

Color Stability of Conventional and Biocompatible Resin Composites After Prolonged Exposure to Staining Agents: An In Vitro Study

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Abstract

Objective:

The aim of this in vitro study was to evaluate and compare the color stability of conventional universal resin composites and so-called biocompatible resin composites following exposure to common dietary staining agents.

Materials and Methods:

Sixteen resin composites from five manufacturers were investigated, including conventional universal composites and biocompatible composites formulated to reduce or eliminate specific methacrylate monomers. Disc-shaped specimens (10 mm × 1 mm) were fabricated in shade A2 and polymerized using a LED light-curing unit. Baseline color measurements were performed after 24 hours of storage at 37°C using a reflection spectrophotometer according to the CIE Lab* color system. Specimens were subsequently immersed for six weeks in coffee, red wine, curry in oil, or distilled water (control) at 37°C. Post-staining color measurements were recorded using the same protocol. Color differences between baseline and post-staining measurements were calculated using the CIEDE2000 (ΔE_{00}) formula.

Results:

Composite discoloration was significantly influenced by both the type of staining medium and the composite material ($p < 0.001$), with a significant interaction between these factors. Coffee and red wine produced the greatest color changes, whereas curry in oil and the control condition resulted in lower ΔE_{00} values. Marked differences in color stability were observed among materials: PUREFILL2 Bio+ A2 and ENAMEL PLUS HRI UE2 exhibited the highest discoloration, while MHC A2 and APT A2 demonstrated the lowest ΔE_{00} values. Exclusion of the control group enhanced discrimination among composites under effective staining conditions, revealing a consistent ranking of materials across staining agents. Comparable results were obtained under both white and black background conditions.

Conclusion:

Within the limitations of this in vitro study, the color stability of resin-based composites was influenced by both material composition and staining medium. Comparative evaluation of conventional and biocompatible resin composites provides relevant information regarding the aesthetic durability of modified resin formulations under staining conditions.

1. Introduction

Resin-based composites are among the most widely used restorative materials in contemporary dentistry due to their favorable aesthetic properties, acceptable mechanical performance, and compatibility with minimally invasive restorative techniques. In aesthetic regions, long-term color stability is essential for clinical success and patient satisfaction, as discoloration remains one of the most common reasons for restoration replacement [1–5].

Conventional universal resin composites typically consist of a methacrylate-based resin matrix—commonly including bisphenol A-glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA), and other diluent monomers—combined with inorganic filler particles and silane coupling agents. Variations in monomer chemistry, particularly in hydrophilicity, molecular weight, and degree of conversion, significantly influence water sorption, mechanical behavior, and long-term material stability [6–8]. Increased water uptake facilitates the diffusion of staining agents and contributes to resin matrix degradation, filler–matrix debonding, and microcrack formation, thereby promoting discoloration over time [9–12].

Beyond aesthetic and mechanical considerations, the matrix composition of conventional resin composites has raised concerns regarding potential adverse biological effects. Incomplete polymerization and long-term degradation of methacrylate-based materials may lead to the release of residual monomers such as Bis-GMA, TEGDMA, and UDMA into the oral environment [14,15]. Bis-GMA is structurally related to bisphenol A (BPA), a compound with documented estrogenic activity, and trace amounts of BPA or BPA-related derivatives may be released from resin composites through mechanical, hydrolytic or enzymatic degradation processes [16–18]. TEGDMA, a low-molecular-weight and relatively hydrophilic monomer, has been associated with increased cytotoxicity, oxidative stress, and genotoxic effects in vitro, as well as enhanced diffusion through dentin [19–21]. In addition, degradation of resin-based materials

may result in the formation of formaldehyde and other potentially toxic by-products, further contributing to biocompatibility concerns [22,23]. These findings have prompted increased scrutiny of conventional composite formulations, particularly in the context of long-term and repeated clinical exposure.

In response to growing concerns regarding the biological safety of conventional methacrylate-based composites, manufacturers have introduced so-called “biocompatible” or “bio” resin composites. These materials are formulated with modified resin matrices and are marketed as reducing or eliminating monomers considered potentially harmful, such as Bis-GMA, TEGDMA, or BPA-related compounds. Alternative resin chemistries, including modified methacrylates and non-BPA-based monomer systems, have been proposed to minimize monomer release and improve biological compatibility [25–27]. However, modifications in resin chemistry may also influence material properties such as water sorption, degree of conversion, and resistance to discoloration, necessitating experimental evaluation of their clinical performance [28–30].

Color instability of resin composites results from a combination of intrinsic and extrinsic factors. Intrinsic factors include resin matrix composition, filler characteristics, degree of conversion, and surface finish, while extrinsic factors primarily involve exposure to dietary chromogens [31–33]. Commonly consumed substances such as coffee, red wine, and curry-based products possess high staining potential and are frequently employed in “in vitro” studies to simulate extrinsic discoloration under controlled conditions [12,30,34,35]. Among these agents, coffee and red wine have consistently been shown to induce greater color changes than other staining solutions [34–36].

