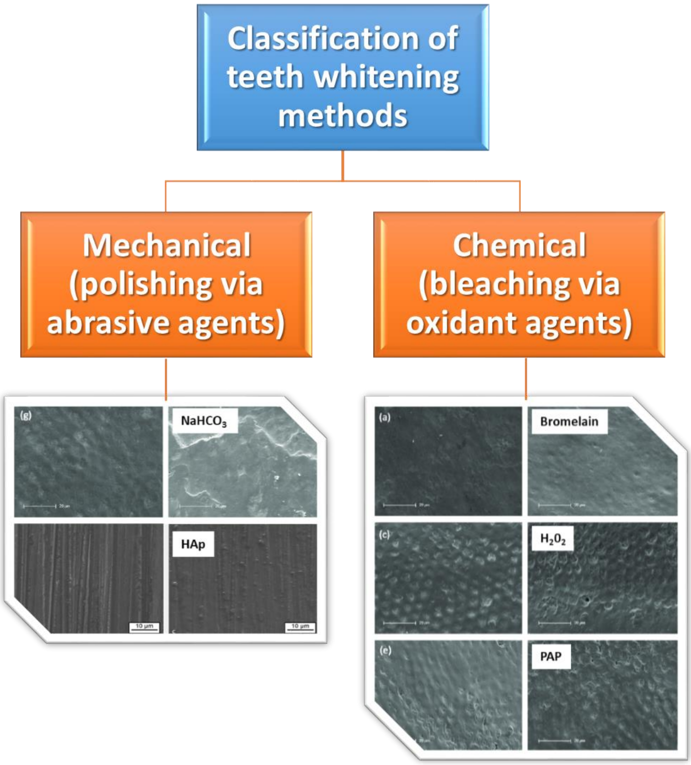


Fig. 2. Classification of teeth whitening methods and the microscopical aspect of teeth enamel before and after different whitening treatments [44, 45, 46]

Some examples of currently used non-vital bleaching techniques are walking bleaching and modified walking bleaching, non-vital power bleaching, and inside/outside bleaching [53]. Walking bleaching is performed by repeated application of a mixture of sodium perborate and distilled water in the pulp chamber until the desired tooth shade is reached, while modified walking bleaching involves the replacement of distilled water with concentrated hydrogen peroxide (~30%) and sealing of the whitening compounds in the pulp chamber for one week. In the case of non-vital power bleaching, a concentrated H2O2 gel is applied in the pulp chamber, activated via light or heat and, after the tooth's temperature decreases, the gel is removed. Finally, inside/outside bleaching involves the combination of the aforementioned techniques with home bleaching procedures [54].

The active compound in most bleaching products is hydrogen peroxide (H_2O_2) which can be found directly under this form or as carbamide peroxide, a stable complex that undergoes slow hydrolysis in contact with water yielding H_2O_2 and urea according to the following reaction (Fig. 3).

