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Effects of different whitening toothpastes on the color and surface properties of resin composites after staining

Elanur Yıldızoğlu¹, Melih Manir² and Muhammet Karadas^{1*}

Abstract

Background This in-vitro study aimed to assess the effects of whitening toothpastes on color and translucency changes and surface roughness of resin composites.

Methods Disk-shaped resin composite samples from each composite (Clearfil Majesty Esthetic, Palfique Estelite Paste, and Charisma Smart) were made and randomly allocated into five groups ($n = 10$): Crest Pro Health Whitening, Advance White Pro, Sensodyne Extra Whitening, a control group (distilled water), and a positive control group (exposed to only stain). The samples were exposed to a tea solution and brushed for 30 days. Surface roughness and color measurements were performed immediately and at 15 and 30 days. Data were evaluated using three-way ANOVA ($\alpha = 0.05$).

Results Significant differences were determined among the groups for ΔL , Δb , and ΔE_{00} values in each resin composite ($p < 0.05$). The positive control group presented considerably higher ΔL values than the other groups ($p < 0.05$). Color changes presented no significant difference among whitening toothpastes. The color change in all groups was above the clinically acceptable level ($\Delta E_{00} > 1.8$) after 30 days, except for the distilled water. Translucency changes remained below the clinically perceptible threshold ($\Delta RTP_{00} < 0.62$) in most groups. For samples brushed with whitening toothpastes, Δb had the greatest impact on ΔE_{00} , whereas in the distilled water and positive control groups, ΔL was the primary factor influencing ΔE_{00} changes. The surface roughness of the resin composites increased significantly over time ($p < 0.001$). Clearfil Majesty Esthetic showed the highest surface roughness above clinically acceptable limits ($Ra > 0.2 \mu m$), regardless of the whitening toothpaste used. Roughness values did not show significant differences among the toothpastes for each resin composite.

Conclusions Whitening toothpaste with blue covarine did not create a different color change. All whitening toothpastes tested increased the surface roughness, regardless of the type of resin composites evaluated. The type of resin composite had a minimal impact on color and translucency changes when exposed to brushing with various whitening toothpastes.

Keywords Color, translucency, toothpaste, roughness, resin composite

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Background

The growing aesthetic expectations of patients have led to a significant rise in the demand for teeth whitening procedures. Bleaching procedures are often conducted under the control of a dental professional. In-office procedures utilize high concentrations of carbamide peroxide or hydrogen peroxide for impressive results; however, at-home bleaching employs reduced concentrations, which people apply using specific trays [1, 2]. However, consumer behavior regarding teeth whitening has recently changed significantly due to the influence of social media and the increase in alternative products. The increase of over-the-counter products like mouthwashes, toothpastes, strips, pens, and varnishes has tended to the whitening process toward home solutions without a dentist's supervision [3]. The user-friendly design, low cost, aggressive marketing, and widespread accessibility have enabled the rapid development of over-the-counter whitening agents [4].

Whitening toothpastes are among the most widely used over-the-counter products designed for regular use without a dentist's visit. They aim to whiten teeth in a short time by avoiding extrinsic stains [2]. To provide whitening effects, some substances, including abrasives, adsorbent particles, polyphosphates, enzymes, peroxides, or agents having optical properties, have been adopted into these products [5, 6]. Abrasives are one of the major ingredients in whitening toothpastes, removing and preventing the formation of external stains [5, 7]. Some common abrasives contain calcium carbonate, hydrated silica, dicalcium phosphate dihydrate, sodium bicarbonate, alumina, and perlite [8, 9]. Also, optical pigments like blue covarine are deposited on the tooth surface that could change the optical properties of the tooth surface, consequently enhancing the perception and measurement of tooth whiteness [2, 10].

Previous studies have reported that tooth brushing with whitening toothpastes was effective in removing stains from the tooth surface [5, 11–13]. However, the use of these toothpastes has been found to increase the surface roughness of the enamel [11, 14–16]. While the abrasives in toothpastes may reduce extrinsic tooth discoloration, their abrasiveness must remain within safe and acceptable limits. On the other hand, many consumers and patients have dental composite restorations or teeth containing fillings, so it is also crucial to investigate whether whitening toothpastes can lead to significant color or surface changes in restorative materials. Some studies have examined the effect of whitening toothpastes on the color change of artificially stained composite materials, but they have reported controversial results [17–21]. In these studies, the surface stain elimination properties of whitening toothpastes have been mostly examined, and their actual color and translucency changes have

not been accurately evaluated. On the other hand, several investigations have stated that whitening toothpastes increase the surface roughness of resin composites due to the use of different abrasive particles [20, 22]. Higher surface roughness might contribute to biofilms colonizing and maturing more quickly, increasing the likelihood of resin composite degradation and the risk of caries [23].

The abrasiveness of toothpaste may be determined by relative dentine abrasivity (RDA) [24]. This value is measured by evaluating in-vitro the capability of a toothpaste mixture to remove radioactive dentin during a brushing routine, compared to a conventional abrasive formulation [25, 26]. According to the International Organization for Standardization (ISO), the RDA for toothpaste should not be more than 250. Whitening toothpastes should have an average RDA between 60 and 100 or more than 100 [24, 25]. However, although RDA values are often used as a measure of toothpaste abrasiveness, the impact of these values on restorative materials has not been evaluated. Nanofilled resin composites exhibit enhanced mechanical properties compared to traditional hybrid or microfilled composites. The addition of nanoparticles, such as zirconium or silica, to the resin matrix can significantly enhance specific characteristics, including fracture toughness and flexural strength [27, 28]. Additionally, nanofill resin composites exhibit excellent abrasion resistance and can achieve wear resistance comparable to that of enamel tissue. This improvement is due to the uniform distribution of nanofillers and a reduction in de-bonding between the filler and the resin matrix [27, 29].

This study aimed to assess the effects of three whitening toothpastes with different RDA scores on color and translucency changes, as well as surface roughness, of stained resin composites. The tested null hypotheses were as follows: (1) there would be no significant differences among whitening toothpastes with respect to color change, translucency change, and surface roughness; and (2) there would be no significant differences among resin composites with respect to color change, translucency change, and surface roughness.

Methods

Study design

In this study, 150 disk-shaped samples from three different resin composites were examined after brushing with three different whitening toothpastes. The resin composites included: Clearfil Majesty Esthetic (CME: microhybrid; Kuraray Noritake Dental, Okayama, Japan), Palfique Estelite Paste (PEP: nano-hybrid; Tokuyama Dental, Vicenza, Italy), and Charisma Smart (CS: sub-micro-hybrid; Kulzer, Hanau, Germany). The whitening toothpastes used in the study were: Crest Pro-Health Whitening (CPW: Procter & Gamble, Cincinnati, Ohio, USA), Advance White Pro (AWP: Church & Dwight LTD,

Folkestone, UK), and Sensodyne Extra Whitening (SEW: SmithKline Beecham LTD, UK). Also, a control group ((DW): stored in only distilled water) and a positive control group ((PC): exposed to only stain, no brushing) were designed. The whitening toothpastes were selected based on their RDA scores: Crest Pro Health Whitening (162), Sensodyne Extra Whitening (104), and Advance White Pro (47) [30–32]. The response variables included color change (ΔE_{00}), relative translucency change (ΔRTP_{00}) measured on the CIEDE2000 system, and surface roughness measured with a surface profilometer at three different time intervals. Table 1 presents the characteristics of the resin composite materials and toothpastes used in this study. Based on a power analysis, resin composite samples from each material were randomly allocated to five groups ($n=10$) through computer-generated randomization (www.random.org). The sample size was determined by reviewing similar studies using G*Power 3.1 software (Heinrich Heine University, Germany) with the F-test family [23, 33]. The input parameters for the research were a statistical power ($1-\beta$) of 0.80, an effect size (Cohen w) of 0.40 [34], a significance level (α) of 0.05, a type II error rate (β) of 0.20, and a confidence level of 95%. A minimum total sample size of 105 was required, with 7 samples per group.

Sample preparation

Resin composite samples were prepared using a cylindrical Teflon mold with dimensions of 8 mm x 2 mm, and the outer surface was covered with a polyester strip. The sample was then pressed against a glass slide with finger pressure to ensure the final layer was homogeneous.

