

Color, Whiteness, and Surface Roughness Changes of Group-Shade and Single-Shade Composite Resins During A Şalgam-Induced Staining and Bleaching Cycle: A Longitudinal In Vitro Study

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ABSTRACT

Resin composites may undergo discoloration and surface degradation after exposure to acidic pigmented beverages, while bleaching may further affect their properties. This study evaluated color difference (ΔE_{00}), whiteness index (WID), and surface roughness (Ra) of conventional, group-shade, and single-shade composites during a şalgam-induced staining and bleaching cycle.

Disk-shaped specimens (8 × 2 mm) were prepared from five resin composites (n = 10/group). Measurements were performed at baseline (T1), after 24 h (T2) and 1 month (T3) of şalgam immersion, and 1 day (T4) and 10 days (T5) after bleaching with 35% hydrogen peroxide. ΔE_{00} and WID were determined spectrophotometrically and Ra using a contact profilometer. WID changes were analyzed using Friedman tests, between-material differences using Kruskal–Wallis and Dunn–Bonferroni tests, and material-by-time interactions using rank-based permutation tests.

Significant material-by-time interactions were detected for ΔE_{00} and WID (both $p < 0.001$) and Ra ($p = 0.049$). At T3, Essentia Universal (S1) showed the greatest discoloration ($\Delta E_{00} = 11.47 \pm 2.75$), whereas OptiShade (G2) showed the lowest (3.39 ± 0.25). After bleaching, Filtek Easy Match (G1) showed the greatest whitening recovery (82%), while S1 showed the lowest (–21%). Surface roughness increased after staining, particularly in S1, and decreased after bleaching.

The tested composites showed material-dependent variability in color stability, whiteness recovery, and surface roughness. Group-shade composites showed more consistent overall performance, whereas single-shade composites showed greater variability. Material selection should consider long-term esthetic behavior in addition to initial shade matching.

Keywords: Single-Shade Composite; Group-Shade Composite; Tooth Bleaching; Color Stability; Whiteness Index; Surface Roughness; Spectrophotometry; Anthocyanins; In vitro study.

Introduction

The long-term clinical success of resin composite restorations in aesthetic dentistry largely depends on maintaining color stability. Chromogenic pigments found in commonly consumed foods and beverages can negatively affect the color properties of composite restorations, leading to decreased aesthetic success and patient dissatisfaction (1–3). Although tooth whitening procedures are widely used to address these color changes, it has been reported that whitening agents can alter the optical and surface properties of existing composite restorations (4–6).

Discoloration is not merely an aesthetic issue; interactions between restorative materials and acidic beverages can lead to surface deterioration and increased roughness, potentially affecting the long-term performance of restorations. Increased surface roughness facilitates pigment adsorption, accelerating secondary discoloration and indirectly reducing the clinical lifespan of the restorations (7,8).

Recent developments in restorative dentistry have led to the introduction of universal resin composite systems designed to simplify shade selection and improve clinical efficiency. These materials aim to reduce chairside shade selection complexity and inventory requirements while

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maintaining acceptable esthetic outcomes. Universal composites are generally marketed according to either a group-shade or a single-shade concept, each relying on different optical mechanisms to achieve color adaptation (9–11).

In recent years, single-shade composites developed to simplify clinical applications have been introduced, claiming that they can adapt to a wide range of colors owing to the “chameleon effect” (9–11). However, the literature on the color stability of these materials is conflicting. While some studies have reported that single-shade composites show greater color changes than conventional multi-shade composites (9,12,13), other studies have reported similar performance (14,15). In addition, there are limited data on the behavior of group-shade composites during the staining and whitening processes.

It has been shown that the coloring and whitening responses of resin composites depend on the material composition and optical design. Systematic reviews have reported that the effectiveness of whitening varies by material type and that whitening procedures may not completely reverse color changes (6,16). In addition, some studies have shown that coloring and whitening procedures can increase surface roughness, which may have clinically significant consequences (2,16).

Şalgam juice is a traditional fermented beverage widely consumed in Türkiye. However, the globalization of dietary habits and the growing integration of multicultural lifestyles have increased its availability and consumption across diverse geographical regions. Owing to its low pH and anthocyanin-rich composition, şalgam juice may represent a clinically relevant staining medium for evaluating the long-term behavior of restorative materials.

Three significant gaps are evident in the current literature. First, few studies have directly compared conventional, group-shade, and single-shade composites using the same staining agent and bleaching protocol. Second, most studies focused on a single time point and did not evaluate color changes and surface roughness over the staining–bleaching cycle. Third, the effects of şalgam juice, a traditional beverage with a highly acidic pH and natural anthocyanin pigments, on resin composites have not been adequately studied.

However, most current studies evaluate color change solely using ΔE values, and few simultaneously consider the whiteness index (WID), which reflects perceptual whiteness

change, and surface roughness (Ra), which represents surface characteristics. Clinical esthetic success is determined not only by color differences but also by perceived whiteness and surface integrity. Therefore, simultaneously evaluating optical and surface parameters may provide a more comprehensive understanding of the clinical performance of restorative materials.