Despite the extensive literature on resin composite discoloration, limited data are available directly comparing the color stability of conventional universal resin composites and biocompatible resin composites under identical experimental conditions. Such comparisons are essential to determine whether modifications in resin chemistry translate into clinically relevant improvements in aesthetic durability.

Therefore, the aim of this in vitro study was to evaluate and compare the color stability of conventional universal resin composites and biocompatible resin composites from different manufacturers following exposure to common dietary staining agents, namely coffee, red wine, and curry in oil. Color changes were assessed using a spectrophotometric method based on the CIE Lab* color system, and color differences were calculated using the CIEDE2000 (ΔE_{00}) formula [38].

Null hypothesis: Resin composites do not stain when immersed in coffee, red wine and curry and there is no statistically significant difference in color stability between conventional universal resin composites and biocompatible resin composites after exposure to staining solutions.

2. Materials and Methods

2.1 Methodology

The experimental design and staining protocol were based on previous laboratory investigations of the staining susceptibility of esthetic resin composites. In particular, the study by Ardu et al. provided methodological support for the immersion protocol, staining media, and spectrophotometric assessment of color changes [12].

2.2 Materials

The resin composites investigated in this study are listed in Table 1. A total of 16 commercially available resin composites from five manufacturers were selected, including both conventional universal composites and biocompatible (“bio”) composites formulated to exclude or reduce certain potentially harmful resin monomers, such as Bis-GMA. All materials were tested in shade A2 or the closest available equivalent.

Information regarding the main resin matrix components, filler types, filler loadings, lot numbers, and expiration dates was recorded to ensure traceability and reproducibility. This characterization enabled comparative analysis of color stability in relation to resin chemistry and filler composition.

2.3 Specimen Preparation

Disc-shaped specimens were prepared for each resin composite. The specimens measured 10 mm in diameter and 1 mm in thickness. Composite material was placed between two microscope glass slides and gently compressed to obtain standardized dimensions.

Polymerization was performed using an LED light-curing unit (Bluephase G2 Ivoclar Vivadent) placed in direct contact with the upper glass slide. Each specimen was light-cured for 20 seconds, with the 1 mm thick glass slide interposed between the light source and the composite material.

A total of 384 specimens were fabricated, corresponding to 24 samples for each one of the 16 composite material tested. Each specimen was randomly assigned to one of four experimental groups, resulting in one specimen per composite material for each staining condition.

Following polymerization, specimens were briefly polished using a Sof-Lex™ polishing disc (3M ESPE, USA) to remove the superficial oxygen-inhibited layer. All specimens were subsequently stored in an incubator at 37°C for 24 hours to allow for post-curing polymerization prior to baseline color measurement [10].

2.4 Baseline Color Measurement

Baseline color measurements (T_0) were performed after the 24-hour storage period using a reflection spectrophotometer (SpectroShade, MHT, Niederhasli, Switzerland). The color parameters L^* (lightness), a^* (green–red axis), and b^* (blue–yellow axis) were recorded according to the CIE Lab* color system [38].

The spectrophotometer was calibrated before each measurement in accordance with the manufacturer's instructions. Measurements were conducted against both white and black backgrounds to account for potential background-related effects on translucency [37, 39].

2.5 Staining Procedure

After baseline color assessment, specimens were divided into four groups according to staining medium: coffee, red wine, curry in oil, and distilled water (control). Each specimen was fully immersed in its respective solution and stored in an incubator at 37°C (INP-500, Memmert, Germany) to simulate oral temperature conditions [34–36].

Staining solutions were renewed weekly to maintain staining efficacy and minimize microbial contamination. The total immersion period was six weeks.

2.6 Post-Staining Cleaning and Final Color Measurement

Following completion of the staining period, specimens were removed from the solutions and cleaned using a nylon prophylaxis brush and Depurder toothpaste to remove superficial deposits. Specimens were then rinsed thoroughly with water and air-dried prior to final color assessment.

Post-staining color measurements (T_1) were performed using the same spectrophotometer and measurement protocol as at baseline. L^* , a^* , and b^* values were recorded against both white and black backgrounds, with the same number of measurement areas per specimen as at T_0 .

2.7 Color Difference Calculation

Color differences between baseline (T_0) and post-staining (T_1) measurements were calculated using the CIEDE2000 (ΔE_{00}) formula, which provides a perceptually relevant method for evaluating color differences in dental materials.

2.8 Statistical Analysis

Composite discoloration was quantified as the CIEDE2000 color difference (ΔE_{00}) between baseline (T_0) and post-staining (T_1) measurements after immersion in the respective staining media. ΔE_{00} values were treated as continuous response variables.

To evaluate the effects of staining medium and composite material on color change, a two-way analysis of variance (ANOVA) was performed, with STAINING and COMPOSITE included as fixed factors and their interaction term (STAINING $\times$ COMPOSITE). The primary analysis included the distilled-water control group to provide a reference condition for assessing color stability.

Because the control condition produced markedly lower discoloration and contributed substantially to the overall variability, a secondary two-way ANOVA was performed after excluding the control group. This complementary analysis focused on differences among composite materials under staining conditions, with the staining solutions considered jointly. Excluding the control group provided greater discrimination of material-related differences under staining exposure.