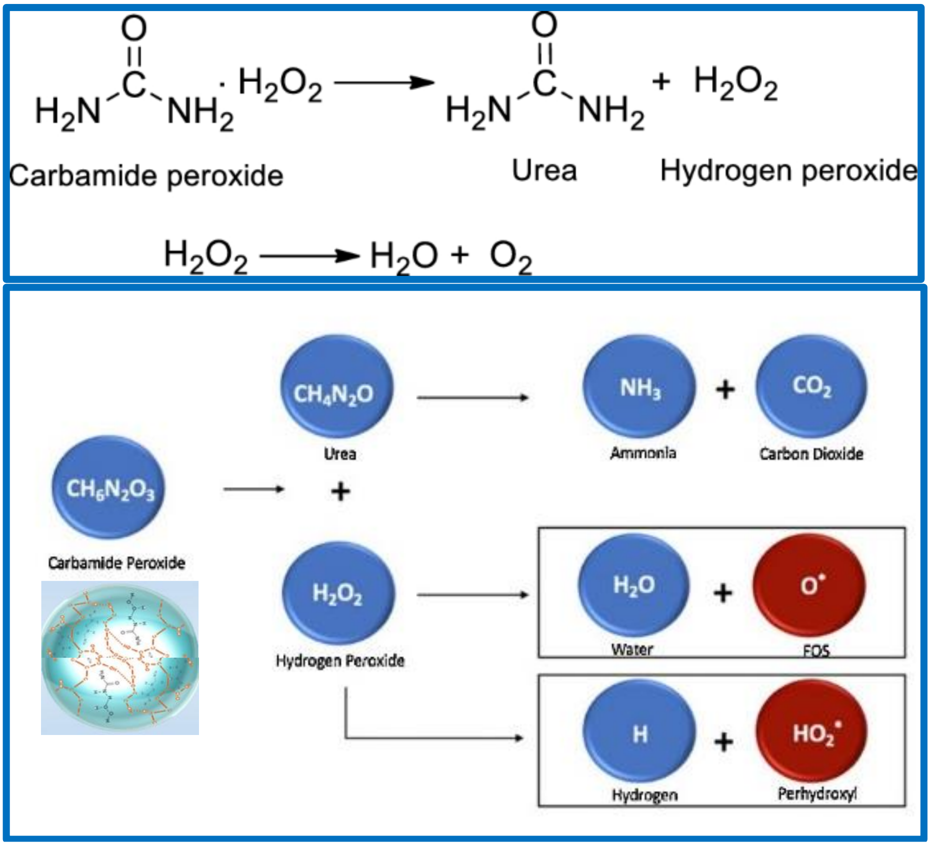


Fig. 3. The decomposition of carbamide peroxide into urea and hydrogen peroxide and further reactions that can occur during chemical bleaching [55]

Due to the fact that hydrogen peroxide is a powerful oxidizing agent, it rapidly reacts with electron-rich chromogens that stain the teeth, decomposing them into smaller, less colored or incolored molecules. From the chemical structure point of view, chromogens can be divided into 2 categories – large organic compounds with extended conjugated chains of alternating single or double bonds (e.g. β-carotene) and metal containing compounds. In contact with hydrogen peroxide, the double bonds from the organic chromogens structure tend to oxidize thus resulting lighter or incolor compounds. Bleaching of metal-containing chromogens however is difficult and H2O2 may not provide the desired results. Alternative options for this type of stains are bleaching with products containing sodium hypochlorite (NaOCl) that reacts with the double bonds of the metal-containing chromogens, or esthetic options such as veneers and crowns [56]. The degree of whitening cannot be fully controlled during chemical bleaching, but it is strongly dependent of the oxidizing agent concentration and chromogen nature. Chemical bleachers can be used as such or activated by light, heat or chemical mixing. So far, chemical activators (e.g. manganese gluconate, ferrous sulphate, manganese chloride) showed a significant improvement of whitening agent's performance by accelerating the chromogen oxidation reactions, thus reducing the application time and consequently post-bleaching sensitivity [57]. Fenton activators and UV light activation systems also showed good results but there are some controversies regarding the potential adverse effects such as pulpal damage and enamel dehydration caused by heat resulted following energy absorption by the tooth [55]. In response to these issues, Papadopolou et al. proposed a blue diode laser (445 nm wavelength), as bleaching agent activator.

According to literature, this particular wavelength allows for a precisely controlled energy delivery thus mitigating heat-related side effects. Considering that orange or orange-red is the complementary color to blue, a red-colored bleaching gel consisting 40% hydrogen peroxide was used in this study. It was concluded that the bleaching process was facilitated by the absorption of blue laser light by the red dye in the bleaching gel, the phenomenon being governed by phototermal and photochemical mechanisms. The penetration of laser light through the tooth was thus avoided and no notable intrapulpal temperature increase was recorded [58].

