

Influence of different opacities on the color stability of composite resins: *in vitro* evaluation

O efeito de diferentes opacidades na estabilidade da cor de resinas compostas utilizadas em odontologia: um estudo *in vitro*

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ABSTRACT

Objective: To evaluate the influence of composite resin opacity on color stability, and to analyze the performance of the ΔE_{ab} and ΔE_{00} formulas in detecting color changes. **Material and Methods:** A total of 180 specimens ($n = 20$ per group) were fabricated using three opacity levels (translucent/incisal, enamel, and dentin) and three commercial composite resins: Vittra APS (FGM), Harmonize (Kerr), and Herculite Précis (Kerr). Specimens ($7\text{ mm} \times 1\text{ mm}$) were prepared using a polytetrafluoroethylene mold between glass slides and light-cured with a Bluephase N unit (650 mW/cm^2 for 40 s). All specimens were stored in distilled water at 37°C until color evaluation. Color measurements were performed using an EasyShade digital spectrophotometer at 24 hours (baseline), 30, 60, and 90 days. Color stability was assessed through color variation (ΔE) according to the CIE system, using both ΔE_{ab} and ΔE_{00} . Data were analyzed using a three-way ANOVA (opacity, resin, and time), followed by Bonferroni post-hoc testing ($\alpha = 0.05$). **Results:** All composite resins exhibited clinically perceptible color changes ($\Delta E_{00} > 2.25$) after 90 days. Vittra APS presented the highest values at 60 and 90 days ($\Delta E_{00} = 5.09 \pm 1.77$ and 5.12 ± 1.62 , respectively), whereas Herculite Précis showed the best overall stability, particularly for the enamel shade ($\Delta E_{00} = 3.49 \pm 1.10$ at 90 days); Harmonize displayed intermediate values. Dentin-shade specimens exhibited the greatest color changes (ΔE_{00} up to 7.59 ± 1.24). **Conclusion:** Color stability was influenced by the interaction among composite resin brand, opacity, and aging time. More translucent shades exhibited less color alteration over time.

KEYWORDS

Color; Colorimetry; Composite resin; Dental materials; Dentistry.

RESUMO

Objetivo: Avaliar a influência da opacidade de resinas compostas na estabilidade de cor, e o desempenho das fórmulas ΔE_{ab} e ΔE_{00} na detecção de alterações cromáticas. **Material e Métodos:** Foram confeccionados 180 espécimes ($n=20$ por grupo) distribuídos em três opacidades (translúcida/incisal, esmalte e dentina) e três resinas compostas comerciais (Vittra APS, da FGM, Harmonize e Herculite Précis, da Kerr). Os espécimes ($7\text{ mm} \times 1\text{ mm}$) foram obtidos utilizando uma matriz de politetrafluoretileno posicionada entre lâminas de vidro e fotopolimerizados com o aparelho Bluephase N ($650\text{ mW/cm}^2/40\text{s}$). Os espécimes foram armazenados em água destilada a 37°C até o momento de avaliação de cor. As leituras foram realizadas com espectrofotômetro digital EasyShade após 24h (baseline), 30, 60 e 90 dias. A estabilidade cromática foi determinada pela variação de cor (ΔE) calculada segundo os sistemas CIELab* (ΔE_{ab}) e CIEDE2000 (ΔE_{00}). Os dados foram submetidos a análise de variância (ANOVA) a três critérios (opacidade, resina e tempo), seguida do teste de Bonferroni (5%). **Resultados:** Todas as resinas apresentaram alterações cromáticas perceptíveis ($\Delta E_{00} > 2.25$) após 90 dias. A Vittra APS exibiu os maiores valores aos 60 e 90 dias ($\Delta E_{00} = 5,09 \pm 1,77$ e $5,12 \pm 1,62$, respectivamente), enquanto a Herculite Précis manteve o melhor desempenho, especialmente para esmalte ($\Delta E_{00} = 3,49 \pm 1,10$ aos

90 dias); a Harmonize apresentou comportamento intermediário. A opacidade dentina exibiu os maiores valores de variação cromática em todas as resinas avaliadas (ΔE_{00} máximo de $7,59 \pm 1,24$). **Conclusão:** A estabilidade de cor das resinas compostas foi influenciada pela interação entre opacidade, tipo de resina e tempo. As resinas mais translúcidas apresentaram menor alteração cromática ao longo do período avaliado.