When statistically significant effects were identified, post hoc multiple comparisons among composite materials were performed using Fisher's Least Significant Difference (LSD) test. Results are presented as mean ΔE_{00} values with corresponding standard deviations. Graphical representations were generated as interval plots displaying 95% confidence intervals for the mean, calculated using individual group standard deviations.

All statistical analyses were performed using Minitab® 19.2020.1 (Minitab LLC, State College, PA, USA). Analyses were conducted separately for measurements obtained against white and black backgrounds to assess the robustness of the findings with respect to background contrast.

Table 1

Resin composites tested in this study. Conventional universal and biocompatible (“bio”) materials are listed with manufacturer, main resin matrix components, filler type, filler loadings, lot number, and expiration date.

Composite (Shade)	Category	Resin Matrix (Main Monomers)	Filler Type	Filler wt (%)	Filler vol (%)	Manufacturer	Lot N°	Expiry date
Brilliant EverGlow (A2/B2)	Conventional	Methacrylate derivatives	BaAl borosilicate + SiO ₂	74	56	Coltene, CH	N60583	17.12.2027
Brilliant NG (A2/B2)	Conventional	Methacrylate derivatives	BaAl borosilicate + SiO ₂	80	65	Coltene, CH	N71883	20.02.2028
Purefill2 Bio+ (A2)	Bio	UDMA-based	BaAl silicate + SiO ₂	~ 80	-	Elsodent, FR	52924	4.2027
Pureshade Bio+ (Shade 2)	Bio	UDMA-based	BaAl silicate + SiO ₂	70–80	-	Elsodent, FR	12225	12.2027
G-aenial A'CHORD (A2)	Conventional	Dimethacrylate-based; proprietary Bis-MEPP system	Ba glass + SiO ₂	-	41	GC, JP	2409261	25.09.2027
G-aenial A'CHORD (A02)	Conventional	Dimethacrylate-based; proprietary Bis-MEPP system	Ba glass + SiO ₂	-	41	GC, JP	2408021	01.08.2027
Enamel Plus HRi (UD2)	Conventional	Bis-GMA + diurethane dimethacrylate	ZrO ₂ + glass	75	53	Micerium, IT	2024007265	31.12.2029
Enamel Plus HRi (UE2)	Conventional	Bis-GMA + BUDMA	ZrO ₂ + glass	80	63	Micerium, IT	2024004880	31.03.2028
Plus HRi Bio Function (BF2)	Bio	UDMA + TCDDM	SiO ₂ + glass	74	60	Micerium, IT	2024003424	30.04.2027
Plus HRi Bio Function (BD2)	Bio	UDMA + TCDDM	SiO ₂ + glass	74	60	Micerium, IT	2024005152	31.08.2027
ELS (A2)	Conventional	Bis-GMA + Bis-EMA	BaAl borosilicate glass	74	49	Saremco, CH	F628	7.2029
ELS (A02)	Conventional	Bis-GMA + Bis-EMA	BaAl borosilicate glass	74	49	Saremco, CH	F492	7.2029
MHC (A2)	Conventional	Bis-GMA + Bis-EMA + TEGDMA	BaAl borosilicate glass	76	52	Saremco, CH	F555	9.2028
APT (A2)	Conventional	Aromatic UDMA + Bis-EMA	BaAl borosilicate glass	74	49	Saremco, CH	F441-1	5.2027
Venus Diamond (A2)	Conventional	TCD-based urethane matrix	BaAl fluoroborosilicate + SiO ₂	-	64	Kulzer, DE	N010204	02.05.2027
Venus Pearl (OLC)	Conventional	TCD-based urethane matrix	BaAl fluoroborosilicate + SiO ₂	-	59	Kulzer, DE	N010304	10.01.2025

3. Results

The two-way ANOVA including the control condition revealed statistically significant main effects of COMPOSITE and STAINING, as well as a statistically significant STAINING × COMPOSITE interaction (all $p < 0.001$; Tables 2.1 and 2.2). These findings indicate that discoloration was significantly influenced by both the staining medium and the composite material, and that the magnitude of color change differed among materials according to the staining medium.

In the secondary analysis excluding the control group, statistically significant differences among composite materials became more clearly defined. Fisher's LSD post hoc comparisons identified distinct groupings of composites based on their mean ΔE_{00} values (Tables 3.1 and 3.2). PUREFILL2 Bio+ A2 and ENAMEL PLUS HRi UE2 exhibited the highest discoloration, whereas MHC A2 and APT A2 demonstrated the lowest ΔE_{00} values, indicating superior color stability. Composites sharing the same grouping letter did not differ significantly, while those assigned to different letters showed statistically significant differences at the selected significance level.

Figure 1.1 and 1.2 display interval plots of mean ΔE_{00} values with corresponding 95% confidence intervals for the different composites, excluding the control condition. In these figures all staining effects were pooled together. These plots reveal a clear ranking of materials with minimal overlap among confidence intervals, supporting the robustness and consistency of the post hoc groupings.