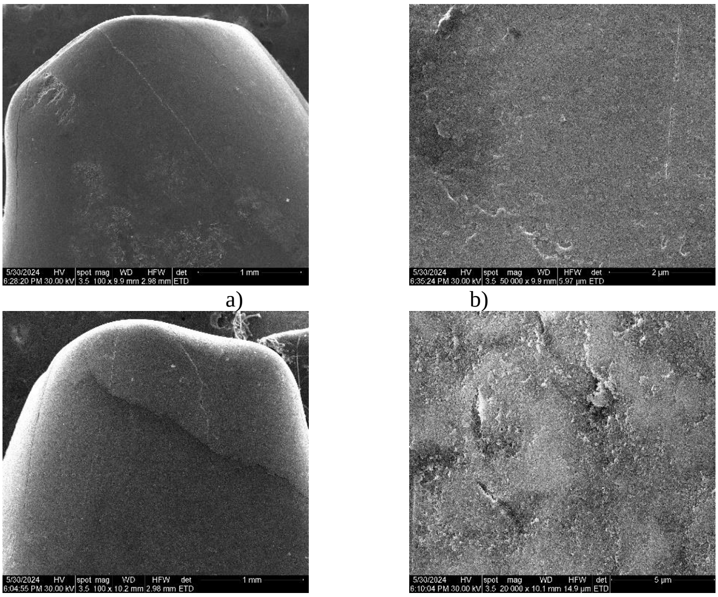
Risk associated with conventional teeth whitening methods and potential safer alternatives

Teeth can be regarded as complex organic/inorganic composites, as their main constituents are an organic protein matrix and calcium phosphates in the form of hydroxyapatite crystals. When mechanical procedures are used for teeth whitening, the risks are mainly associated with the use of abrasives with a higher hardness compared to natural hydroxyapatite (e.g. alumina, perlite). It was found that incorrect use or excessive use of such agents may damage the enamel and exposed dentin layers, particularly if a high pressure is applied during brushing [55].

The research in this field is directed towards the replacement of conventional abrasives with safer options while maintaining the whitening effect. Labib et al. developed a novel fluoride dentifrice containing microfibrilated cellulose (MFC) and entrapped silica and assessed it using the pellicle cleaning ratio method, and radioactive dentin abrasivity in order to calculate the cleaning efficiency index. It was found that the inclusion of MFC in the dentifrice induced a 3 to 4 fold improvement in plaque reduction while the entrapped silica provided the necessary force to remove biofilm from the tooth surface, all these with a lower abrasion level compared to other similar products [51]. Other studies targeted the development of silica gels and hydrated silica-based dentifrices, and it was revealed that hydrated silica has approximately 25% better cleaning effect compared to normal silica [59]. The whitening ability of sodium bicarbonate was also assessed and it was found that bicarbonate removes stains with less abrasion through a combination of mechanical and chemical processes [60]. Negative results were also recorded, a notable example being activated charcoal. Despite it is marketed as a natural agent that whitens teeth quick and easy, experimental studies revealed that activated charcoal containing toothpastes in fact haw a lower whitening effect compared to other products and the high abrasive potential of this agent makes it unsafe for intraoral use [61].

Moving forward to chemical bleaching, it is well known that the level of teeth whitening is proportional to the concentration of the bleaching agent that is, in most cases, hydrogen peroxide. However, hydrogen peroxide is a strong oxidizing agents that produces skin, eyes and mucous membranes irritations at concentrations higher than 10%. Moreover, the hydroxyl radicals generated upon hydrogen peroxide decomposition can give rise to lipid peroxidation, DNA damage and apoptosis. The maximum concentration at which hydrogen peroxide does not produce adverse effects was established as 5%, but the majority of dental bleaching products contain higher amounts of H_2O_2. In-office bleaching particularly, uses hydrogen peroxide gels with up to 40% concentration, and while whitening the teeth surface, H_2O_2 also diffuses into the pulp chamber causing inflammatory reactions that could initiate cervical and damage in soft tissues or DNA [62]. A comparative perspective between the untreated teeth and teeth treated with hydrogen peroxide gels with 35% concentration are shown in Fig. 4, using scanning electron microscopy technique (SEM) for surface analysis.