Photoactivation was performed for 20 s using a light-emitting diode device (VALO, Ultradent, USA) at an irradiance of 1000 mW/cm². Then, mechanical polishing of the top surface of the composite disks was performed using a metallographic polishing instrument (Forcipol 102, Metkon, Türkiye) with grits of #600, #1000, and #2500 silicon carbide papers under running water. Final polishing was performed using a felt disc associated with polishing paste (Diamond Polish, Ultradent, South Jordan, USA). The thickness of the composite discs was checked by a digital micrometer (Meşem, Guangzhou, China) with an accuracy of 0.02 mm. After polishing procedures, the samples were immersed in distilled water in an incubator at 37 °C for 24 h to complete polymerization.

Brushing protocol

The samples were prepared for the toothbrushing process after the initial color and surface roughness measurements (T1). An electric toothbrush (3D White, Oral-B, Braun GmbH, Germany) with a soft brush head was used to brush the composite samples in the clean mode. Each group had its brush head. The sample was brushed horizontally for 10 s after being covered in a slurry made from a 1:1 ratio of toothpaste and distilled water [35]. The toothbrush was attached to a stand so that its head was parallel to the sample surface. Brushing was performed under a 200 g load, controlled with an orthodontic gauge (Correx; Haag-Streit, Switzerland) [36]. Before brushing, samples were kept in a tea solution at 37 °C for 15 min, then washed under running water for 1 min [35]. Tea was used as the staining solution because

Table 1 Chemical components of whitening toothpastes and resin composite materials used in this study

Material (Lot number)	Manufacturer	Composition
Crest Pro Health Whitening (3186GR)	Procter & Gamble, Cincinnati, Ohio, USA	Water, sorbitol, hydrated silica, sodium lauryl sulfate, sodium gluconate flavor, cargeenan, sodium citrate, xanthan gum, zinc citrate, sodium saccharin, sodium hydroxide, stannous chloride, sucralose, titanium dioxide
Advance White Pro (FE4104)	Church & Dwight LTD, Folkestone, UK	Aqua, sodium bicarbonate, hydrogenated starch hydrolysate, hydrated silica, glycerin, tetrasodium pyrophosphate, aroma, alumina, sodium saccharin, sodium lauryl sarcosinate, sodium lauryl sulfate, cellulose gum, sodium fluoride, limonene, CI 74,160.
Sensodyne Extra Whitening (4329EKWC)	Smith Beecham LTD, UK	Aqua, hydrated silica, sorbitol, glycerin, pentasodium triphosphate, potassium nitrate, PEG-6, alumina, aroma, titanium dioxide, sodium methyl cocoyl taurate, cocamidopropyl betaine, xanthan gum, sodium hydroxide, sodium saccharin, sodium fluoride.
Clearfil Majesty Esthetic (5L0096)	Kuraray Noritake Dental, Okayama, Japan (Microhybrid)	Silanated barium glass filler, silica filler, bisphenol A diglycidil ether dimethacrylate, triethylene glycol dimethacrylate, dl-camphorquinone. Filler content: 85.5 wt%
Palfique Estelite Paste (009E92)	Tokuyama Dental, Vicenza, Italy (Nano-hybrid)	Silica zirconia spherical filler, bisphenol A diglycidil ether dimethacrylate, triethylene glycol dimethacrylate, titanium dioxide. Filler content: 82 wt%
Charisma Smart (N010535)	Kulzer, Hanau, Germany (Submicro-hybrid)	Barium aluminium fluoride glass, bisphenol A diglycidil ether dimethacrylate, triethylene glycol dimethacrylate, titanium dioxide, fluorescent pigments, pyrogenic silicon dioxide. Filler content: 78 wt%

of its high chromogenic content and its frequent use in in-vitro studies evaluating extrinsic discoloration of resin composites [33, 37]. The tea solution was prepared by brewing 3.5 g of black tea in 100 mL of boiling water for 10 min (Caykur Altınbaş, Rize, Türkiye). The samples were brushed twice daily, after which they were rinsed to remove the toothpaste and immersed in distilled water [38]. This daily routine was repeated twice a day for 30 days, simulating two months of brushing. Samples were kept in distilled water until the next experimental cycle. In the positive control group, the samples were only exposed to the tea solution; they were not brushed. The measurements were retaken after 15 days (T2) and 30 days (T3). The workflow diagram for the study is shown in Fig. 1.

Color and translucency measurements

A spectrophotometer (VITA Easyshade Advance, Zahnfabrik, Bad Säckingen, Germany) was used to determine the color values against white and black backgrounds according to the Commission Internationale de l'Éclairage (CIE) $L^*a^*b^*$ method. A calibration plate was used to set the spectrophotometer up according to the manufacturer's instructions before each measurement. The CIE $L^*a^*b^*$ measurements were recorded as the L^* scale from white to black (100-0) brightness, the a^* axis for red-green, and the b^* axis for yellow-blue coordinates. For each sample, three readings were taken, and the average was calculated. The CIEDE2000 formula was employed to quantify color differences (ΔE_{00}) in the samples. The calculation was performed using the following Eqs. [39, 40]:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}$$

$\Delta L'$, $\Delta C'$, and $\Delta H'$ in the CIEDE2000 (ΔE_{00}) equation are the differences between the lightness (L), chroma (C), and hue (H) measurements of the samples before (T1) and after (T2 or T3) the brushing procedure, respectively. C and H values were calculated from the measured a^* and b^* values using $C^* = \sqrt{a^{*2} + b^{*2}}$ and $H^* = \arctan(b^*/a^*)$. In equations, S_L , S_C , and S_H are weighting functions used in the calculation to correct the problems detected in the CIELAB system. K_L , K_C , and K_H are parametric correction factors for errors arising from experimental settings. R_T (rotation function) denotes the relationship between variations in color intensity and alterations in color tone within the blue spectrum. The relative translucency parameter (RTP00) was calculated by applying the CIEDE2000 color difference formula to the L^* , a^* , and b^* coordinates obtained over standardized black and white backgrounds [40, 41]:

$$RTP00 = \left[\left(\frac{L_B - L_W}{k_L S_L}\right)^2 + \left(\frac{C_B - C_W}{k_C S_C}\right)^2 + \left(\frac{H_B - H_W}{k_H S_H}\right)^2 + R_T \left(\frac{C_B - C_W}{k_C S_C}\right) \left(\frac{H_B - H_W}{k_H S_H}\right) \right]^{1/2}$$

In the equation, the subscripts “B” and “W” indicate the lightness (L'), chroma (C'), and hue (H') coordinates of the samples measured on black and white backgrounds, respectively. All other terms correspond to those used in the standard CIEDE2000 formula. The change in relative translucency parameter (ΔRTP_{00}) was calculated as follows: $\Delta RTP_{00} = RTP_{01} - RTP_{23}$, where the subscript 1 denotes the initial measurements, and subscript 23 refers to the values obtained after brushing at 15 and 30 days.

ΔE_{00} values for perception (PT) and acceptance (AT) thresholds (50:50%) were 0.8 (PT) and 1.8 (AT) units, respectively [39, 40]. The relative translucency parameter difference (ΔRTP_{00}) was calculated (T1 – T2 and T1 – T3). ΔRTP_{00} for PT and AT thresholds (50:50%) were 0.62 and 2.62 units, respectively [40, 41].

Surface roughness measurements

A contact profilometer (PCE-RT 1200, PCE Instruments, Germany) was used to measure the surface roughness (R_a , μm) on day 0 and after 15 and 30 days. The profilometer was calibrated prior to each measurement in accordance with the manufacturer's guidelines. Surface roughness parameters were adopted at a traverse speed of 0.25 mm/s with a cut-off length (λ_c) of 0.80 mm [17]. Five measurements were made at different points on the surface. The R_a value for each sample was recorded as the mean of five measurements.