Figures 2.1 and 2.2 present interval plots stratified by staining medium. Although the magnitude of ΔE_{00} varied substantially among staining agents, with the highest values observed for coffee and red wine and lower values for curry in oil and the control condition, the relative ordering of the composite materials was broadly similar across staining media. This observation should be interpreted alongside the significant STAINING × COMPOSITE interaction observed in the ANOVA, which indicates that the magnitude of discoloration depended on the combination of material and staining medium.

Analyses performed using a black background yielded findings consistent with those obtained using a white background in terms of statistical significance and the overall ordering of the composite materials. The higher absolute ΔE_{00} values observed against the black background may reflect differences in optical contrast and translucency rather than differences in intrinsic material behavior.

Table 2.1
Two-Way Analysis of Variance (with Control) – White Background

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Composite	15	12679	845.27	263.07	< 0.001
Staining	3	18800	6266.78	1950.40	< 0.001
Composite × Staining	45	6621	147.13	45.79	< 0.001
Error	320	1028	3.21		
Total	383	39129			

Table 2.2
Two-Way Analysis of Variance (with Control) – Black Background

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Composite	15	9445.2	629.68	227.16	< 0.001
Staining	3	14574.1	4858.03	1752.58	< 0.001
Composite × Staining	45	3946.9	87.71	31.64	< 0.001
Error	320	887	2.77		
Total	383	28853.2			

Table 3.1
Fisher LSD Grouping (without Control) – White Background where A represents the higher ΔE_{00} and J the lower.

Composite	N	Mean ΔE_{00}	SD	Group
PUREFILL2 Bio+ A2	18	30.4234	5.36	A
ENAMEL PLUS HRi UE2	18	25.6792	4.49	B
PURES H ADE Bio+ Shade 2	18	24.3153	4.07	C
BIOFUNCTION HRi BF2	18	21.4663	3.84	D
BIOFUNCTION HRi BD2	18	19.3766	3.25	E
ELS AO2	18	16.1172	2.99	F
ELS A2	18	15.4596	2.61	F
ENAMEL PLUS HRi UD2	18	15.3742	2.53	F
Venus Diamond A2	18	13.1971	2.49	G
Venus Pearl OLC	18	13.0684	2.35	G H
GAENIAL A'CHORD A2	18	11.8630	2.34	H I
Brilliant Everglow A2B2	18	11.7244	2.31	I
GAENIAL A'CHORD AO2	18	11.6577	1.84	I
Brilliant NG A2B2	18	11.5303	1.69	I
MHC A2	18	7.8815	1.48	J
APT A2	18	6.7987	1.33	J

Table 3.2
Fisher LSD Grouping (without Control) – Black Background where A represents the higher ΔE_{00} and J the lower.

Composite	N	Mean ΔE_{00}	SD	Group
PUREFILL2 Bio+ A2	18	35.7920	8.05	A
ENAMEL PLUS HRi UE2	18	31.4650	6.67	B
PURES H ADE Bio+ Shade 2	18	24.9810	4.26	C
BIOFUNCTION HRi BF2	18	22.2260	4.06	D
BIOFUNCTION HRi BD2	18	18.8010	3.71	E
ELS A2	18	16.0200	3.62	F
ELS AO2	18	15.9710	3.61	F
ENAMEL PLUS HRi UD2	18	15.8300	3.34	F
Venus Diamond A2	18	14.6850	3.13	F G
Venus Pearl OLC	18	14.4350	2.96	G
Brilliant NG A2B2	18	14.0260	2.96	G
Brilliant Everglow A2B2	18	12.6750	2.63	H
GAENIAL A'CHORD A2	18	12.1900	2.56	H I
GAENIAL A'CHORD AO2	18	11.2710	2.08	I
MHC A2	18	8.3970	1.40	J
APT A2	18	7.2843	1.34	J

4. Discussion

The present in vitro study evaluated the color stability of a wide range of contemporary universal and so-called biocompatible resin composites following prolonged immersion in commonly consumed staining agents. The results clearly demonstrated that composite discoloration is significantly influenced by both the staining medium and the composite material itself, with a highly significant interaction between these factors. On the basis of these findings, both null hypothesis—stating that resin composites do not stain when immersed in coffee, red wine and curry and that no difference exists in color stability among the tested materials—must be rejected.

4.1 Influence of Staining Media

Among the staining solutions investigated, coffee and red wine produced the highest ΔE_{00} values, whereas curry in oil and the distilled water control resulted in markedly lower color changes. These findings are consistent with previous studies reporting the strong staining potential of coffee and red wine, which contain high concentrations of chromogenic compounds capable of penetrating the resin matrix [7,9,34–36]. In addition, the acidic pH and ethanol content of red wine may contribute to softening of the resin surface and increased permeability, thereby facilitating pigment diffusion and exacerbating discoloration.

Conversely, curry in oil induced relatively limited color changes despite its intense pigmentation. This behavior may be explained by the lipophilic nature of oil-based colorants, which exhibit reduced affinity for the predominantly hydrophilic resin matrix. As a result, pigment adsorption and diffusion into the polymer network are limited. Similar observations have been reported in previous investigations, suggesting that hydrophilic staining solutions generally produce more pronounced discoloration than lipophilic media [28,29]. The minimal ΔE_{00} values observed in the distilled water control confirm that intrinsic aging and water sorption alone contributed only marginally to color change over the experimental period.