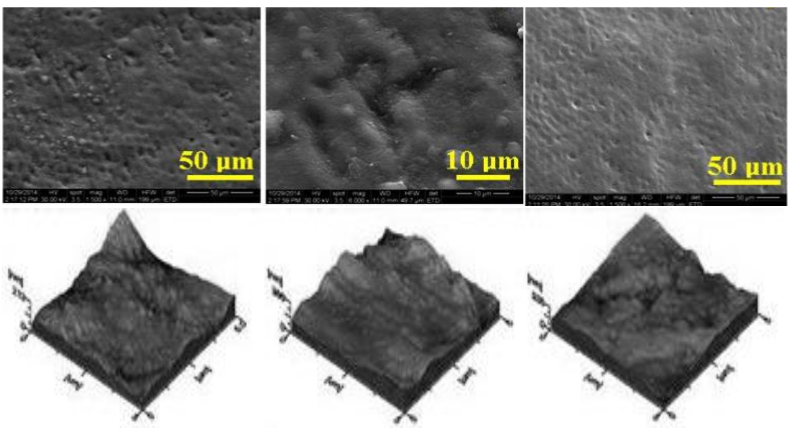
Studies showed that highly concentrated oxidizing compounds have the potential of damaging the teeth protein matrix, the dentin being the most affected. Enamel can also be influenced by these procedures, a loss of the aprismatic layer being observed after a carbamide peroxide gel (35% concentration) was used for chemical bleaching, 35 minutes a day for a 14 days time period [63]. This further leads to changes in the mechanical properties of the teeth due to the generation of microscopic defects and subsurface pores, their clinical manifestations being reversible pulpitis and thermal sensitivity. Even if guidelines and policies regarding the use of hydrogen peroxide were instituted to ensure public safety there is still the need of developing safer alternatives to this whitening agent.



a) b) c) d)

Fig. 4. Experimental SEM images of the: a) human teeth surface before bleaching/sample 1, b) surface detail at higher magnification of the sample 1, c) human teeth surface after bleaching with hydrogen peroxide gels with 35% concentration/sample 2, d) surface detail at higher magnification of the sample 2

Considering the results obtained so far, natural ingredients seem to be the most promising solution for this issue (Fig. 5). For example, limonene found in the essential oil of citrus peel, caproic acid extracted from vanilla fruits and strawberry juice, possess favorable teeth whitening properties, caproic acid being already incorporated in OTC whitening toothpastes.



a) b) c)

Fig. 5. Images of the human enamel obtained by SEM (up) and AFM (down): a) before bleaching; b) and c) after bleaching with gel extracted by different fruits

Other compounds such as weak organic acids (e.g. l-ascorbic acid, citric acid, malic acid) and enzymes (e.g. lactoperoxidase, bromelain, papain, actinidain) extracted from fruits, vegetables or dairy products are also under research, early studies revealing they have a mild whitening effect by polishing the superficial layer of enamel and reducing plaque formation [44].

Moreover, natural ingredients can also be used for soothing and remineralizing previously bleached teeth. Banana peel, aloe vera, antioxidant essential oils (e.g. eucalyptus, rosemary, bergamot) or sweet potato extracts, used in combination with hydrogen peroxide or after the bleaching procedure, not only restore natural tooth color, but also prevent peroxide-induced enamel morphology alterations, compared to the use of H_2O_2 alone [44,63].

Conclusions

As a general conclusion, two main approaches can be distinguished for teeth whitening, mechanical cleaning via abrasive particles and chemical bleaching with peroxides, each of them being associated with specific risks and benefits. In both cases, optimal results are achieved only if the tooth discoloration nature is correctly determined, preferably at a dental office, and the whitening method is chosen consequently. When mechanical procedures are used for teeth whitening, adverse effects are mainly associated with incorrect or excessive use of abrasive products or the use of abrasives with a higher hardness compared to natural tooth hydroxyapatite. In order to develop safer options, current studies are directed towards the selection of abrasive agents that provide an optimization of radioactive dentin abrasion (RDA) and pellicle cleaning ratio (PCR) proportion in dentifrices, the most promising results being obtained with sodium bicarbonate, hydrated silica and microfibrilated cellulose-based formulations. Chemical bleaching provides superior results, especially when it is performed with high peroxide concentrations in a controlled environment, but studies showed that highly concentrated oxidizing compounds have the potential of damaging the teeth protein matrix. Laser-assisted techniques, particularly the one implying blue diode lasers (445 nm wavelength), show great potential for bleaching agents activation, thus speeding up the chromogens oxidation reactions at the tooth surface, and reducing overall exposure time. Also, the replacement of peroxide-based bleaching agents with weak organic acids or enzymes extracted from natural ingredients could also be a solution for safer teeth whitening. However, the modes of action from a chemical and biological point of view as well as the long-term effects of these novel techniques are insufficiently documented, and mechanistic studies are still required for the development and marketing of more efficient teeth whitening formulations.