PALAVRAS-CHAVE

Cor; Colorimetria; Resina composta; Materiais dentários; Odontologia.

INTRODUCTION

Resin composites have become the material of choice for adhesive restorations because they allow minimally invasive preparations, present satisfactory durability, and offer excellent aesthetic outcomes. In contemporary dental practice, aesthetic demands have gained increasing importance and are often the main concern of patients after the resolution of pain. This is particularly relevant for restorations in anterior teeth, where the ability of restorative materials to reproduce the optical characteristics of natural dental tissues is essential for achieving harmonious results [1-4].

The aesthetic success of composite restorations depends not only on anatomical form and surface texture but also on the accurate reproduction and long-term maintenance of color. Color stability is therefore a critical factor for the longevity of aesthetic restorations. Clinical studies have shown that color mismatch or discoloration represents one of the most common reasons for patient dissatisfaction with restorative treatments, accounting for approximately 38% of reported aesthetic complaints [5].

Color changes in composite resins may occur as a result of intrinsic or extrinsic factors. Intrinsic factors are related to the physicochemical properties of the restorative material, including the composition of the organic matrix, the type and concentration of inorganic fillers, the degree of polymerization, and the interaction between the matrix and filler particles. Extrinsic factors are associated with the oral environment and include dietary habits, smoking, oral hygiene conditions, and exposure to staining agents over time [6-8]. Although extrinsic staining agents have been extensively investigated in the literature [6-8], the present study focused exclusively on the intrinsic color stability of composite resins, in order to isolate the influence of opacity under standardized conditions, without interference from external staining sources. These variables

influence important chromatic parameters such as hue, value, chroma, and translucency, which together determine the optical behavior of restorative materials [9].

Among the intrinsic characteristics of composite resins, opacity plays an important role in aesthetic reproduction. Different opacity levels are commonly used in restorative procedures to simulate the optical stratification of natural teeth, typically represented by dentin, enamel, and translucent or incisal shades. However, variations in opacity may also influence the interaction between light and restorative materials, which can affect polymerization behavior and potentially influence color stability over time. Previous studies have demonstrated that the optical properties of composite resins and their interaction with light may influence aesthetic performance and susceptibility to color alteration over time [7,10].

Recent in vitro investigations have further explored factors associated with color stability in composite materials. Studies evaluating modified composite resins containing antibacterial nanoparticles have demonstrated that alterations in the composition of restorative materials may affect their optical behavior and color stability over time [11]. Similarly, laboratory studies have shown that staining media, bleaching protocols, and accelerated aging may significantly influence the color stability and translucency of composite resins [12-14].

These findings reinforce the importance of understanding how intrinsic characteristics of composite resins contribute to color alteration under controlled experimental conditions.

Color assessment in dentistry has traditionally been performed through visual comparison using shade guides. However, visual evaluation is subjective and may be influenced by several variables, including lighting conditions, observer experience, surface characteristics,

tooth dehydration, age, and individual differences in color perception [15-17]. In order to overcome these limitations, objective instrumental methods, particularly digital spectrophotometry, have been widely adopted in dental research [15-18]. These techniques are commonly based on the CIELab color system, which allows the quantitative assessment of color coordinates and the calculation of color differences. Among the available formulas, ΔE_{ab} and ΔE_{00} are the most widely used approaches for evaluating color differences in dental materials [19,20].

Despite the advances in instrumental color analysis, further investigation is still necessary to clarify how intrinsic characteristics of composite resins influence their color stability over time. In particular, the role of opacity in determining chromatic behavior during aging remains insufficiently explored. Understanding this relationship is important for improving the aesthetic longevity of restorative treatments and for guiding the selection of restorative materials in clinical practice. Therefore, the aim of this study was to evaluate the influence of different opacity levels on the color stability of composite resins and to compare the performance of the ΔE_{ab} and ΔE_{00} formulas in detecting color changes over time. The null hypothesis tested was that the opacity of composite resins does not significantly influence their color stability during the aging process.