4.2 Influence of Composite Material and Resin Chemistry

Significant differences in discoloration susceptibility were observed among the tested composites, as confirmed by both the two-way ANOVA and the Fisher LSD post hoc analyses. Materials such as PUREFILL2 Bio+ A2 and ENAMEL PLUS HRI UE2 consistently exhibited the highest ΔE_{00} values under both white and black background conditions, whereas MHC A2 and APT A2 demonstrated the lowest mean color changes, indicating superior color stability.

These differences may be related to intrinsic material properties (Table 4), including resin-matrix composition, filler characteristics, filler–matrix interfacial quality, and water sorption behavior. Although biocompatible composites are often marketed as reducing or eliminating specific monomers such as Bis-GMA or TEGDMA, the present findings indicate that these compositional modifications do not necessarily confer improved color stability. Several of the tested biomaterials, in fact, exhibited greater discoloration than conventional composites.

One possible explanation lies in the use of alternative monomers with increased hydrophilicity, which may promote higher water sorption and facilitate the diffusion of staining agents into the resin matrix [6,25–27]. Increased water uptake has been consistently associated with greater discoloration and long-term degradation of resin composites thus leakage of monomers [8,12,30].

In addition, filler-related factors may play a decisive role. A sub-optimal silanization of inorganic filler particles can compromise the integrity of the filler–matrix interface, creating pathways for water and pigment penetration. This effect may be particularly relevant for composites containing prepolymerized filler particles, where microcrack formation within the organic–inorganic structure has been described. Such microstructural defects can act as reservoirs for staining agents, thereby enhancing discoloration over time. Materials with unperfect filler silanization or increased interfacial defects may therefore exhibit greater susceptibility to extrinsic staining, even when their resin chemistry is modified for improved biocompatibility.

Conversely, the lower ΔE_{00} values observed for MHC A2 and APT A2 may reflect differences in resin chemistry, filler characteristics, and filler–matrix interfacial properties. However, these properties were not independently measured in the present study. Overall, the findings support the view that color stability cannot be predicted solely on the basis of material classification (biocompatible versus conventional), but is likely influenced by the combined characteristics of the resin matrix, filler system, and composite microstructure [13,30].

Table 4
Hydrophilicity classification of the investigated resin composites

Rank	Dental composite	Hydrophilicity	Main matrix / chemical rationale
1	Enamel Plus HRi (UD2, UE2)	☒ Very high	UDMA + Bis-GMA + 1,4-butanediol dimethacrylate
2	ELS (A2, AO2)	☒ Very high	Conventional dimethacrylate matrix; Bis-GMA-containing
3	Brilliant	☒ High	Conventional methacrylate matrix
4	Brilliant NG	☒ Moderate–high	Methacrylate matrix; high filler loading
5	Brilliant EverGlow	☒ Moderate	Bis-GMA + TEGDMA + Bis-EMA
6	MHC	☒ Moderate	Bis-GMA + Bis-EMA + TEGDMA
7	Plus HRi Bio Function (BF2/BD2)	☒ Moderate–low	Modified/proprietary organic matrix
8	G-ænial A'CHORD (A2/AO2)	☒ Low–moderate	Proprietary Bis-MEPP monomer system
9	Venus Diamond	☒ Low	UDMA + TCD-DI-HEA; no Bis-GMA
10	Venus Pearl	☒ Low	UDMA + TCD-DI-HEA; no Bis-GMA
11	Purefill2 Bio+	☒ NOT verifiable	Exact monomer composition not verifiable
12	Pureshade Bio+	☒ NOT verifiable	Exact monomer composition not verifiable

4.3 Interaction Between Staining Medium and Composite Material

The statistically significant STAINING × COMPOSITE interaction observed in the two-way ANOVA indicates that the magnitude of discoloration depended on both the composite material and the staining agent. This interaction was also apparent in the interval plots stratified by staining medium, which showed substantial differences in ΔE_{00} values among the staining conditions.

Despite these differences in magnitude, the overall ordering of the composite materials was broadly similar across staining conditions. Materials with higher discoloration under one staining medium generally also showed greater discoloration under other media, whereas materials with lower ΔE_{00} values tended to remain among the more color-stable materials. Nevertheless, the significant interaction indicates that the effect of staining medium was not identical across all composites.

From a clinical perspective, these findings may be relevant to material selection in esthetically demanding situations. However, because the present study was performed in vitro under an accelerated immersion protocol, the observed differences should not be interpreted as direct predictions of long-term clinical performance. Further clinical investigation is required to establish whether the observed differences translate into clinically relevant discoloration.

4.4 Effect of Background Color on Color Measurements

Color measurements performed against both white and black backgrounds yielded consistent statistical outcomes in terms of factor significance, material ranking, and post hoc groupings. Although higher absolute ΔE_{00} values were observed under black background conditions, this effect can be attributed to differences in materials' transparency rather than intrinsic differences in material behavior. These findings align with previous studies demonstrating that background contrast influences absolute color difference values but does not affect comparative conclusions when standardized measurement protocols are applied [37,39].