References

[1] Z. Wang, H. Mao, Y. Li, F. Liu, *Smile Big or Not? Effects of Smile Intensity on Perceptions of Warmth and Competence*, **J Consum Res** 2017, 43:787-805.

[2] https://www.mordorintelligence.com/industry-reports/teeth-whitening-market (accessed on 13.08.2024).

[3] Y.Kapadia, V.Jain, *Tooth staining: A review of etiology and treatment modalities*, **Acta Sci Dent Sci** 2018, 2:67-70.

[4] Carey, CM, *Tooth Whitening: What We Now Know*, **J Evid Based Dent Pract** 2014, 14:70-76.

[5] M.R. de Freitas, M.M. de Carvalho, P.C.S. Liporoni, A.C.B. Fort, R. de Morais e Moura, R.F. Zanatta, *Effectiveness and Adverse Effects of Over-the-Counter Whitening Products on Dental Tissues*, **Front Dent Med** 2021, 2:687507.

[6] A. Devila, R. Lasta, L. Zanella, M.D. Agnol, S.A. Rodrigues-Junior, *Efficacy and Adverse Effects of Whitening Dentifrices Compared With Other Products: A Systematic Review and Meta-analysis*, **Operative Dent** 2020, 45:e77-e90.

[7] R.F. Abidia, A.A. El-Hejazi, A. Azam, S. Al-Qhatani, K. Al-Mugbel, M. AlSulami, A.S. Khan, *In vitro comparison of natural tooth-whitening remedies and professional tooth-whitening system*, **Saudi Dent J** 2023, 35:165-171.

[8] V.T.P. Vaz, D.P. Jubilato, M.R.M. Oliveira, J.F. Bortolatto, M.C. Floros, A.A.R. Dantas, O.B. Oliveira Junior, *Whitening toothpaste containing activated charcoal, blue covarine, hydrogen peroxide or microbeads: which one is the most effective?*, **J Appl Oral Sci** 2019, 27:e20180051.

[9] L. Zhang, Y. Morsi, Y. Wang, Y. Li, S. Ramakrishna, *Review scaffold design and stem cells for tooth regeneration*, **Japan Dent Sci Rev** 2013, 49:14-26.

[10] R.S. Lacruz, S. Habelitz, J.T. Wright, M.L. Paine, *Dental enamel formation and implications for oral health and disease*, **Physiol Rev** 2017, 97:939-993.

[11] M. Oprea, S.I. Voicu, *Recent Advances in Applications of Cellulose Derivatives-Based Composite Membranes with Hydroxyapatite*, **Materials** (Basel, Switzerland) 2020, 13:2481.

[12] S. Bechtle, T. Fett, G. Rizzi, S. Habelitz, A. Klocke, G.A. Schneider, *Crack arrest within teeth at the dentinoenamel junction caused by elastic modulus mismatch*, **Biomaterials** 2010, 31:4238-4247.

[13] A.A. Algarni, P.S. Ungar, F. Lippert, E.A. Martínez-Mier, G.J. Eckert, C. González-Cabezas, A.T. Hara, *Trend-analysis of dental hard-tissue conditions as function of tooth age*, **J Dentistry** 2018, 74:107-112.

[14] T.R. Santana, R.M.F. BraganÇa, A.C.C. Correia, I.M. Oliveira, A.L. Faria e Silva, *Role of enamel and dentin on color changes after internal bleaching associated or not with external bleaching*, **J Appl Oral Sci** 2020, 29:e20200511.

[15] https://www.ncbi.nlm.nih.gov/books/NBK537112/ (accesed on 18.08.2024).

[16] T. Yamamoto, T. Hasegawa, H. Hongo, N. Amizuka, *Alternating lamellar structure in human cellular cementum and rat compact bone: Its structure and formation*, **J Oral Biosci** 2019, 61:105-114.

[17] A. Watts, M. Addy, *Tooth discolouration and staining: A review of the literature*, **British Dent J** 2001, 190:309-316.