To our knowledge, this is the first longitudinal study to simultaneously compare conventional, group-shade, and single-shade resin composites using a şalgam-induced staining model while integrating assessments of color difference (ΔE_{00}), whiteness index (WID), and surface roughness (Ra) throughout the entire staining–bleaching cycle.

This study aimed to compare the time-dependent optical and surface behaviors of resin composites with different color concepts during a şalgam-induced staining and bleaching cycle by evaluating color difference (ΔE_{00}), whiteness index (WID), and surface roughness (Ra). The null hypothesis was that the longitudinal ΔE_{00} , WID, and Ra response profiles would not differ among the tested resin composites.

Materials and Methods

This in vitro study evaluated the color stability, whiteness change, and surface roughness of resin composite materials with different shade concepts after exposure to a staining beverage and subsequent whitening. The study design was planned as a longitudinal experimental model, involving repeated measurements. The overall experimental workflow of the study is illustrated in Figure 1. Prior to the study, a sample size analysis was conducted using G*Power software (Heinrich-Heine University, Düsseldorf, Germany). Considering the repeated-measures experimental design, the calculation was based on a repeated-measures analysis of variance (ANOVA) model. The effect size was set to medium ($f = 0.25$), the significance level to $\alpha = 0.05$, and the statistical power ($1 - \beta$) to 0.80. Considering five groups and five measurement times, it was determined that at least eight samples per group would be sufficient. In this study, 10 samples per group were used, exceeding the required sample size.

Five different resin composite materials were selected to represent different color concepts. The control group represented conventional multishade composites, the G1 and G2 groups represented the group-shade concept, and the S1

Workflow Chart for In Vitro Color Stability and Whitening Study

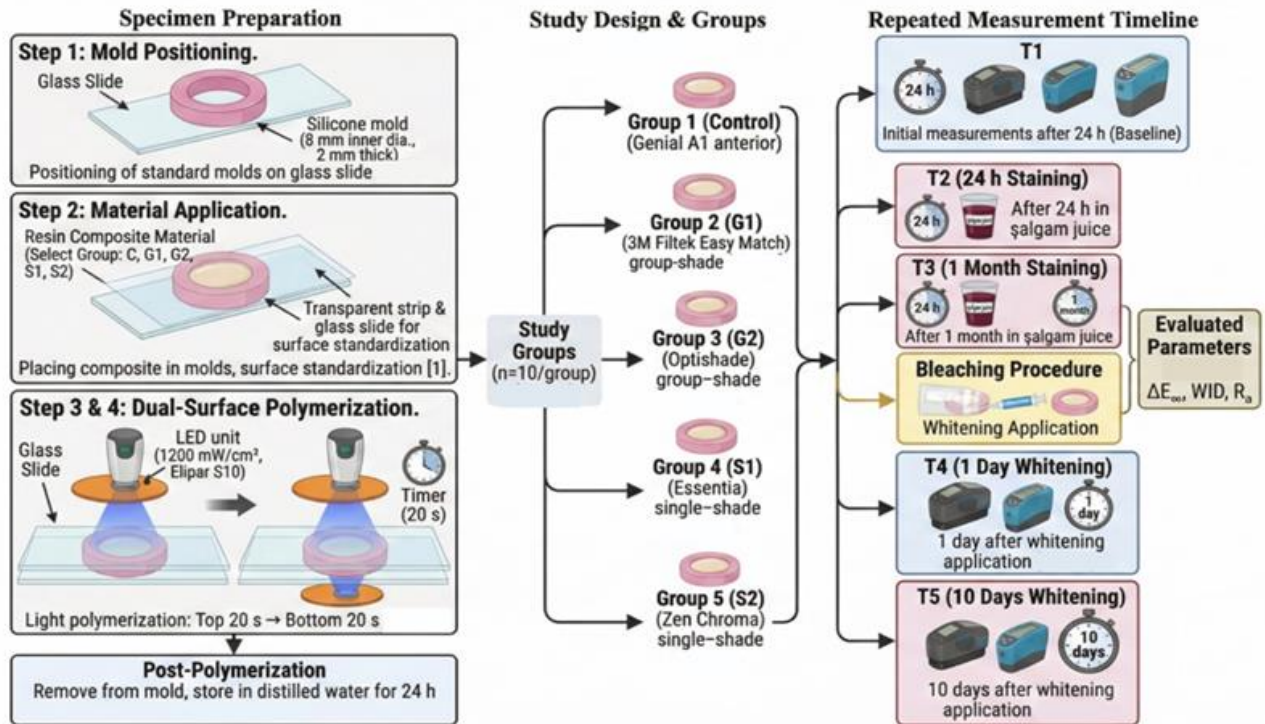


Fig. 1. Study Workflow Chart

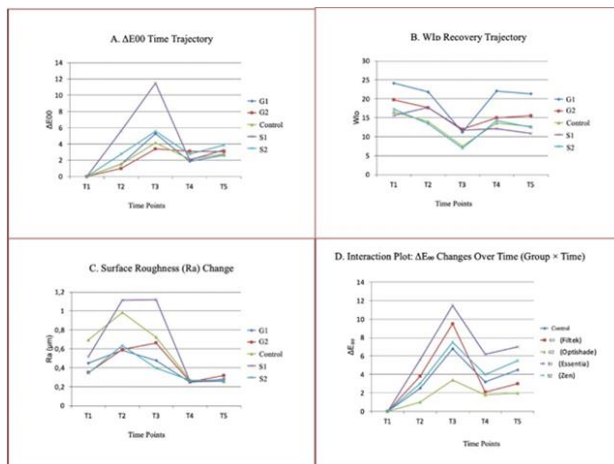


Fig. 2. **A.** Longitudinal changes in color difference (ΔE_{005}), **B.** Whiteness index (WID), and **C.** Surface roughness (Ra) of resin composite materials during the staining-bleaching cycle. **D.** Integrated Performance at Peak Staining (T3)

and S2 groups represented the single-shade concept (Table 1).