SEM analysis

Representative composite samples were analyzed using a scanning electron microscope (SEM) (JEOL JSM-6610, Massachusetts, USA) at a magnification of 5000 $\times$. SEM images of samples were taken before and 30 days after brushing. The samples were coated with gold using a sputter coater under vacuum conditions and an acceleration voltage of 15 kV. The toothpastes were placed uniformly on the measuring base and kept in a dryer for one week. After the drying period, they were examined using SEM equipped with energy-dispersive X-ray spectroscopy (EDS) at a magnification of 1000 $\times$ and an acceleration voltage of 15 kV.

Statistical analysis

The Shapiro–Wilk and Levene's tests showed that the color parameters (ΔL , Δa , Δb , ΔE_{00} , RTP_{00} , and ΔRTP_{00}) and R_a data had a normal distribution and equal variances. Data were assessed using repeated measures three-way ANOVA (resin composite material, toothpaste, and time). Time was considered a repeated measurement. Tukey's post hoc test was used to assess differences between groups. Also, a multiple regression analysis was performed to assess the reasons for changes in ΔE_{00} values of the toothpaste groups ($p < 0.05$). ΔE_{00}

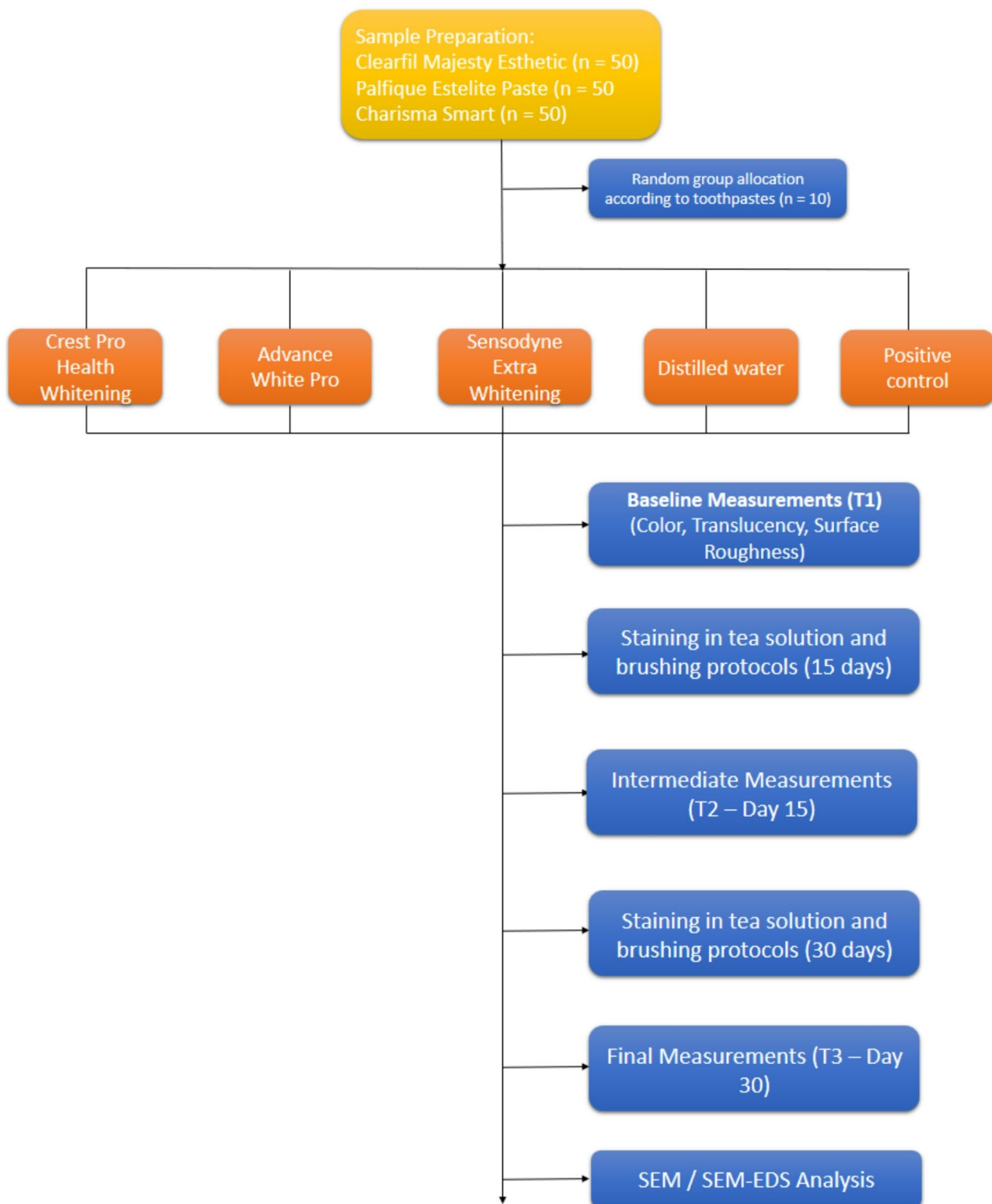


Fig. 1 Workflow diagram illustrating the study design and experimental sequence

Table 2 Means and standard deviations ($\pm$) of color change evaluation at different time points

Resin composite	Tooth-paste	ΔL		Δa		Δb		ΔE_{00}	
		T1 vs. T2	T1 vs. T3	T1 vs. T2	T1 vs. T3	T1 vs. T2	T1 vs. T3	T1 vs. T2	T1 vs. T3
CS	CPW	-0.5 ± 1.8^A	$1.2 \pm 1.7^{AB\#}$	-0.2 ± 1.3^A	-0.1 ± 1.1^A	1.0 ± 2.3^A	1.1 ± 1.7^B	1.8 ± 1.4^{Aa}	1.8 ± 1.0^{Aa}
	AWP	-0.5 ± 2.1^A	0.0 ± 2.1^A	-0.4 ± 2.0^A	-0.4 ± 2.0^A	0.1 ± 1.6^A	$3.2 \pm 4.2^{B\#}$	2.2 ± 1.1^{Aa}	$4.3 \pm 2.3^{Ba\#}$
	SEW	0.2 ± 2.1^A	$2.7 \pm 2.2^{BC\#}$	0.4 ± 0.8^A	0.3 ± 2.1^A	1.1 ± 1.6^A	1.9 ± 5.9^B	1.7 ± 0.8^{Aa}	$3.6 \pm 2.8^{Ba\#}$
	DW	0.2 ± 0.4^A	1.3 ± 0.6^{AB}	0.1 ± 0.1^A	-0.5 ± 0.4^A	0.1 ± 0.2^A	0.8 ± 0.1^{AB}	0.4 ± 0.1^{Aa}	1.3 ± 0.1^{Aa}
	PC	2.8 ± 0.3^B	4.1 ± 1.0^C	-0.2 ± 0.1^A	-0.9 ± 0.3^A	-0.8 ± 0.3^A	-2.2 ± 0.4^A	2.1 ± 0.2^{Aa}	3.4 ± 0.6^{Ba}
PEP	CPW	0.4 ± 1.3^A	$2.1 \pm 2.2^{A\#}$	-0.4 ± 2.3^A	-0.6 ± 1.9^A	4.0 ± 3.1^B	2.0 ± 1.3^B	4.2 ± 2.6^{Bb}	3.4 ± 1.6^{Bb}
	AWP	0.1 ± 1.2^A	1.2 ± 1.3^A	-0.8 ± 2.2^A	-0.9 ± 2.4^A	1.4 ± 1.7^A	1.0 ± 1.6^{AB}	3.2 ± 1.2^{Ba}	3.2 ± 1.7^{Ba}
	SEW	0.2 ± 2.0^A	1.6 ± 1.3^A	0.2 ± 2.1^A	-0.1 ± 2.1^A	1.1 ± 2.0^A	0.9 ± 1.6^{AB}	2.8 ± 1.6^{Ba}	2.8 ± 1.4^{Ba}
	DW	0.2 ± 0.3^A	0.9 ± 0.1^A	0.1 ± 0.1^A	0.2 ± 0.0^A	-0.3 ± 0.3^A	0.3 ± 0.2^{AB}	0.3 ± 0.1^{Aa}	0.7 ± 0.1^{Aa}
	PC	3.9 ± 0.6^B	$6.3 \pm 0.7^{B\#}$	-1.0 ± 0.8^A	-1.2 ± 0.7^A	-0.2 ± 0.4^A	-1.0 ± 0.9^A	3.7 ± 1.5^{Ba}	4.3 ± 0.7^{Ba}
CME	CPW	-1.2 ± 0.9^A	$0.5 \pm 0.9^{A\#}$	0.7 ± 1.5^A	0.8 ± 1.8^A	3.7 ± 1.2^C	3.2 ± 0.9^B	3.1 ± 1.0^{Bab}	2.8 ± 1.2^{ABab}
	AWP	-1.3 ± 0.9^A	$0.3 \pm 2.4^{A\#}$	0.6 ± 1.9^A	0.7 ± 2.1^A	2.6 ± 1.6^{BC}	2.8 ± 1.3^B	2.7 ± 1.6^{Ba}	3.2 ± 1.7^{Ba}
	SEW	-1.6 ± 1.4^A	-0.3 ± 1.4^A	0.9 ± 1.9^A	1.0 ± 1.8^A	2.3 ± 1.5^{BC}	2.8 ± 2.1^B	2.7 ± 1.8^{Ba}	3.0 ± 1.4^{Ba}
	DW	0.3 ± 0.1^{AB}	1.6 ± 0.2^A	0.1 ± 0.0^A	0.1 ± 0.1^A	-0.1 ± 0.0^{AB}	0.5 ± 0.6^{AB}	0.4 ± 0.1^{Aa}	1.2 ± 0.1^{Aa}
	PC	2.2 ± 0.3^B	4.1 ± 1.1^B	-0.3 ± 0.2^A	-0.6 ± 0.4^A	-0.5 ± 0.7^A	-1.6 ± 0.8^A	1.6 ± 0.3^{ABa}	3.1 ± 0.7^{Ba}