[18] R. Hosdurga, *Extrinsic stains and management: A new insight*, **J Acad Indus Res** 2013, 1:465-442.

[19] G.R. Scott, *Dental Anthropology, In Reference Module in Biomedical Sciences*, **Elsevier**, 2014.

[20] B. Bagis, E. Baltacioglu, M. Özcan, S. Ustaomer, *Evaluation of chlorhexidine gluconate mouthrinse-induced staining using a digital colorimeter: An in vivo study*, **Quint Int** 2011, 42:213-223.

[21] Maanen-Schakel N., Slot D., Bakker E., Weijden G., *The effect of an oxygenating agent on chlorhexidine-induced extrinsic tooth staining: A systematic review*, **Int J Dent Hygiene** 2012, 10:198-208.

[22] Joiner A., Luo W., *Tooth colour and whiteness: A review*, **J Dentistry** 2017, 67:S3-S10.

[23] Sánchez A.R., Rogers R.S., Sheridan PJ, *Tetracycline and other tetracycline-derivative staining of the teeth and oral cavity*, **Int J Dermatol** 2004, 43:709-715.

[24] Faus-Matoses V., Faus-Matoses I., Ruiz-Bell E., Faus-Llácer V.J., *Severe tetracycline dental discoloration: Restoration with conventional feldspathic ceramic veneers: A clinical report*, **J Clin Experiment Dent** 2017, 9:e1379-e1382.

[25] Molina-Frechero N., Gaona E., Angulo M., Sánchez Pérez L., González González R, Nevarez Rascón M, Bologna-Molina R, *Fluoride Exposure Effects and Dental Fluorosis in Children in Mexico City*, **Int Med J Experiment Clin Res** 2015, 21:3664-3670

[26] Irusa K., Alrahaem I.A., Ngoc C.N., Donovan T., *Tooth whitening procedures: A narrative review*, **Dent Rev** 2022, 2:100055.

[27] McEvoy S.A., *Combining chemical agents and techniques to remove intrinsic stains from vital teeth*, **General Dent** 1998, 46:168-172.

[28] Walmsley A.D., Walsh T.F., Lumley P.J., Burke F.J.T., Shortall A.C.C., *Hayes-Hall R, Pretty IA, Caries and other reasons for restoring teeth* Chapter 7, **In Restorative Dentistry** (Second Edition), Eds, Churchill Livingstone: Edinburgh, 2007, p. 57-72.

a. Vladescu, M.A. Surmeneva, C.M. Cotrut, R.A. Surmenev, I.V. Antoniac, *Bioceramic Coatings for Metallic Implants*. In: Antoniac, I. (eds) **Handbook of Bioceramics and**

[29] Antoniac, *Biologically responsive biomaterials for tissue engineering*, **Springer Science & Business Media**, 2012

[30] E. Craciunescu, C. Sinescu, M.L. Negrutiu, D.M. Pop, H.C. Lauer, M. Rominu, I. Antoniac, *Shear bond strength tests of zirconia veneering ceramics after chipping repair*. **Journal of Adhesion Science and Technology**, **30**(6), 666–676, 2015.

[31] Dawod, N.; Stoia, D.I.; Focșăneanu, S.; Antoniac, A.; Robu, A.; Dura, H.; Dana Cârstoc, I.; Dragomir, B.R. *Sheat Stress Analysis by Finite Elements of a Metal-Ceramic Dental Bridge on a CoCr Alloy Support*; **Bull., Series B**,Vol. 85, 2023.

[32] Forna, D.A.; Robu, A.; Budacu, C.; Petre, M.; Topoliceanu, C.; Dana, S.M.; Stamatin, O.; Antoniac, I.; Forna, N. *Study Regarding the Role of Barrier Membranes in Guided Bone Regeneration Techniques*; 2023; Vol. 15;.

[33] Dawod, N.; Antoniac, A.; Antoniac, I.; Miculescu, M.; Robu, A.; Ungureanu, E.; Agop-Forna, D.; Dana Cârstoc, I.; Dura, H.; Dragomir, B.R. *Corrosion Behavior and Microstructural Analysis of Some Co-Cr Alloys Used for Metal-Ceramic Restorations in Dentistry*. ***Bull., Series B***, *85*, 2023.