Group 1 (C): GC G-aenial Anterior A1 (conventional multi-shade composite)

Group 2 (G1): Filtek Easy Match Bright (group-shade composite)

Group 3 (G2): OptiShade Light (group-shade composite)

Group 4 (S1): Essentia Universal (single-shade composite)

Group 5 (S2): Zen Chroma (single-shade composite)

Ten disk-shaped samples were prepared from each material ($n=10$). The samples were prepared using standard molds with an inner diameter of 8 mm and a thickness of 2 mm. After placement of the resin composite materials into the molds, the surfaces were standardized using a transparent strip and a glass slide. The specimens were then light-cured for 20 s from each surface using a light-emitting diode (LED) curing unit (Elipar S10, 3M ESPE, St. Paul, MN, USA; 1200 mW/cm²). The light power density (1200 mW/cm²) was measured for every five specimens using a digital dental radiometer (Hilux Light Meter, Benlioğlu, Türkiye). After polymerization, the samples were removed from the molds and stored in distilled water for 24 h, prior to measurement. A single-increment placement technique was used because the specimens were standardized disc-shaped samples with a thickness of 2 mm. In addition, universal composites based on single-shade and group-shade concepts are frequently intended for simplified, minimally invasive esthetic restorations in which a single-layer application may be clinically relevant. This approach allowed standardized comparison of the

Table 1: Resin Composite Materials Evaluated In The Study And Their Manufacturer-Reported Compositions

Group	Materials (Manufacturer)	Composition/ Type
Group 1 (Control)	GC G-aenial Anterior A1 (GC Corporation, Tokyo, Japan) Conventional multi-shade composite	Matrix: UDMA, dimethacrylate co-monomers. Fillers: silica and prepolymerized fillers. Filler loading: 68 vol%.
Group 2 (G1)	Filtek Easy Match (Bright) (Solventum, St. Paul, MN, USA) Group-shade universal composite	Matrix: UDMA, Bis-EMA, Bis-GMA, PEGDMA, TEGDMA. Fillers: silica and ytterbium trifluoride-based fillers. Filler loading: 64.5 vol%. Type: Nanohybrid universal resin composite.
Group 3 (G2)	OptiShade (Light) (Kerr Corporation, Orange, CA, USA) Group-shade universal composite	Matrix: Proprietary methacrylate resin matrix (exact composition not disclosed by the manufacturer). Fillers: Adaptive Response Technology (ART) filler system; barium glass, silica, and prepolymerized fillers. Filler loading: 65 vol% (manufacturer-reported value) Type: Nanohybrid universal resin composite.
Group 4 (S1)	GC Essentia Universal (GC Corporation, Tokyo, Japan) Single-shade universal composite	Matrix: UDMA, Bis-EMA, Bis-GMA, TEGDMA. Fillers: Barium glass and silica fillers. Filler loading: 65 vol%. Particle size: 0.02–2.0 µm. Type: Microhybrid universal resin composite.
Group 5 (S2)	Zen Chroma (President Dental, Germany) Single-shade universal composite	Matrix: Bis-GMA, UDMA, TEGDMA. Fillers: 53 vol%. Particle size: 0.005–3.0 µm. Type: Nanohybrid universal resin composite.

Material compositions were obtained from the manufacturers' instructions for use (IFUs) and technical data sheets

optical and surface behavior of the tested materials.

Composite samples were subjected to short- and long-term exposure to staining solutions after baseline measurements, followed by a bleaching procedure. The color and surface properties were evaluated longitudinally at five consecutive time points as follows:

- T1: 24 hours after polymerization (initial measurement)
- T2: Measurement after 24 hours of storage in şalgam juice
- T3: Measurement after 1 month of storage in şalgam juice
- T4: Measurement 1 day after the whitening application
- T5: Measurement 10 days after whitening application

The şalgam juice (Doğanay, Türkiye; pH 3.3–3.8) was renewed daily, and the samples were stored at

room temperature. A 35% hydrogen peroxide bleaching gel (Whiteness HP, FGM Dental Group, Joinville, SC, Brazil) was used as the in-office bleaching agent. The peroxide and thickener phases were mixed at a ratio of 3:1 according to the manufacturer's instructions. The bleaching gel was applied to the specimen surfaces for 15 min and renewed after each application, for a total of three consecutive applications (3 × 15 min; 45 min total exposure time). The gel was completely removed from the specimen surfaces between applications.