Different capital letters in vertical columns indicate significant differences among groups for each resin composite. Different lowercase letters in horizontal rows indicate significant differences among resin composites for each toothpaste group. # denotes significant differences between time points for each parameter ($p < 0.05$)

was designated as the dependent variable, whereas ΔL , Δa , and Δb were designated as independent variables. Regression analyses were conducted for whitening toothpastes individually, using L^* , a^* , and b^* values of all resin composites ($n = 30$). Data were analyzed using IBM SPSS 27 Statistics software (Chicago, IL, USA).

Results

Color and translucency analysis

The ANOVA analysis revealed that resin composite ($p = 0.014$), toothpaste group ($p < 0.001$), and time ($p = 0.002$) had a significant effect on ΔE_{00} values. The interaction between resin composite and toothpaste group was significant ($p = 0.027$), whereas all other interactions were not significant ($p > 0.05$). For all groups, the ΔL , Δa , Δb , and ΔE_{00} values are presented in Table 2. Significant differences were found among the groups for

ΔL , Δb , and ΔE_{00} values in each composite ($p < 0.001$). No significant difference was found among the groups regarding Δa , regardless of time ($p > 0.05$). The PC group presented significantly higher ΔE_{00} values than the DW group after 30 days, regardless of the resin composite used. In all resin composites, toothpastes showed significantly higher ΔE_{00} values than DW after 30 days, except for CPW in CS and CME, which displayed similar ΔE_{00} values to DW. Time did not statistically affect color change in the groups, except the AWP and SEW groups in CS, which showed statistically increased ΔE_{00} values. The PC group showed significantly higher ΔL values than other groups, regardless of time and resin composite (Table 3). Whitening toothpastes in all resin composites showed statistically similar ΔL values to the DW group at both times. After 30 days, the CPW and AWP groups presented considerably higher Δb values than the DW

Table 3 Total means and standard deviations ($\pm$) of the color parameters (ΔE_{00} , ΔRTP_{00} , ΔL , Δa , and Δb) for whitening toothpastes and resin composites

	ΔE_{00}	ΔRTP_{00}	ΔL	Δa	Δb
Toothpaste group					
CPW	2.88 ± 1.71^B	-0.18 ± 1.07^A	0.43 ± 1.90^A	0.01 ± 1.77^A	2.46 ± 2.26^C
AWP	3.17 ± 2.24^B	-0.32 ± 1.95^A	-0.33 ± 2.46^A	-0.13 ± 2.17^A	1.88 ± 3.62^C
SEW	2.82 ± 1.78^B	-0.30 ± 2.07^A	0.48 ± 2.21^A	0.46 ± 1.89^A	1.73 ± 2.91^{BC}
DW	0.76 ± 0.43^A	0.17 ± 0.46^A	0.79 ± 0.68^A	0.02 ± 0.30^A	0.24 ± 0.49^{AB}
PC	3.30 ± 1.60^B	0.89 ± 0.93^A	4.21 ± 1.95^B	-0.74 ± 0.60^A	-1.08 ± 0.93^A
Resin composite					
CS	2.40 ± 2.17^A	0.24 ± 1.39^A	0.93 ± 2.62^{AB}	-0.10 ± 1.44^A	0.88 ± 3.85^A
PEP	3.16 ± 1.95^A	-0.60 ± 1.75^A	1.54 ± 2.39^B	-0.48 ± 1.92^A	1.25 ± 2.14^{AB}
CME	2.61 ± 1.49^A	-0.12 ± 1.66^A	0.07 ± 1.97^A	0.57 ± 1.66^B	2.10 ± 2.02^B

Different capital letters in vertical lines indicate statistical difference among groups (one-way ANOVA results, $p < 0.05$)

group, regardless of the resin composite. The PC group showed negative Δb values, which indicates increased yellowness (Table 3). Whitening toothpastes produced statistically similar color parameters (ΔE_{00} , ΔRTP_{00} , ΔL , Δa , and Δb), regardless of resin composites (Table 3).

All groups showed clinically perceptible color change ($\Delta E_{00} > 0.8$) after 30 days. Color changes for all resin composites were above clinically acceptable levels ($\Delta E_{00} > 1.8$) in all groups, except the DW group (Fig. 2). Multiple regression analysis revealed a correlation between ΔE_{00} value and change in color parameters (ΔL , Δa , and Δb). Changes in ΔE_{00} values caused by whitening toothpastes were affected mainly by Δb (particularly CPW and AWP samples). In contrast, changes in ΔE_{00} values in the DW and PC groups were affected by ΔL (Table 4).

RTP_{00} values were significantly affected only by the resin composite factor ($p < 0.001$). Toothpaste group and time had no significant effect on RTP_{00} values ($p > 0.05$), and none of the interactions between the factors were significant ($p > 0.05$). Statistical analysis revealed significant differences in translucency values among the resin composites ($p < 0.001$), regardless of the toothpaste used (Table 5). CS showed the lowest translucency values. For each resin composite, translucency values did not show a significant difference among the groups ($p > 0.05$) at all times. After 30 days, translucency changes for most groups were below the clinically perceptible value ($\Delta RTP_{00} < 0.62$) at each time (Fig. 3). AWP (-0.69) and SEW (-1.00) groups in PEP showed perceptible translucency values after 30 days. Translucency changes for

all groups were below acceptable values ($\Delta RTP_{00} < 2.62$) (Fig. 3).

Surface roughness analysis

The ANOVA analysis revealed that R_a values were significantly influenced by resin composite ($p < 0.001$) and time ($p < 0.001$), while toothpaste group had no significant effect. The interaction between resin composite and time was significant ($p = 0.002$), but the remaining interactions were not significant ($p > 0.05$). The R_a values varied significantly among the groups at each time point ($p < 0.001$, Table 6). CME significantly displayed the highest R_a values, regardless of the toothpastes. The R_a of the resin composites increased significantly over time ($p < 0.001$), except for SEW samples in CS. R_a for all groups did not differ significantly between 15 and 30 days ($p < 0.05$). For each resin composite, R_a values showed no significant differences among the toothpastes ($p = 0.215$) at both time points (Table 6). After 15 or 30 days, CME samples in all groups showed highest R_a values above clinically acceptable limits ($R_a > 0.2 \mu m$).

SEM analysis

The surface of CME without brushing (in distilled water) showed lines that were probably left by the polishing system. CS and PEP exhibited a smoother surface. In all resin composites, the resin matrix was observed to wear in all toothpaste groups compared to the control group, leaving behind filler particles. The density and size of filler particles are different among the resin composites.