[34] Sulieman M, A*n Overview of Tooth Discoloration: Extrinsic, Intrinsic and Internalized Stains*. **Dent Update** 2005, 32:463-464.

[35] Cimpean, S.I.; Burtea, A.L.C.; Chiorean, R.S.; Dudescu, M.C.; Antoniac, A.; Robu, A.; Campian, R.S.; Timis, L.I. *Evaluation of Bond Strength of Four Different Root Canal Sealers*. **Materials** 2022, *15*.

[36] I.V. Antoniac, M. Filipescu, K. Barbaro, A. Bonciu, R. Birjega, C.M. Cotrut, E. Galvano, M. Fosca, I.V. Fadeeva, G. Vadalà, M.D., Julietta V. Rau, *Iron ion-doped tricalcium phosphate coatings improve the properties of biodegradable magnesium alloys for biomedical implant application*, **Advanced Materials Interfaces, 7** (16), 2020.

[37] A.A. Matei, I. Pencea, S.G. Stanciu, R. Hristu, I. Antoniac, E. Ciovica, C.E. Sfat, *Structural characterization and adhesion appraisal of TiN and TiCN coatings deposited by CAE-PVD technique on a new carbide composite cutting tool*, **Journal of Adhesion Science and technology**, **29** (23), 2576-2589, 2015.

[38] S. Cavalu, I.V. Antoniac, L. Fritea, I.M. Mates, C. Milea, V. Laslo, S. Vicas, *Surface modifications of the titanium mesh for cranioplasty using selenium nanoparticles coating,* **Journal of Adhesion Science and Technology**, **32** (22), 2509-2522, 2018

[39] R. Oancea, A. Bradu, C. Sinescu, R.M. Negru, M.L. Negrutiu, I. Antoniac, *Assessment of the sealant/tooth interface using optical coherence tomography*, **Journal of Adhesion Science and Technology, 29** (1), 49-58, 2015.