Color measurements were performed using a spectrophotometer (SpectroShade Micro, Medical High Technologies, Italy) according to the CIE L*a*b* color system. The device has a measurement area of 18 × 14 mm. During each measurement, the black positioning mouthpiece was placed in direct contact with the specimen surface, and the 8 - mm - diameter specimen

Table 2: Color Difference (ΔE_{00}) Values (mean $\pm$ SD) of The Tested Resin Composites Relative To Baseline (T1) at Different Evaluation Periods

Group	T1-T2	T1-T3	T1-T4	T1-T5
Control (GC G-aenial Anterior A1)	1.53 $\pm$ 0.35	4.16 $\pm$ 0.99	2.13 $\pm$ 0.53	2.78 $\pm$ 0.33
G1 (Filtek Easy Match)	1.52 $\pm$ 0.55	5.28 $\pm$ 1.20	1.87 $\pm$ 0.23	2.62 $\pm$ 0.27
G2 (OptiShade)	0.99 $\pm$ 0.30	3.39 $\pm$ 0.25	3.10 $\pm$ 0.34	3.06 $\pm$ 0.32
S1 (Essentia Universal)	5.61 $\pm$ 1.77	11.47 $\pm$ 2.75	2.01 $\pm$ 0.47	3.26 $\pm$ 0.52
S2 (Zen Chroma)	2.76 $\pm$ 1.12	5.55 $\pm$ 1.29	2.75 $\pm$ 0.49	3.86 $\pm$ 0.50

Values are presented as mean $\pm$ standard deviation (SD). Color differences (ΔE_{00}) were calculated relative to the baseline measurements (T1) using the CIEDE2000 formula. T2: after 24 h of şalgam juice immersion; T3: after 1 month of immersion; T4: 1 day after bleaching; T5: 10 days after bleaching

Table 3: Between-Material Comparisons At Each Evaluation Period

Outcome	Time	Kruskal–Wallis χ^2	Omnibus p	Significant Dunn comparisons, adjusted p
ΔE_{00}	T2	36.327	<0.001	Control–S1, 0.003; G1–S1, 0.002; G2–S1, <0.001; G2–S2, <0.001
	T3	36.427	<0.001	Control–S1, <0.001; G1–G2, 0.022; G2–S1, <0.001; G2–S2, 0.007
	T4	26.836	<0.001	Control–G2, 0.007; G1–G2, <0.001; G1–S2, 0.018; G2–S1, 0.002
	T5	25.834	<0.001	Control–S2, 0.001; G1–S1, 0.045; G1–S2, <0.001
	T1	42.846	<0.001	Control–G1, <0.001; Control–G2, 0.032; G1–S1, <0.001; G1–S2, 0.004; G2–S1, <0.001
WID	T2	30.819	<0.001	Control–G1, <0.001; G1–S2, <0.001
	T3	23.214	<0.001	Control–G2, 0.018; Control–S1, 0.019; G1–S2, 0.039; G2–S2, 0.007; S1–S2, 0.007
	T4	37.772	<0.001	Control–G1, <0.001; G1–S1, <0.001; G1–S2, 0.009; G2–S1, 0.002
	T5	43.342	<0.001	Control–G1, 0.002; G1–S1, <0.001; G1–S2, <0.001; G2–S1, <0.001
	T1	7.882	0.096	None
Ra	T2	16.976	0.002	Control–G1, 0.048; G1–S1, 0.013
	T3	11.080	0.026	G1–S1, 0.033
	T4	4.793	0.309	None
	T5	2.049	0.727	None

remained entirely within the measurement field. Three consecutive measurements were taken for each specimen, and the mean values were used for the analyses. Three consecutive measurements were taken for each sample, and the average values were used in the analyses. The device was calibrated every five measurements. The color difference (ΔE_{00}) between baseline (T1) and each subsequent measurement period (T2–T5) was

calculated from the measured CIELAB coordinates (L^* , a^* , and b^*) using the CIEDE2000 formula:

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

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ represent the differences in lightness, chroma, and hue, respectively; S_L , S_C , and S_H are weighting functions; k_L , k_C , and

Table 4: Within-material Comparisons of Whiteness Index Values Across The Evaluation Periods

Resin composite	Friedman χ^2	df	p value	Kendall's W
Control	35.840	4	<0.001	0.896
G1	35.440	4	<0.001	0.886
G2	40.000	4	<0.001	1.000
S1	25.840	4	<0.001	0.646
S2	38.720	4	<0.001	0.968

Friedman tests were based on 10 specimens measured at five evaluation periods. Kendall's W was calculated as $\chi^2/[n(k-1)]$ and is reported as the effect-size measure. Statistical significance was set at $p < 0.05$.

Table 5: Whitening Recovery (%) of the Tested Resin Composites After Bleaching

Resin composite	Whitening recovery (%)
Control (GC G-aenial Anterior A1)	64
G1 (Filtek Easy Match)	82
G2 (OptiShade)	55
S1 (Essentia Universal)	-21
S2 (Zen Chroma)	53

kH are parametric factors; and RT is the rotation term.