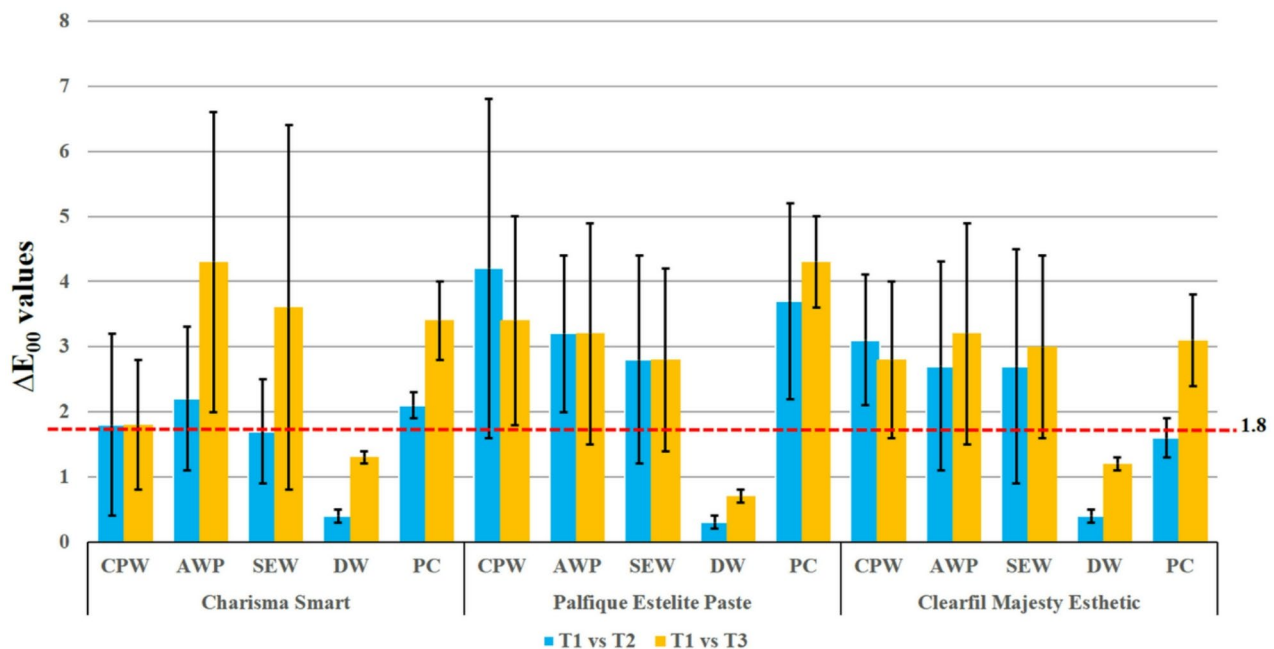


Fig. 2 Means and standard deviations of ΔE_{00} after 15 (T1 vs. T2) and 30 (T1 vs. T3) days. The acceptable threshold (1.8) is shown by the red dotted line

Table 4 Multiple regression analysis between ΔE_{00} and ΔL , Δa , Δb in whitening toothpaste groups after 30 days

ΔE_{00}		Unstandardized coefficients		Standardized coefficients		Sig.
		B	SE	β	t	
CPW	(Constant)	1.519	0.250		6.162	< 0.001
	ΔL	0.043	0.092	0.47	0.508	0.642
	Δa	-0.274	0.099	-0.284	-2.814	0.008
	Δb	0.549	0.077	0.726	7.193*	< 0.001
AWP	(Constant)	2.276	0.259		8.794	< 0.001
	ΔL	-0.085	0.096	-0.094	-0.893	0.376
	Δa	-0.209	0.121	-0.203	-1.735	0.088
	Δb	0.460	0.075	0.746	6.141*	< 0.001
SEW	(Constant)	2.080	0.209		9.955	< 0.001
	ΔL	0.229	0.082	0.285	2.788	0.007
	Δa	-0.115	0.125	-0.123	-0.925	0.359
	Δb	0.400	0.079	0.655	5.065*	< 0.001
DW	(Constant)	0.371	0.049		7.554	< 0.001
	ΔL	0.461	0.057	0.722	8.104*	< 0.001
	Δa	-0.453	0.112	-0.323	-4.040	< 0.001
	Δb	0.153	0.084	0.174	1.825	0.079
PC	(Constant)	-0.109	0.045		-2.458	0.021
	ΔL	0.760	0.013	0.926	56.484*	< 0.001
	Δa	-0.229	0.046	-0.086	-4.989	< 0.001
	Δb	-0.034	0.020	-0.020	-1.697	0.102

* indicates higher effect among parameters (ΔL , Δa , and Δb) for each group. SE: standard error; β : beta

Table 5 Means and standard deviations ($\pm$) of translucency values (RTP_{00}) and translucency changes (ΔRTP_{00}) of composite materials at different time points

Resin composite	Tooth-paste	Translucency value			Translucency change	
		$RTP_{00}T1$	$RTP_{00}T2$	$RTP_{00}T3$	ΔRTP_{00} (T1 vs. T2)	ΔRTP_{00} (T1 vs. T3)
CS	CPW	2.7 $\pm$ 0.8	2.6 $\pm$ 0.9	3.2 $\pm$ 0.9	0.14 $\pm$ 1.4	-0.44 $\pm$ 1.0
	AWP	3.1 $\pm$ 1.1	3.2 $\pm$ 1.9	3.7 $\pm$ 2.6	-0.13 $\pm$ 2.7	-0.55 $\pm$ 2.3
	SEW	3.5 $\pm$ 1.6	3.0 $\pm$ 0.5	2.8 $\pm$ 1.0	0.50 $\pm$ 1.6	0.56 $\pm$ 1.8
	DW	3.7 $\pm$ 0.2	3.6 $\pm$ 0.1	3.5 $\pm$ 0.3	0.15 $\pm$ 0.4	0.18 $\pm$ 0.1
	PC	3.7 $\pm$ 0.2	3.3 $\pm$ 0.2	3.0 $\pm$ 0.8	0.47 $\pm$ 0.1	1.88 $\pm$ 0.3
PEP	CPW	4.9 $\pm$ 0.9	4.8 $\pm$ 1.3	5.1 $\pm$ 1.2	0.08 $\pm$ 1.8	-0.24 $\pm$ 1.4
	AWP	5.1 $\pm$ 1.4	5.6 $\pm$ 0.8	5.8 $\pm$ 0.9	-0.51 $\pm$ 1.5	-0.69 $\pm$ 2.0
	SEW	4.9 $\pm$ 1.3	5.2 $\pm$ 1.2	5.9 $\pm$ 1.5	-0.35 $\pm$ 1.9	-1.00 $\pm$ 1.8
	DW	4.8 $\pm$ 0.1	4.7 $\pm$ 0.3	4.3 $\pm$ 0.2	0.14 $\pm$ 0.2	0.47 $\pm$ 0.3
	PC	5.8 $\pm$ 0.2	5.3 $\pm$ 0.2	4.2 $\pm$ 0.2	0.3 $\pm$ 0.2	0.78 $\pm$ 0.8
CME	CPW	4.9 $\pm$ 0.8	4.8 $\pm$ 1.0	5.0 $\pm$ 0.7	0.17 $\pm$ 1.2	-0.00 $\pm$ 0.8
	AWP	5.6 $\pm$ 1.2	5.1 $\pm$ 1.1	5.4 $\pm$ 1.1	0.50 $\pm$ 1.5	0.22 $\pm$ 1.55
	SEW	5.1 $\pm$ 1.1	4.9 $\pm$ 0.9	5.6 $\pm$ 1.9	0.07 $\pm$ 1.5	-0.57 $\pm$ 2.3
	DW	5.8 $\pm$ 0.2	5.5 $\pm$ 0.1	5.9 $\pm$ 0.4	0.27 $\pm$ 0.1	-0.13 $\pm$ 0.6
	PC	4.9 $\pm$ 0.3	4.8 $\pm$ 1.0	4.2 $\pm$ 0.7	0.19 $\pm$ 0.3	0.69 $\pm$ 0.46

The very small particles can be observed in PEP at 5000 $\times$ magnification. Irregular fillers were observed in the surfaces for CME and CS (Fig. 4). SEM/EDS analysis demonstrated the various elements (silica, sodium, titanium, calcium, and phosphorus) in each toothpaste (Fig. 5), with color coding for mapping. All toothpastes included silica in significant amounts and had particle-like structures. In CPW, no calcium or phosphorus was found.