MATERIAL AND METHODS

Selection of composites and specimen preparation

Three opacities (translucent/incisal, enamel, and dentin) from three commercial brands of restorative composites were evaluated: Harmonize (Kerr Corporation, Orange, USA) shade A2, Herculite Précis (Kerr Corporation, Orange, USA) shade A2, and Vittra APS (FGM, Joinville, Brazil) shade A1. Shade selection was not intended to match shades across brands, since the analysis focused on opacity as the primary variable within each resin system; chromatic coordinates for a nominally equivalent shade are known to vary between manufacturers, so this difference did not compromise the interpretation of the results. The structural composition of these composites is listed in Tables I and II.

A total of 180 disk-shaped specimens ($n = 20$ per group) were fabricated, each measuring 7 mm in diameter and 1 mm in thickness. The sample size was determined based on previous studies with similar experimental designs and effect sizes, which reported adequate statistical power with $n=20$ per group [6,21,22].

As illustrated in Figure 1, the composites were inserted in a single increment into a cylindrical polytetrafluoroethylene mold (20 mm total diameter and 1 mm thickness), which contained a central circular cavity (7 mm in

Table I - Structural composition of the composite resins (Resin, Opacity, Description)

Resin	Opacity	Description
Herculite Précis™ (Kerr)	Dentin, Enamel, and Incisal (Translucent)	Universal nanohybrid light-curing composite resin
Harmonize™ (Kerr)	Dentin, Enamel, and Translucent	Universal nanohybrid light-curing composite resin.
Vittra APS® (FGM)	Dentin, Enamel, and Translucent (Trans N / Trans OPL)	Universal nanohybrid light-curing composite resin with APS system (Advanced Polymerization System)

Table II - Structural composition of the composite resins (Resin, Composition, Monomer)

Resin	Composition	Monomer
Herculite Précis (Kerr)	Silane-treated glass and silica fillers (approx. 75-80% by weight), pigments, and photosensitive initiators.	Bis-GMA, UDMA, and TEGDMA (methacrylate monomers).
Harmonize (Kerr)	Barium glass, silica, mixed oxides, ytterbium trifluoride; particles between 40 nm and 6 µm (dentin/enamel) and up to 30 µm (translucent). Inorganic content ~75% by weight (55% by volume).	Bis-GMA, Bis-EMA, UDMA and/or TEGDMA.
Vittra APS (FGM)	Silanized radiopaque glass (40-60%), silicon dioxide (20-30%), methacrylate monomers (15-25%), APS photoinitiator system (<1%), stabilizers, and pigments (<1%).	UDMA, TEGDMA (Bis-GMA and Bis-EMA free).