The surface roughness values were measured using a Surfest SJ 301 profilometer (Mitutoyo Corporation, Japan), and the average surface roughness (R_a , μm) was recorded. Three measurements were taken for each sample, and mean values were calculated. A 5 μm tip with a 90° angle was employed for the measurement, with a standardized measurement force of 4 mN. The profilometer sampling length was set to 8 mm, and the cut-off length to 8 mm/8 μm . The measuring speed was set to 0.75 mm/s.

Standardization procedures were applied to minimize experimental variability during sample preparation and measurement. All composite discs were prepared by the same operator using the same mold system, in accordance with the manufacturer's instructions. During polymerization, a transparent strip and glass slide were placed over the specimen surface, and the light-curing tip was positioned in direct contact with the glass slide (0 mm tip-to-glass distance) to standardize the irradiation geometry.

The prepared specimens were randomly coded prior to the experimental procedures, and the measurement sequence was randomized. The operator performing the measurements was

blinded to group allocation throughout the study. Color and surface roughness measurements were always conducted at the same point, under the same environmental conditions, and using the same device settings.

This study used an in vitro experimental design and did not involve human participants, human-derived biological materials, or personal data. Therefore, ethics committee approval was not required according to national regulations governing in vitro experimental studies.

Statistical Analysis: The original statistical analyses were performed using IBM SPSS Statistics for Windows, version 23.0 (IBM Corp., Armonk, NY, USA). The additional Dunn post hoc and rank-based permutation analyses performed during revision were conducted using custom Python scripts in Python 3.12.14 with NumPy 2.3.5 and SciPy 1.17.0. Continuous variables are presented as mean $\pm$ standard deviation (mean $\pm$ SD). Considering the distribution characteristics of the data and the sample size, non-parametric tests were used. When a Kruskal–Wallis test was significant, two-sided Dunn tests were used for pairwise comparisons between materials. The Bonferroni correction was applied separately within each outcome-specific time point, comprising the 10

possible pairwise comparisons among the five materials. Adjusted p values were calculated as the raw Dunn p value multiplied by 10 and truncated at 1.00. Pairwise comparisons were performed only following a significant omnibus test. Whitening recovery was calculated as a percentage using the baseline (T1), post-staining (T3), and post-bleaching (T5) measurements. Within-material changes in WID across the five evaluation periods were assessed using the Friedman test. Between-material differences in ΔE_{00} , WID, and Ra at each applicable evaluation period were evaluated using the Kruskal–Wallis test. To formally determine whether the longitudinal response profiles differed among the materials, material-by-time interactions were evaluated separately for ΔE_{00} , WID, and Ra using rank-based synchronized permutation tests. Observations were ranked within each evaluation period, and the interaction F statistic was calculated from the ranked responses. During permutation, the complete repeated-measures vector of each specimen was retained, and material-group labels were permuted at the specimen level, thereby preserving the within-specimen dependence. The ΔE_{00} analysis included the four post-baseline color-difference measurements; the structural baseline value of zero was not treated as an observed measurement. Monte Carlo p values were based on at least 99,999 permutations, with additional permutations used to verify borderline results. The family of three interaction tests was controlled using the Holm procedure. To examine the specific observation of limited post-bleaching whiteness recovery in S1, bleaching-phase change was calculated as WID at T5 minus WID at T3. These change scores were first compared among the five materials using the Kruskal–Wallis test. Exact permutation comparisons between S1 and each of the remaining materials were subsequently performed, with Holm adjustment across the four comparisons. A fixed random seed of 260918 was used for the permutation analyses. Statistical significance for the overall analyses was set at $p < 0.05$.

Results

Color Change ΔE_{00} : The mean ΔE_{00} values of the tested resin composites at each evaluation period are presented in Table 2. After 24 h of salgam immersion (T2), the lowest ΔE_{00} value was observed in G2 (0.99 ± 0.30), whereas the highest value was observed in S1 (5.61 ± 1.77). Following one month of immersion (T3), discoloration

increased in all groups, with S1 exhibiting the highest ΔE_{00} value (11.47 ± 2.75) and G2 the lowest (3.39 ± 0.25). After bleaching, ΔE_{00} values decreased from their T3 levels in all groups. At the final evaluation (T5), G1 demonstrated the lowest residual color difference (2.62 ± 0.27), whereas S2 exhibited the highest value (3.86 ± 0.50) (Table 2, Figure 2A).

Kruskal–Wallis tests demonstrated significant differences among the materials at T2, T3, T4, and T5 (all $p < 0.001$). Dunn–Bonferroni comparisons showed that the significant pairwise differences varied across the evaluation periods. At T2, S1 had higher ΔE_{00} values than the Control, G1, and G2 groups, while S2 had higher values than G2. At T3, S1 had higher values than the Control and G2 groups; G1 and S2 also had higher values than G2. At T4, G2 had higher values than the Control, G1, and S1 groups, while S2 had higher values than G1. At T5, S2 had higher values than the Control and G1 groups, and S1 had higher values than G1. The omnibus and significant pairwise results are summarized in Table 3.

Whiteness Index WID: Friedman tests demonstrated significant within-material changes in WID across the five evaluation periods for the Control ($\chi^2 = 35.840$), G1 ($\chi^2 = 35.440$), G2 ($\chi^2 = 40.000$), S1 ($\chi^2 = 25.840$), and S2 ($\chi^2 = 38.720$) groups (all $df = 4$, all $p < 0.001$; Table 4). Kendall's W values ranged from 0.646 to 1.000, indicating strong temporal effects.