4.5 Limitations and Clinical Implications

Several limitations of this study should be acknowledged. As an in vitro investigation, the experimental model does not fully replicate the complex oral environment, where factors such as salivary flow, biofilm formation, mechanical wear, thermal fluctuations, and oral hygiene practices may influence discoloration behavior. The continuous immersion protocol represents an accelerated and exaggerated exposure to staining agents, which may not directly correspond to clinical consumption patterns. Furthermore, only one shade (A2) and one polishing protocol were evaluated, which may limit the generalizability of the findings.

Despite these limitations, the standardized methodology, prolonged immersion period, and robust statistical analysis provide valuable comparative data on the relative color stability of contemporary resin composites. Clinically, the results suggest that claims of improved biocompatibility should be interpreted cautiously with respect to esthetic performance. Material selection in esthetically demanding areas should consider not only biological considerations but also optical stability and long-term resistance to staining.

4.6 Future Perspectives

Future research should aim to correlate color stability with quantitative measures of water sorption, degree of conversion, filler silanization quality, and surface roughness. The influence of different finishing and polishing protocols, as well as artificial aging procedures such as thermocycling and mechanical wear, should also be explored. Ultimately, long-term clinical studies are required to determine whether the differences in discoloration observed in vitro translate into clinically perceptible and relevant outcomes over time.

5. Conclusion

Within the limitations of this in vitro study, the color stability of the tested resin composites was significantly influenced by both the staining medium and the composite material, with a significant interaction between these factors. Coffee and red wine produced the greatest discoloration, whereas curry in oil and distilled water produced comparatively smaller color changes.

Marked differences in discoloration susceptibility were observed among the tested materials. Composites marketed as biocompatible did not consistently demonstrate greater color stability than conventional universal composites. These findings suggest that modifications intended to alter the resin chemistry do not necessarily result in improved resistance to staining.

The observed differences in color stability may be related to intrinsic material properties, including resin-matrix composition, water sorption, filler characteristics, and filler–matrix interfacial integrity. Inadequate silanization and microstructural defects may facilitate water and pigment penetration; however, these mechanisms were not directly evaluated in the present study and therefore remain hypotheses requiring further investigation.

From a clinical perspective, the results emphasize that material selection in esthetically demanding areas should not rely solely on material classification or marketing claims, but should consider comprehensive optical performance under simulated dietary staining conditions. Further investigations incorporating additional aging protocols and long-term clinical evaluations are warranted to better predict the esthetic longevity of contemporary resin composites.

Declarations

Author Contributions

S. Ardu: Conceptualization, study design, and manuscript writing.

O. Karagiannis: Sample fabrication and experimental analysis.

I. Rossier: Assistance with experimental analysis.

E. Di Bella: Statistical analysis.

R. Daher: Contribution to study design and critical review of the manuscript.

All authors reviewed and approved the final version of the manuscript.

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Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests.

This study was an in-vitro laboratory investigation and did not involve human participants or animals. Therefore, ethical approval was not applicable.