The highest titanium concentrations were seen in CPW (Fig. 5).

Discussion

Several methods are available for assessing color changes in teeth and restorative materials. These methods can be divided into two categories: subjective methods, such as using a standard tooth shade guide, and objective

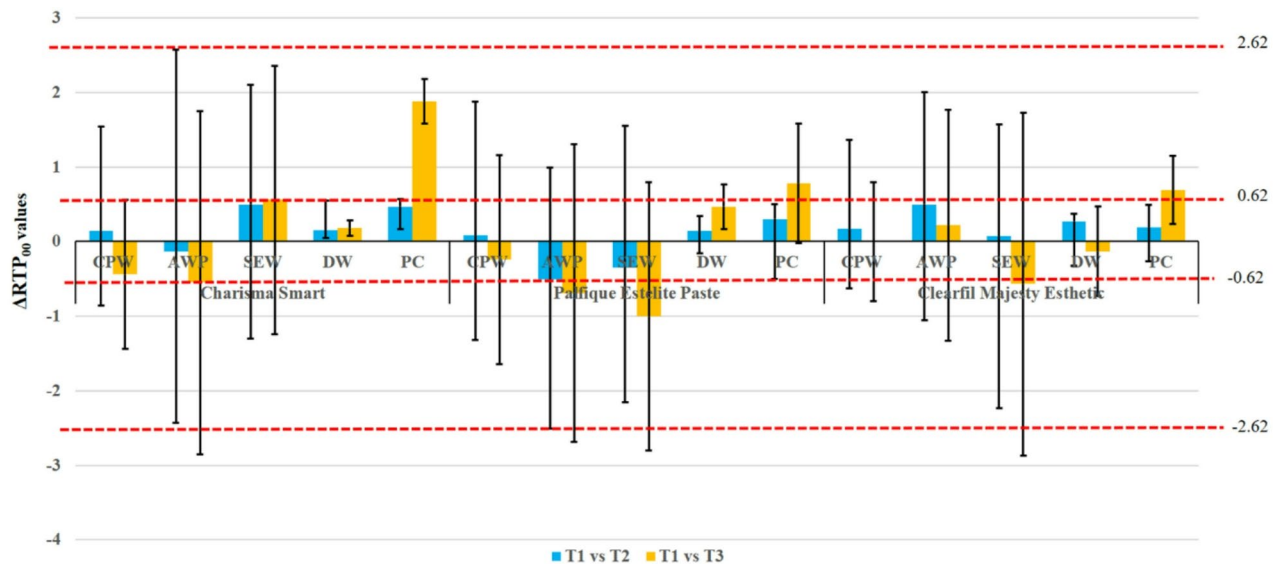


Fig. 3 Means and standard deviations of ΔRTP_{00} after 15 (T1 vs. T2) and 30 (T1 vs. T3) days. The perception (0.62) and acceptance (2.62) thresholds are shown by the red dotted lines

Table 6 Means and standard deviations ($\pm$) of surface roughness (R_a , μm) of composite materials at different time points

Resin composite	Tooth-paste	Ra1	Ra2	Ra3
CS	CPW	0.11 $\pm$ 0.02 ^{Aa}	0.24 $\pm$ 0.08 _{Ab}	0.25 $\pm$ 0.08 _{Ab}
	AWP	0.11 $\pm$ 0.04 ^{Aa}	0.19 $\pm$ 0.04 _{Aab}	0.23 $\pm$ 0.05 _{Ab}
	SEW	0.14 $\pm$ 0.04 _{ABa}	0.18 $\pm$ 0.04 _{Aa}	0.20 $\pm$ 0.04 _{Aa}
PEP	CPW	0.10 $\pm$ 0.02 ^{Aa}	0.23 $\pm$ 0.06 _{Ab}	0.29 $\pm$ 0.08 _{Ab}
	AWP	0.10 $\pm$ 0.05 ^{Aa}	0.21 $\pm$ 0.04 _{Ab}	0.28 $\pm$ 0.06 _{Ab}
	SEW	0.18 $\pm$ 0.25 _{ABa}	0.20 $\pm$ 0.04 _{Aab}	0.26 $\pm$ 0.05 _{Ab}
CME	CPW	0.26 $\pm$ 0.11 ^{Ba}	0.46 $\pm$ 0.10 _{Bb}	0.51 $\pm$ 0.11 _{Bb}
	AWP	0.25 $\pm$ 0.11 _{ABa}	0.40 $\pm$ 0.09 _{Bb}	0.45 $\pm$ 0.09 _{Bb}
	SEW	0.26 $\pm$ 0.15 _{ABa}	0.42 $\pm$ 0.13 _{Bb}	0.49 $\pm$ 0.13 _{Bb}

Different capital letters in vertical lines indicate statistical differences among groups. Different lowercase letters in horizontal lines indicate statistical difference between times ($p < 0.05$)

methods, which include colorimeters, spectrophotometers, and computerized digitization [42]. Spectrophotometers measure the spectral composition and amount of light transmitted or reflected, which must then be converted into tristimulus data. In contrast, colorimeters, which contain green, blue, and red color filters, bypass this conversion by directly measuring tristimulus values for particular illuminants [43]. Studies have shown that spectrophotometers are more accurate and reliable devices than visual shade determination, with acceptable

inter-rater and intra-rater reliability [44–46]. Based on these findings, a spectrophotometer (VITA Easyshade Advance) was used in this study. Previous research has shown that VITA Easyshade Advance produced consistent and accurate measurements, highlighting its device reliability [47].

In this study, the CIEDE2000 system was utilized to assess color changes. Notably, some studies have indicated that the CIEDE2000 color change system is more effective than the CIELab formula for evaluating visual tolerances, which supports its application in dentistry [39, 41]. In the current study, the ΔL , Δa , and Δb values in most of the toothpaste groups did not differ from those in the DW group, and the color change did not show a significant variation over time in most of the groups. Based on these findings, the whitening toothpastes caused a higher color change when compared to distilled water. Whitening toothpastes contain various abrasives such as hydrated silica, pyrophosphates, sodium bicarbonate, calcium carbonate, and alumina, as well as whitening agents like blue covarine and titanium dioxide. These abrasives can eliminate the accumulation of extrinsic stains [9]. However, some studies have reported that whitening toothpastes did not reduce the staining of composite materials [17, 18]. In contrast, other studies have found that whitening toothpaste was effective in eliminating the discoloration of different restorative materials [19, 21], which supports the results of the present study. These different results may be explained by the differences in methodology. Additionally, it has been reported that the type of discoloration and the content of the whitening agent were effective in improving the color of resin composite materials [20].