Kruskal–Wallis tests also demonstrated significant between-material differences at T1 ($\chi^2 = 42.846$), T2 ($\chi^2 = 30.819$), T3 ($\chi^2 = 23.214$), T4 ($\chi^2 = 37.772$), and T5 ($\chi^2 = 43.342$; all $p < 0.001$). The significant Dunn–Bonferroni pairwise comparisons are presented in Table 3.

At baseline (T1), G1 exhibited the highest WID value, whereas S1 showed the lowest. WID values generally decreased following salgam exposure and reached their lowest levels after one month of immersion (T3). Following bleaching, the recovery patterns varied among the materials. At T5, G1 presented the highest WID value (21.31 ± 0.74), whereas S1 exhibited the lowest value (10.82 ± 0.78) (Figure 2B).

The whitening recovery percentages are presented in Table 5. G1 demonstrated the highest whitening recovery (82%), whereas S1 showed the lowest recovery (−21%). The recovery percentages for the Control, G2, and S2 groups were 64%, 55%, and 53%, respectively (Table 5, Figure 2B).

Surface Roughness Ra: Between-material differences in Ra were not significant at T1 ($\chi^2 = 7.882$, $p = 0.096$), T4 ($\chi^2 = 4.793$, $p = 0.309$), or

Table 6: Rank-Based Permutation Tests of Material-By-Time Interactions For The Evaluated Outcomes

Outcome	Number of evaluation levels	Interaction F	df	Raw p value	Holm-adjusted p value
ΔE_{00}	4	15.378	12, 135	<0.001	<0.001
WID	5	13.110	16, 180	<0.001	<0.001
Ra	5	1.842	16, 180	0.049	0.049

Values were ranked within each time point, and group labels were permuted at the specimen level to preserve within-specimen dependence. Holm adjustment was applied across the three interaction tests. For ΔE_{00} , the structural baseline value of zero was excluded

T5 ($\chi^2 = 2.049$, $p = 0.727$). Significant differences were detected at T2 ($\chi^2 = 16.976$, $p = 0.002$) and T3 ($\chi^2 = 11.080$, $p = 0.026$). At T2, the Control and S1 groups had significantly higher Ra values than G1. At T3, S1 had a significantly higher Ra value than G1 after Bonferroni adjustment (Table 3).

S1 exhibited the highest mean Ra values following şalgam immersion, whereas G2 showed comparatively small descriptive changes during the same period. Surface roughness decreased after bleaching, with no significant between-material differences detected at T4 or T5 (Figure 2C).

Evaluation of Parameters Together: When the optical (ΔE_{00} and WID) and surface (Ra) parameters were evaluated together, distinct performance profiles emerged among the tested materials. G2 generally demonstrated lower discoloration during the staining period, while G1 showed the highest whitening recovery. In contrast, S1 exhibited pronounced discoloration and increased surface roughness during staining (Figure 2D).

The rank-based permutation analyses demonstrated significant material-by-time interactions for ΔE_{00} , $F(12, 135) = 15.378$, $p < 0.001$; WID, $F(16, 180) = 13.110$, $p < 0.001$; and Ra, $F(16, 180) = 1.842$, $p = 0.049$. These findings indicate that the longitudinal staining and bleaching response profiles differed among the tested materials. The interaction results remained significant after Holm adjustment across the three outcome-specific tests (Table 6).

During the bleaching phase, the mean change in WID from T3 to T5 was +5.23 for the Control, +10.15 for G1, +3.58 for G2, -0.88 for S1, and +5.60 for S2. These changes differed significantly among the materials (Kruskal-Wallis $\chi^2 = 34.210$, $p < 0.001$). S1 showed a significantly smaller change than each of the other four materials in Holm-adjusted exact permutation comparisons (all adjusted $p \leq 0.0013$).

Discussion

This longitudinal in vitro study demonstrated that the temporal responses of the tested resin composites to şalgam-induced staining and subsequent bleaching differed according to material. The formal interaction analyses confirmed material-dependent longitudinal profiles for ΔE_{00} and WID, while the corresponding interaction for Ra was weaker and should be interpreted cautiously. The statistical analyses revealed significant differences in ΔE_{00} , WID, and Ra according to the evaluated experimental factors, leading to rejection of the null hypothesis. The findings suggest that resin composites may exhibit material-dependent behavior not only in initial esthetics but also in staining susceptibility, bleaching response, and surface stability.

Unlike many previous studies that evaluated staining or bleaching effects at a single endpoint, the present study employed a longitudinal repeated-measurement design, allowing the dynamic behavior of composite materials throughout the entire staining-bleaching cycle to be monitored. This approach provides a more realistic representation of clinical conditions, where restorations are repeatedly exposed to staining challenges and aesthetic interventions over time.

Color Stability Findings

Among the group-shade composites, Filtek Easy Match (G1) showed a significant color change upon exposure to şalgam juice. This finding suggests that color stability may differ among materials marketed under the same group-shade concept, highlighting the influence of material-specific composition.