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Figures

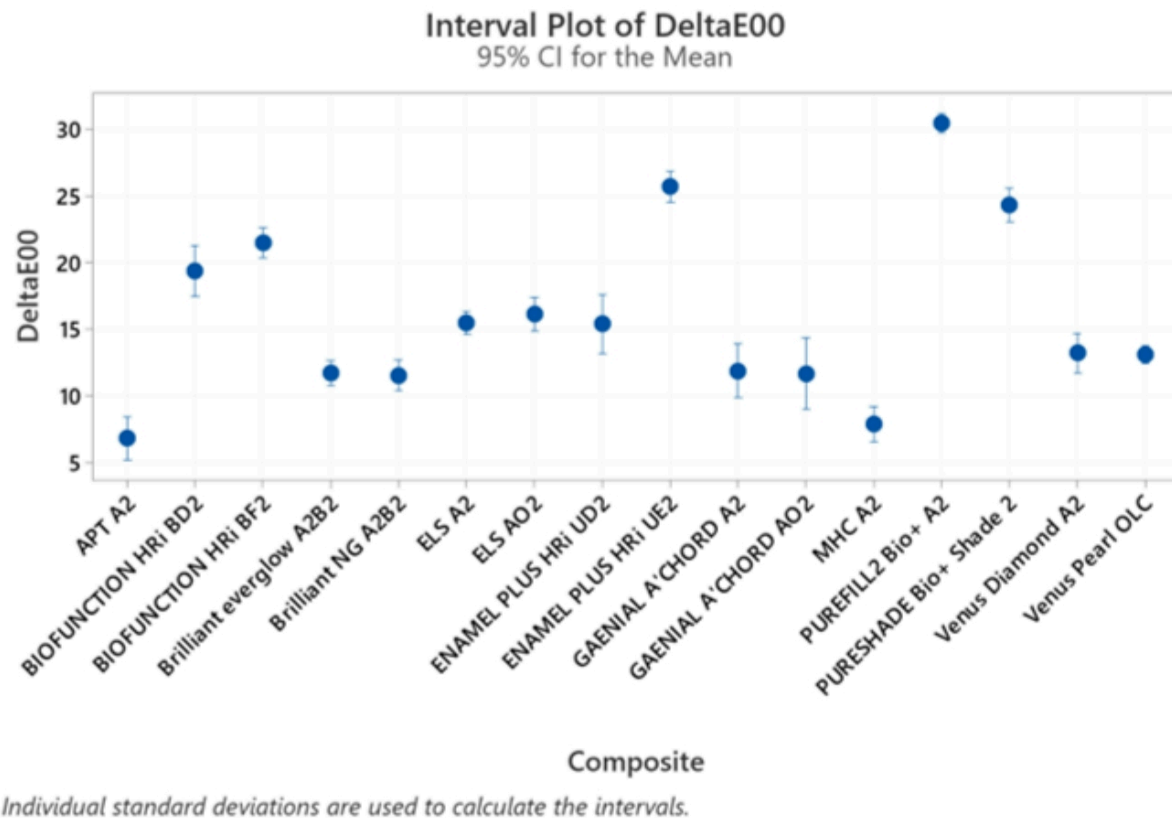


Figure 1

Figure 1.1: Interval Plot (without Control) – White Background

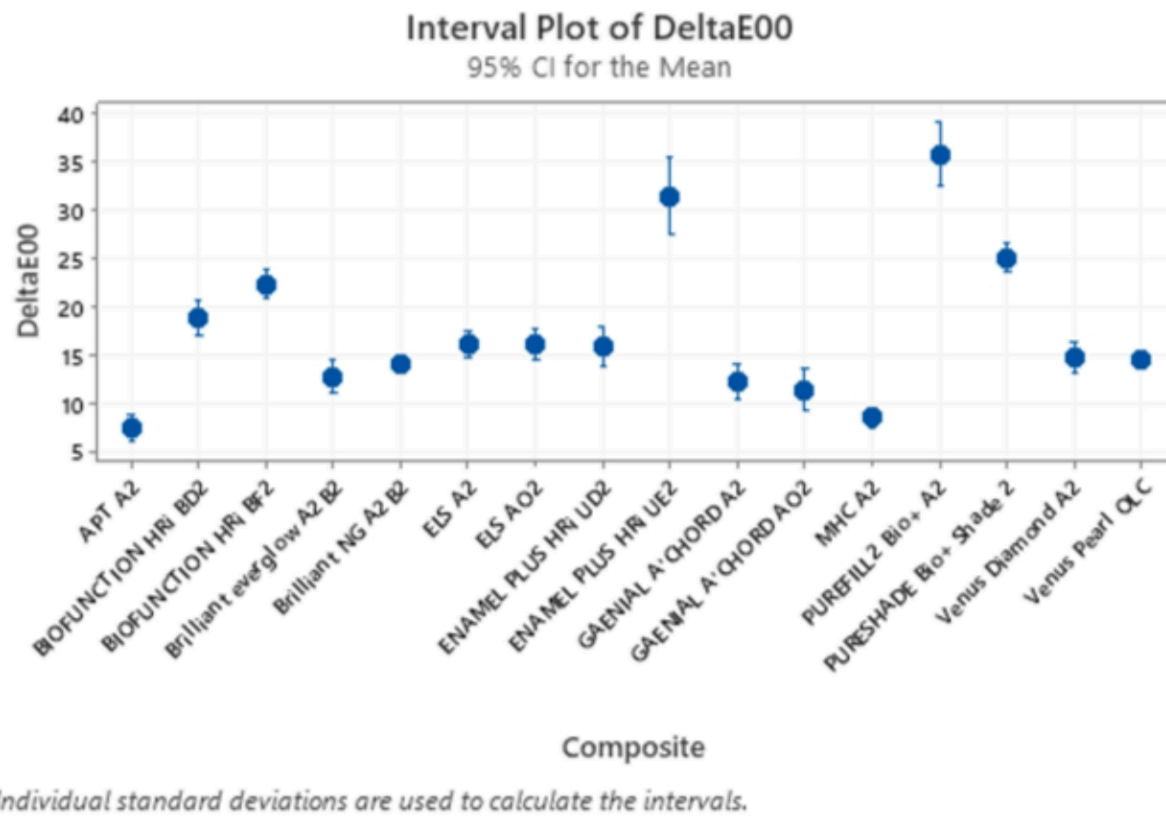


Figure 2

Figure 1.2: Interval Plot (without Control) – Black Background