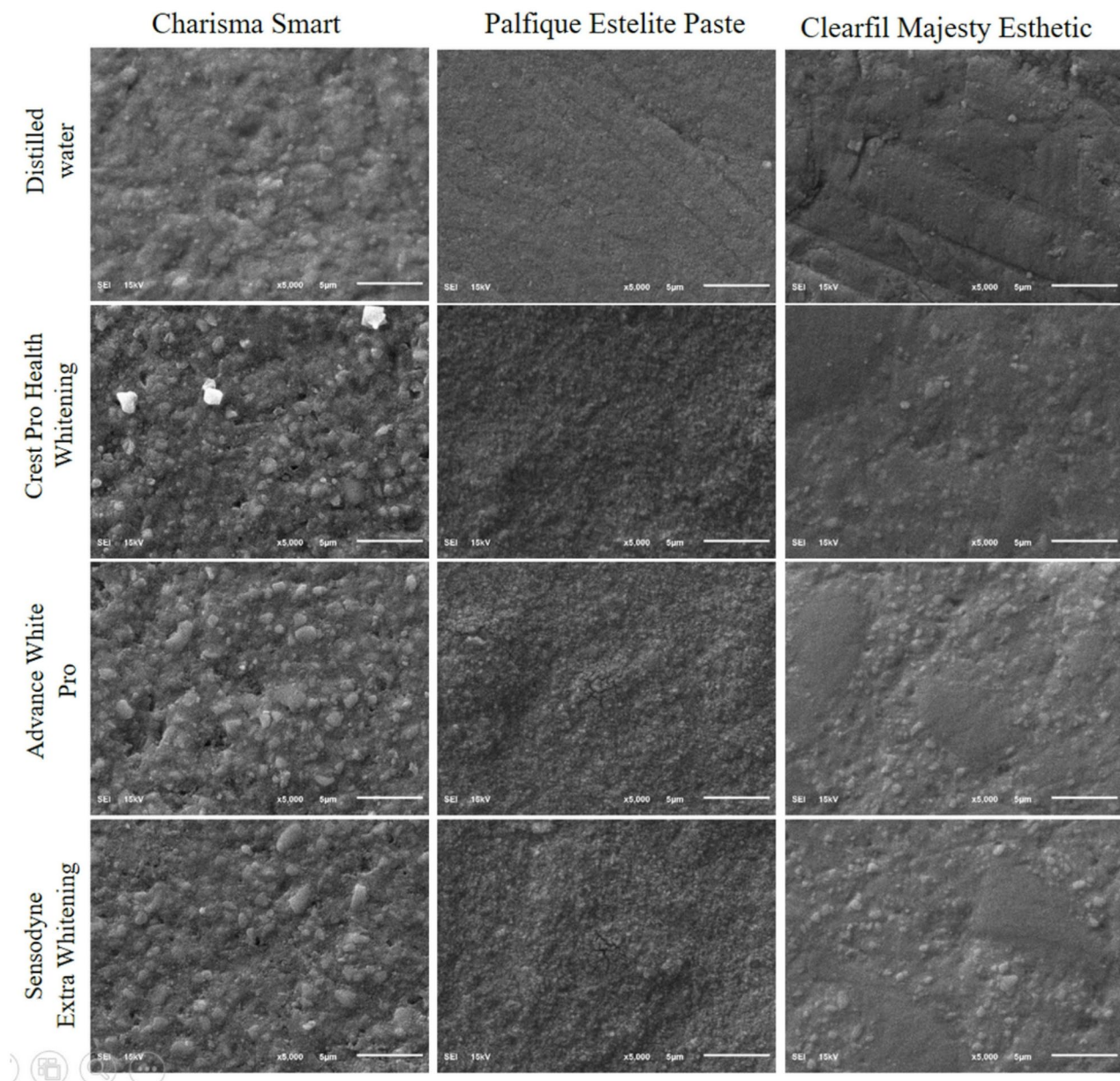


Fig. 4 Scanning electron microscopy images of resin composites after brushing with different whitening toothpastes

The color change in the whitening toothpaste groups was above the clinically acceptable value ($\Delta E_{00} > 1.8$) after 30 days. The color changes of resin composites in DW were at a clinically acceptable level ($\Delta E_{00} < 1.8$), which is consistent with the results of previous studies [33, 48]. In the PC group, a significant reduction in L^* values and negative Δb^* values, compared to the DW group, indicate a tendency toward staining to dark-yellow. In contrast, within the whitening toothpaste groups, a decrease in b^* values indicates a shift toward a bluish appearance. Blue covarine (CI 74160) and tetrasodium pyrophosphate in APW, and titanium dioxide in CPW and SEW, provide optical properties. These elements have contributed to

diminishing the yellow color dimension by depositing a translucent blue pigment film on the surface of the resin composite. This film alters the way light interacts with objects, making them appear cleaner and lighter [2]. A previous study reported that whitening toothpaste containing blue covarine provided a greater color change on composite samples stained with a coffee solution compared to peroxide-based toothpaste [17]. Another study reported that the blue covarine toothpaste with silica did not permanently stain the resin composites and glass-ionomer materials or their margins [21]. These results corroborate the findings of the present study. It has been determined that silica whitening toothpaste, including

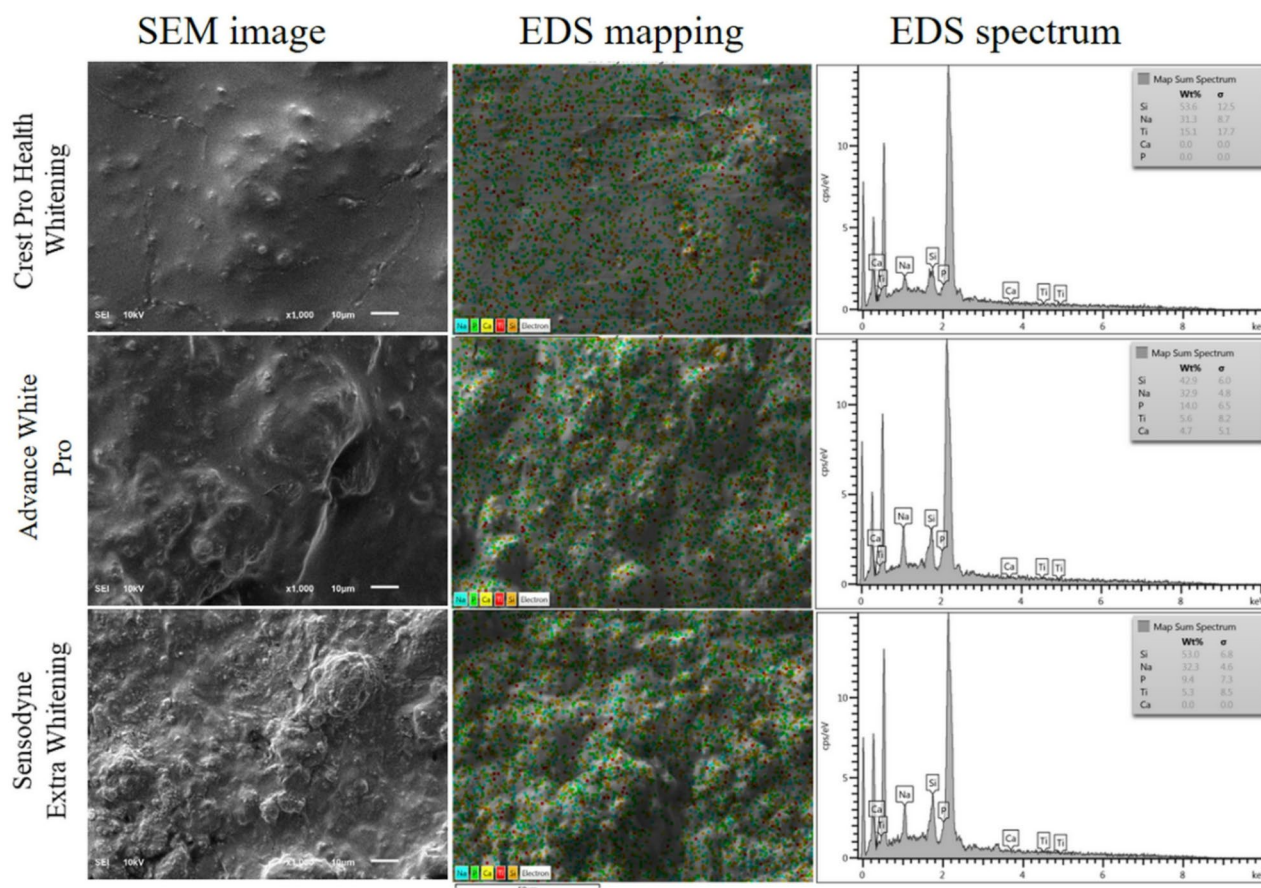


Fig. 5 Scanning electron microscopy (SEM) / energy-dispersive X-ray spectroscopy (EDS) analysis of whitening toothpastes (Si: silica, Na: sodium, Ti: titanium, Ca: calcium, P: phosphorus)

blue covarine, led to color changes in resin composites, similar to those found in enamel surfaces, depending on the decrease in b^* values [19]. On the contrary, another study found that blue covarine-containing toothpastes had no different effect than conventional toothpastes on the discoloration of various resin composites [49]. In the current study, no significant difference in color change was determined between whitening toothpastes. The different results observed in the studies may be explained by factors such as the brand of toothpaste, the type of resin composites used, variations in brushing techniques, and the duration of brushing [20].