OptiShade (G2) generally showed low ΔE_{00} values during staining; at T3, its ΔE_{00} value was significantly lower than those of G1, S1, and S2 after Bonferroni adjustment. The limited color change after şalgam exposure may indicate that the filler-matrix interface displays greater

resistance to acidic environments. Previous studies have reported that the surface and optical stability of resin composites depend on the material composition, which supports these findings (2,3,17). The fact that G2 largely preserves both color stability and surface integrity suggests that it may provide more predictable clinical performance in individuals with high consumption of staining beverages.

Among the single-shade composites, Essentia (S1) exhibited the most pronounced color change. The literature reports that single-shade composites exhibit different behaviors after aging and whitening (12,13,18,19). The low pH and anthocyanin pigment content of şalgam juice may have facilitated pigment penetration by increasing hydrolytic degradation within the organic matrix (2,17,20). It has previously been shown that increased surface roughness can enhance pigment retention (7,21,22). This may explain the pronounced color change observed in the S1 group.

The material-dependent differences observed in the present study may be related to variations in resin-matrix chemistry and filler characteristics. Previous studies have demonstrated that monomer composition can influence water sorption, water solubility, and color stability of resin composites (23), while filler size can influence surface roughness and surface-property retention (24). In the present study, S1, a microhybrid resin composite containing barium glass and silica fillers with a particle size range of 0.02–2.0 µm, exhibited pronounced discoloration together with increased surface roughness after staining. In contrast, G2, a nanohybrid material with a similar manufacturer-reported filler loading but a different filler system incorporating barium glass, silica, and prepolymerized fillers, showed lower discoloration and comparatively small changes in surface roughness. Thus, the different behavior of S1 and G2 despite their similar filler loading suggests that filler content alone may not account for staining susceptibility; differences in resin-matrix chemistry, filler characteristics, and filler-matrix interactions may collectively contribute to the observed material-specific responses.

Zen Chroma (S2), in contrast to other single-shade composites, demonstrated more balanced performance. This finding indicates that the concept of a “single-shade” does not guarantee homogeneous clinical behavior among different materials (9,11,25–27). Therefore, the performance of single-shade composites may vary by brand and formulation characteristics.

The shade concept itself may also influence optical behavior, although it should not be considered independently of material composition. Single-shade composites are designed to achieve color harmony across a broad range of tooth shades through enhanced color adjustment and chameleon effects, whereas group-shade systems use a limited number of shades intended to cover predefined shade ranges (10,11,28). However, the present findings indicate that the ability to simplify shade selection does not necessarily imply greater resistance to discoloration. The two group-shade materials showed different staining responses, while the single-shade materials also behaved heterogeneously, with S1 exhibiting the greatest discoloration and S2 showing a more balanced response. Therefore, shade concept may contribute to initial color adaptation and color harmony, but long-term color stability after staining and bleaching appears to remain strongly material-dependent. Because only two materials represented each universal shade concept in the present study, these findings should be interpreted at the material level rather than generalized to all single-shade or group-shade resin composites.

Whitening Findings

The differences in whitening recovery rates indicate that the efficacy of whitening may vary depending on the material composition (6). Better preservation of surface integrity may facilitate more effective access of whitening agents to the pigments (4,5). In contrast, in materials with increased surface degradation, deeper pigment penetration may limit the efficacy of the whitening agent (13,18). This finding supports the clinical importance of evaluating existing restorations before tooth whitening (29,30).

Filtek Easy Match (G1) demonstrated the highest recovery after bleaching. This finding may suggest that the pigments were retained more superficially and could be removed more effectively through the oxidative action of bleaching agents (4,5,14). In line with previous reports, bleaching effectiveness appears to be influenced by the composition and structure of the restorative material (6,17,18).

Hydrogen peroxide-based bleaching may interact differently with resin composites depending on their material characteristics. Peroxide-derived oxidative species can react with chromophoric molecules, while the accessibility and distribution of staining pigments within the resin matrix may influence the extent of color recovery (5,6). In the present study, G1, which contains UDMA, Bis-EMA, Bis-GMA, PEGDMA, and TEGDMA, demonstrated the highest whitening recovery

(82%), whereas S1, containing UDMA, Bis-EMA, Bis-GMA, and TEGDMA, showed no recovery in WID and had the lowest calculated recovery (−21%). Because these two materials share several dimethacrylate monomers but exhibited markedly different bleaching responses, the observed difference cannot be attributed to the presence of a single monomer. Instead, differences in the overall resin-matrix formulation, filler system, and the extent and depth of pigment penetration may collectively contribute to material-dependent bleaching responses (5,6,13).

The control group (G-enial A1) showed a moderate level of recovery and demonstrated that conventional multi-shade composites can respond consistently to the staining–whitening cycle (1,31). In contrast, Essentia (S1) did not show recovery in WID between T3 and T5, whereas WID increased in the other four materials during the same period. The bleaching-phase WID change in S1 was significantly smaller than that observed in each of the other materials after adjustment for multiple comparisons. This finding supports a material-specific difference in post-bleaching whiteness response; however, the underlying compositional or structural mechanism cannot be established from the present data.