[40] G. Plotino, L. Buono, N.M. Grande, C.H. Pameijer, F. Somma, *Nonvital tooth bleaching: A review of the literature and clinical procedures*, **J Endodontics** 2008, 34, 394-407.
[41] G. Malcangi, A. Patano, A.D. Inchingolo, A.M. Ciocia, F. Piras, G.Latini, C.Di Pede, G. Palmieri, C. Laudadio, V.Settanni, et al., E*fficacy of Carbamide and Hydrogen Peroxide Tooth Bleaching Techniques in Orthodontic and Restorative Dentistry Patients: A Scoping Review*, **Appl Sci** 2023, 13:7089.
[42] D. Dionysopoulos, S. Papageorgiou, C. Papadopoulos, S. Davidopoulou, A.Konstantinidis, K. Tolidis, *Effect of Whitening Toothpastes with Different Active Agents on the Abrasive Wear of Dentin Following Tooth Brushing Simulation*, **J Funct Biomater** 2023, 14:268.
[43] A. Gasmi Benahmed, A. Gasmi, A. Menzel, I. Hrynovets, S. Chirumbolo, M. Shanaida, R. Lysiuk, Shanaida Y, Dadar M, Bjørklund G, *A review on natural teeth whitening*, **J Oral Biosci** 2022, 64:49-58.
[44] L.K. Müller-Heupt, N. Wiesmann-Imilowski, S. Kaya, S. Schumann, M. Steiger, M. Bjelopavlovic, J. Deschner, B. Al-Nawas, K.M. Lehmann, *Effectiveness and safety of over-the-counter tooth-whitening agents compared to hydrogen peroxide in vitro*, **Int J Mol Sci** 2023, 24(3):1956
[45] S. Sarembe, J. Enax, M. Morawietz, A. Kiesow, Meyer F., *In vitro whitening effect of a hydroxyapatite-based oral care gel*, **Eur J Dent**, 2020, 14(3):335-341.
[46] S. Subramanian, D. Appukuttan, A. Tadepalli, Prakash P., Victor D., *The role of abrasives in dentifrices*, **J Pharm Sci Res** 2017, 9:221-224.
[47] M. Epple, F. Meyer, J. Enax, *A Critical Review of Modern Concepts for Teeth Whitening*, **Dent J** 2019, 7:79.
[48] S.B. de Andrade Luz, R.I.M. da Cunha Oliveira, L.A.L. Guanabara, B.B. Viana, R.T.A. Dias, A.U.D. Batista, M.R.G.R. Caldas, D.F.G. de Araújo, *Effect of whitening dentifrices on dental enamel: an analysis of color, microhardness, and surface roughness in vitro*, **Quint Int** 2024, 0:0.
[49] J. Enax, F. Meyer, E. Schulze Zur Wiesche, I. Fuhrmann, *Fabritius HO, Toothpaste abrasion and abrasive particle content: correlating high-resolution profilometric analysis with relative dentin abrasivity (RDA)*, **Dent J** 2023, 11:79.
[50] M.E. Labib, A. Perazzo, J.L. Manganaro, Y. Tabani, C.J. Durham, B.R. Schemehorn, H.C. McClure, L.J. Walsh, *Stain removal, abrasion and anticaries properties of a novel low abrasion dentifrice containing micro-fibrillated cellulose: In vitro assessments*, **J Dent** 2024, 146:105038.
[51] M.Q. Alqahtani, *Tooth-bleaching procedures and their controversial effects: A literature review*, **Saudi Dent J** 2014, 26:33-46.
[52] A.S. Coelho, L. Garrido, M. Mota, C.M. Marto, I. Amaro, E. Carrilho, A. Paula, *Non-vital tooth bleaching techniques: A systematic review*, **Coatings** 2020, 10:61.
[53] S. Şişmanoğlu, *Bleaching of nonvital teeth: A review*, **J Health Sci** 2020, 2:91-114.
[54] R. Alkahtani, S. Stone, M. German, P. Waterhouse, *A review on dental whitening*, **J Dentistry** 2020, 100:103423.
[55] M. Pascolutti, D. de Oliveira, *A radical-free approach to teeth whitening*, **Dent J** 2021, 9:148.
[56] G.R. Batista, D.C. Barcellos, C.R. Torres, E.H. Goto, C.R. Pucci, A.B. Borges, *The influence of chemical activation on tooth bleaching using 10% carbamide peroxide*, **Operative Dent** 2011, 36:162-168.
[57] A. Papadopoulou, D. Dionysopoulos, D. Strakas, P. Kouros, E. Vamvakoudi, P. Tsetseli, Kolokitha O.E., Tolidis K., *Exploring the efficacy of laser-assisted in-office tooth bleaching:*

A study on varied irradiation times and power settings utilizing a diode laser (445 nm), **J Photochem Photobiol B: Biol** 2024, 257:112970.

[58] M. Cho, *The tooth whitening effect of toothpaste containing high cleaning silica and sodium hexametaphosphate and the preventive effect of staining by coffee, tea and wine,* **Int J Clin Prevent Dent** 2020, 16:192-199.

[59] S. Rath, V. Sharma, C.B. Pratap, T. Chaturvedi, *Abrasivity of dentrifices: An update,* **SRM J Res Dental Sci** 2016, 7:96.

[60] D.B.M. Tomás, M.P. Pecci-Lloret, J. Guerrero-Gironés, *Effectiveness and abrasiveness of activated charcoal as a whitening agent: A systematic review of in vitro studies,* **Ann Anatomy** 2023, 245:151998.

[61] H. Altınışık, S. Akgül, M. Nezir, S. Özcan, E. Özyurt, *The effect of in-office bleaching with different concentrations of hydrogen peroxide on enamel color, roughness, and color stability*, **Materials** (Basel, Switzerland) 2023, 16:1389.

[62] J. Fearon, *Tooth whitening: Concepts and controversies,* **J Irish Dent Assoc, 53,** 2007, 132-140.

[63] S. Gopinath, V. James, V. Sampath, K. Karthikeyan, K. Sanjeev, S. Mahalaxmi, *Effect of bleaching with two different concentrations of hydrogen peroxide containing sweet potato extract as an additive on human enamel: An in vitro spectrophotometric and scanning electron microscopy analysis,* **J Conserv Dent 16,** 2013,:45-49.

Received: March 12, 2024
Accepted: September 29, 2024