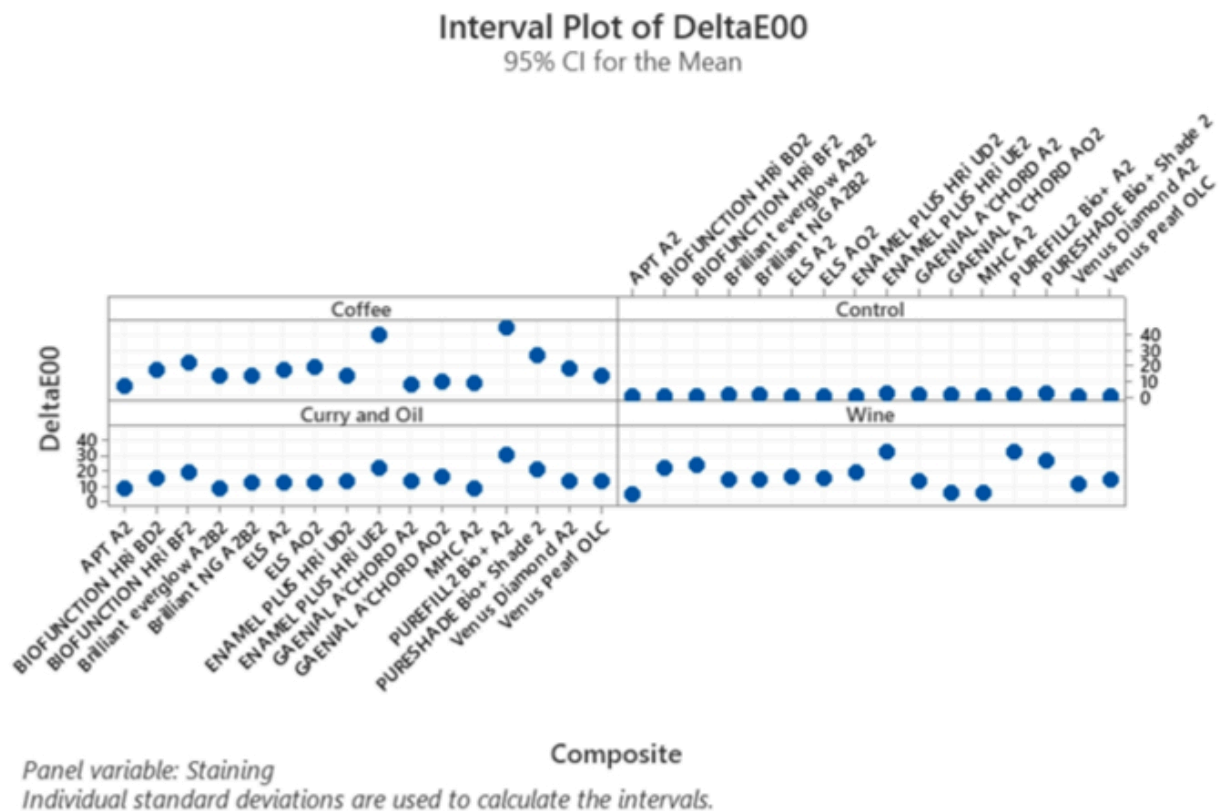


Figure 3

Figure 2.1: Interval Plot (per staining liquid) – White Background

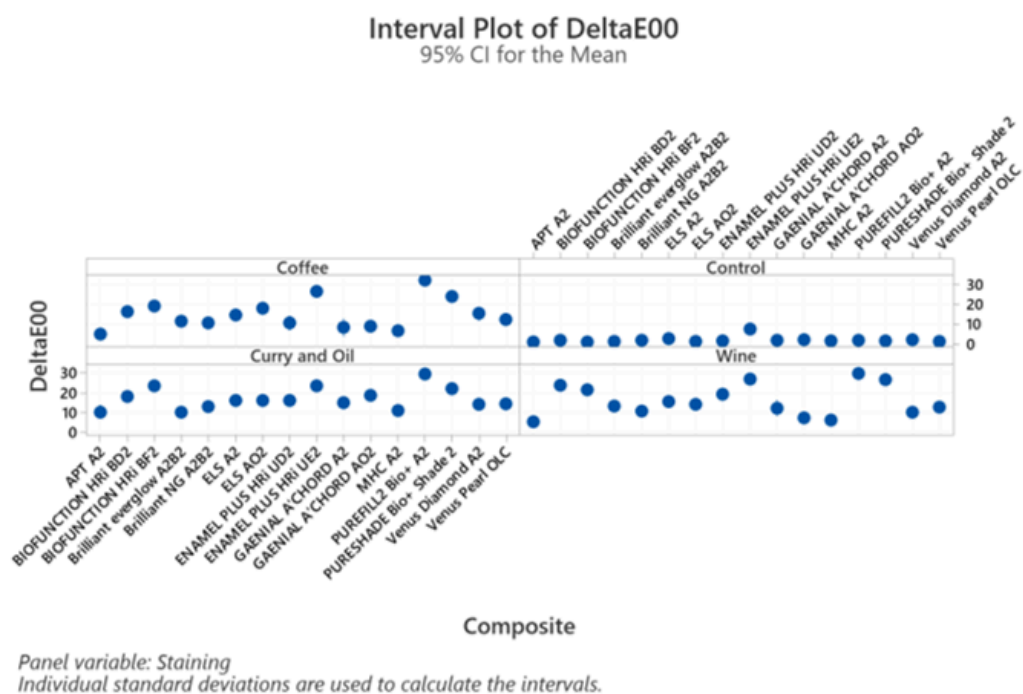


Figure 4

Figure 2.2: Interval Plot (per staining liquid) – Black Background