Overall, the bleaching response differed considerably among the tested materials, indicating that recovery from discoloration is influenced not only by the degree of staining but also by the intrinsic characteristics of the resin composite.

Surface Roughness Findings

Significant between-material differences in surface roughness were detected at T2 and T3, and the rank-based permutation analysis indicated a borderline material-by-time interaction. Among the tested materials, Essentia (S1) exhibited the highest roughness values following şalgam exposure, whereas OptiShade (G2) showed comparatively small descriptive changes in surface roughness during the experimental period. However, because the material-by-time interaction for Ra was borderline, material-specific roughness trajectories should be interpreted cautiously. These findings suggest that the resistance of resin composites to surface degradation may be influenced by differences in filler composition, filler loading, and matrix characteristics.

The present findings demonstrated a parallel trend between increased surface roughness, greater color change, and reduced whiteness values. It has been reported in the literature that increased surface roughness can facilitate pigment retention and

accelerate secondary staining (7,8,16). Therefore, evaluating the clinical aesthetic success of resin composites not only by color difference but also by surface stability and changes in perceptual whiteness may provide a more holistic approach to clinical practice. The simultaneous evaluation of ΔE_{00} , WID, and Ra provides a multidimensional interpretation of composite behavior that may better reflect clinical perception than studies evaluating color change alone.

Interestingly, surface roughness values decreased after the bleaching procedure in all groups. Although bleaching agents have been reported to adversely affect surface characteristics under certain conditions, the present findings suggest that the response may vary according to material composition and the extent of prior surface degradation. These observations further support the importance of evaluating optical and surface properties together when assessing the long-term clinical behavior of restorative materials.

The Effect of Şalgam Juice: Şalgam juice was selected as the staining medium because of its low pH and high anthocyanin content, both of which may influence the optical and surface properties of resin composites. Acidic environments have been reported to soften the resin matrix and facilitate pigment adsorption, thereby increasing the susceptibility of restorative materials to discoloration and surface degradation (16,17,32). In addition, anthocyanins exhibit a high affinity for organic matrices and may contribute to color changes through enhanced pigment penetration (3,20). Although the staining effects of beverages such as coffee and tea have been extensively investigated, evidence regarding fermented beverages remains limited (1,21,33). Therefore, the present findings contribute to understanding how traditionally consumed acidic, pigment-rich beverages may affect the long-term behavior of composite restorations.

Clinical Implications: The present findings suggest that the long-term esthetic performance of resin composites depends not only on their initial color-matching ability but also on their resistance to staining and their response to bleaching procedures. Materials exhibiting lower discoloration and greater color recovery may be advantageous for patients who frequently consume acidic or pigment-rich beverages or who undergo periodic tooth-whitening treatments. Therefore, restorative material selection should be based not only on immediate esthetic outcomes but also on the material's anticipated long-term

behavior under everyday dietary and esthetic challenges.

The use of a single-increment application protocol may also be considered clinically relevant, as contemporary universal composites are frequently promoted for simplified restorative procedures, particularly in minimally invasive anterior restorations, where color adaptation and the chameleon effect are expected to reduce the need for complex layering techniques. Therefore, the present design reflects one of the intended clinical applications of these materials.

Limitations of the Study: This study was conducted in vitro, and the biological and mechanical factors of the oral environment could not be fully simulated (10,28,30). The continuous-immersion model may not accurately reflect clinical consumption patterns. The bleaching protocol was limited to a single whitening agent (6,18,34), and mechanical properties and translucency changes were not evaluated (20,35,36). Surface roughness was assessed using a contact profilometer (35,37), and visual color evaluation was not performed (14,38). These limitations should be considered when interpreting the findings.

Future studies incorporating intraoral aging conditions and biofilm interactions are needed to further clarify the clinical behavior of these materials.

This study represents one pre-specified outcome domain of a broader experimental project designed to investigate multiple optical and surface-related properties of contemporary resin composites. To ensure methodological clarity and focused interpretation, each outcome domain was planned a priori and analyzed separately. Although rank-based permutation analysis allowed formal evaluation of material-by-time interactions, it identifies differences in longitudinal response profiles rather than the compositional or mechanistic causes of these differences. In addition, the interaction observed for Ra was borderline and requires confirmation in studies with larger sample sizes.

This longitudinal study demonstrated significant material-dependent differences in ΔE_{00} and WID trajectories across the staining–bleaching cycle, while the material-dependent Ra trajectories were less pronounced. Although the two group-shade materials generally showed favorable performance, heterogeneous responses were observed among the tested single-shade materials. The combined evaluation of ΔE_{00} , WID, and Ra parameters provided a more comprehensive understanding of

the clinical aesthetic performance of resin composites. The null hypothesis was rejected, and significant differences were observed between the groups.

Understanding these combined optical and surface responses may help clinicians select restorative materials based not only on initial esthetics but also on long-term behavior under dietary and whitening challenges.

Ethical Approval: This study was conducted using an in vitro experimental design, and no human participants, human-derived biological materials, or personal data were used. Therefore, ethics committee approval was not required under the relevant national research ethics guidelines.

Clinical trial number: Not applicable.

Credit Authorship Contribution Statement:

IEP: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Supervision. **SK:** Investigation, Data curation, Writing – review & editing.

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