Translucency values showed significant differences among the resin composites, regardless of the toothpaste groups. Increased translucency in a material leads to higher visibility of the colors of the deeper layers beneath the restorative material. Several factors influence the optical characteristics of resin composites, including filler and matrix composition, the disparity in refractive indices between the matrix phase and inorganic particles, filler size, particle size distribution, and pigment ingredients [50, 51]. Notably, CS exhibited lower translucency despite its low filler content [52]. To match tooth color,

gray, yellow, and sometimes blue or green pigments are combined into the white base material [52]. The use of filler material and pigments for color matching or fluorescence can influence both color and translucency [51].

In the present study, whitening toothpastes led to no significant changes in the translucency of resin composites compared to DW. In most samples, changes in translucency were undetectable ($\Delta RTP_{00} < 0.62$); however, in the positive control group, the perceptible ΔRTP_{00} was observed. However, all ΔRTP_{00} values were below the acceptable level ($\Delta RTP_{00} < 2.62$). Despite the perceptible color change of the resin composites, translucency was not significantly affected, and negative ΔRTP_{00} was observed in some groups, indicating increased translucency. Also, the translucency changes (ΔRTP_{00}) in the whitening toothpaste groups showed higher standard deviation (Fig. 3). A difference in refractive index between the resin matrix and the filler particles causes scattering, while the resin matrix itself causes light absorption [53]. Nanoclusters and larger filler particles could have been selectively removed from the material surface, leading to a decrease in the refractive index. Lowering the refractive index difference between filler particles and resin

matrix reduces light surface scattering, enhancing light penetration and translucency [33, 48]. Brushed surfaces after staining have exhibited superficial wear and texture changes, resulting in varied color perceptions due to light scattering and reflection [54].

In the present study, color change, translucency change, and surface roughness of resin composites did not show a significant difference among whitening toothpastes (Table 3). Therefore, the first null hypothesis was accepted. However, whitening toothpastes were found to increase the surface roughness of resin composites. Some whitening toothpastes might include more abrasives. Alumina, sodium bicarbonate, calcium carbonate, hydrated silica, and dicalcium phosphate dihydrate are among the most commonly used abrasives in whitening toothpastes [9]. Additionally, the hardness, size, and shape of abrasives can affect tooth brushing, leading to increased abrasion and roughness, as well as a color change on the surface [55]. Previous studies have reported that whitening toothpastes increased the surface roughness of resin composites, which supports the findings of this study [17, 22, 24]. Tooth brushing has been shown to wear down the polymer matrix of the resin composite, leaving behind filler particles that create a rough surface [56]. In this study, SEM images show that the resin matrix has been worn, showing inorganic filler particles. The filler particles have a higher elasticity modulus than the resin matrix and can carry greater loads. However, the particle-matrix bond is not as strong as the tension generated by the filler particle's hardness, leading to particle migration and material loss [57].

In the study, three different whitening toothpastes were selected based on their RDA scores. However, a significant difference was not found in roughness among the whitening toothpastes, which was unexpected. This finding may be explained by the SEM/EDS analysis, which showed that the whitening toothpastes contained almost equal proportions of abrasive particles (silica and sodium). It should also be noted that, although the RDA test was performed on dentin, its results may not be directly applicable to composite materials due to structural differences between them. Supporting this, a study examining the effect of toothpastes and toothbrushes on resin composites determined that the content of toothpaste, the type of brush, and the structure of the resin composite influenced the surface properties of the resin composite [58].

Previous studies have reported that the tea solution caused higher staining than other solutions on resin composites [33, 37]. This is likely because the tea solution contains black and yellow pigments that accumulate in the organic phase of the resin composites by penetration and absorption [33, 59]. Furthermore, highly polar colorants can also cause staining by adsorbing to the

surface of resin composites. In the present study, black tea solution caused clinically unacceptable color changes in the positive control group (Table 3), which agrees with previous studies [33, 60]. Notably, the resin composites tested showed similar color change (ΔE_{00}) and translucency change (ΔRTP_{00}), regardless of the toothpaste used (Table 3). This similarity can be explained by the comparable resin monomer structure (Bisphenol A diglycidyl ether dimethacrylate and triethyleneglycol dimethacrylate). A previous study has suggested that the susceptibility to staining of resin composites may be related to the hydrophilicity and water absorption of the resin matrix [59]. However, CME showed the highest surface roughness above clinically acceptable limits ($R_a > 0.2 \mu\text{m}$). Thus, the second null hypothesis, that there would be no significant differences among resin composites with respect to color change, translucency change, and surface roughness, was partially rejected. High surface roughness of CME may be related to its microhybrid structure and larger filler particle size. A previous study has reported that microhybrid composites can exhibit higher surface roughness after brushing and abrasive treatments compared to nano-hybrid and submicron composites [61]. Increased surface roughness may facilitate biofilm adhesion, potentially affecting the durability of resin composite restorations and increasing the risk of caries and periodontal inflammation. It has been suggested that surface roughness values $\geq 0.2 \mu\text{m}$ favor biofilm accumulation, while values $> 0.3 \mu\text{m}$ may become perceptible to patients, possibly leading to clinical discomfort [17, 23]. High standard deviations for all parameters assessed were observed in some experimental groups compared to the distilled water. This may be due to surface changes resulting from brushing and uneven distribution of abrasives and pigments in toothpastes.

The brushing protocol used in this study was meticulously designed to simulate clinically relevant mechanical abrasion under controlled in vitro conditions. The applied brushing force of 200 g was consistent with the average manual brushing forces documented in clinical studies, which typically range from 150 to 250 g. Previous in-vitro studies have employed similar loads to replicate realistic brushing abrasion on resin composite materials [17, 57]. The brushing frequency, set twice daily for 30 days, was designed to approximate two months of regular oral hygiene. Although in vitro models cannot fully replicate the complex oral environment, accelerated brushing protocols are commonly used to approximate the clinical conditions. While our protocol does not directly equate to in vivo conditions, it provides a standardized and reproducible model consistent with previous studies [17, 38, 62].

This in-vitro study has several limitations. Although it provides controlled conditions for evaluating the effects of whitening toothpastes on resin composites over a

two-month simulated period, it cannot fully replicate the complex oral environment. Factors such as thermal fluctuations in the oral environment, biofilm adhesion, and saliva clearance were not reflected. However, the study's results may be used to inform the planning of clinical trials. Additionally, as customers' demand for teeth whitening rises, more whitening toothpastes will be produced. It is suggested that future studies cover such situations. Further long-term studies in clinical settings are necessary to better understand the impact of whitening toothpastes.

Conclusions

Whitening toothpastes affected the color parameters (ΔE_{00} , ΔL , and Δb) of all resin composites, with clinically perceptible changes observed after 30 days of use. While color and translucency changes were similar among toothpastes, all increased the surface roughness of resin composites, particularly CME. These results indicate that whitening toothpastes can alter the color of composites but may compromise surface smoothness, potentially affecting esthetics and plaque retention. Clinicians should weigh the benefits of whitening against possible surface damage, and future studies should explore formulations that minimize roughness while maintaining efficacy.

Abbreviations

CS	Charisma Smart
PEP	Palfique Estelite Paste
CME	Clearfil Majesty Esthetic
CPW	Crest Pro Health Whitening
AWP	Advance White Pro
SEW	Sensodyne Extra Whitening
DW	Distilled water
PC	Positive control
ΔE_{00}	Color change
$RT\bar{P}_{00}$	Translucency parameter
Ra	Surface roughness

Acknowledgements

This study has been supported by the Recep Tayyip Erdoğan University Development Foundation (Grant number: 02025011017787).

Authors' contributions

Conceptualization: EY and MK; Methodology: EY, MM, and MK; Formal analysis: MM and MK; Writing—original draft preparation: EY and MK; Writing—review and editing: MK; Supervision: MK. All authors reviewed the manuscript.

Funding

This study was funded by the Research Fund of University (project no. TSA-2024-1733).

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 10 August 2025 / Accepted: 16 April 2026

Published online: 22 April 2026

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