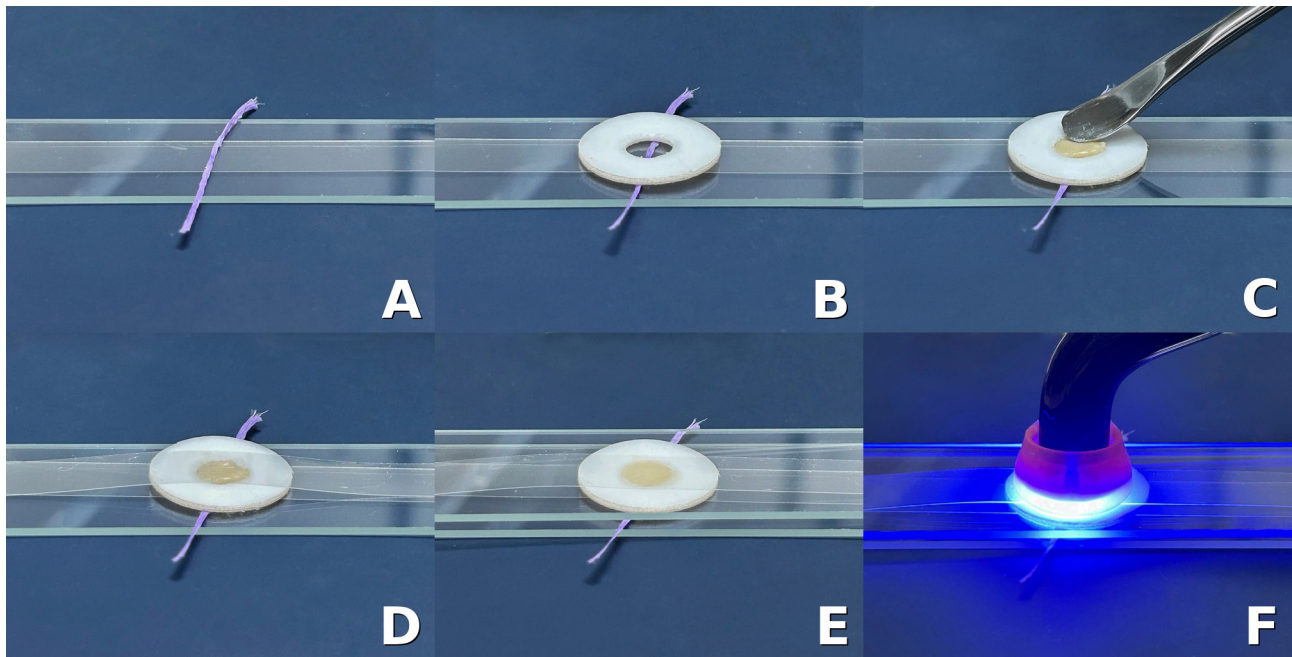


Figure 1 - Specimen fabrication: (A) Positioning of the glass slide, polyester strip, and dental floss; (B) Positioning of the disk; (C) Insertion of the composite resin increment; (D) Positioning of the second polyester strip; (E) Positioning of the second glass slide; (F) Light curing.

diameter) used to shape the specimens. The assembly was positioned on a 1 mm thick glass slide covered with a polyester strip (Mylar strip), on which a segment of dental floss was placed to create an indentation on the lower surface of the disk to standardize the side on which color evaluations would be performed. The molds were then positioned over the dental floss and filled with the resin increment. A second polyester strip and another glass slide were placed over the mold, and continuous digital pressure was applied to extrude excess material and obtain a smooth surface. The specimens were light-cured for 40 s using a Bluephase N curing unit (Ivoclar Vivadent, Liechtenstein), with an irradiance of 650 mW/cm², based on the manufacturer's specifications; the irradiance was not independently verified with a radiometer before specimen preparation. No polishing procedures were performed, as the use of a polyester strip in contact with the glass slide provides high surface smoothness and prevents variations in specimen thickness.

Immersion and color measurement

After mold removal and without any polishing, all specimens were stored in distilled water in a light-protected incubator at 37 °C for 24 h. The first color evaluation (baseline) was performed after this period using an EasyShade spectrophotometer (Vita Zahnfabrik, Germany). Readings were obtained with the specimens

positioned on a flat, standardized background, with the optical probe placed at a 90° angle to the sample surface opposite to the floss mark created during fabrication. For each reading, the L*, a*, and b* values of each specimen were noted. The device was calibrated prior to each experimental group and whenever required by the device. The specimens were then stored under the same conditions, and additional measurements were taken after 30, 60, and 90 days following the same protocol and conducted by the same evaluators (JPAC and JMSM). No additional drying procedure was performed prior to color measurement, and a single reading was obtained per specimen at each evaluation time point. The distilled water storage medium was not replaced during the 90-day experimental period.

Color evaluation

The measurements were based on the CIELAB* color space defined by the International Commission on Illumination (CIE). This system represents color in three coordinates: L* (lightness, from 0 = black to 100 = white), a* (green to red, with negative values toward green and positive values toward red), and b* (blue to yellow, with negative values toward blue and positive values toward yellow). For neutral colors, the a* and b* values are close to zero, increasing in magnitude as the colors become more saturated or intense.

The color differences (ΔE) caused by aging were calculated for each group at 30, 60, and 90 days relative to the baseline using both the ΔE_{ab} and ΔE_{00} formulas:

$$\Delta E_{ab} = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

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

Both ΔE_{ab} and ΔE_{00} were calculated because ΔE_{ab} is the classic, more widely reported metric, allowing direct comparison with earlier studies, whereas ΔE_{00} incorporates perceptual weighting for lightness, chroma, and hue and therefore approximates human visual perception more closely [19,20]; using both formulas allowed a more complete interpretation of color stability. The interpretation of color differences followed the perceptibility and acceptability thresholds defined in previous studies [23-25]. These thresholds correspond to ΔE_{ab} values of 1.8 and 3.3, and to ΔE_{00} values of 1.3 and 2.25, respectively. In the present study, $\Delta E_{00} = 2.25$ was adopted as the clinical acceptability threshold.

Statistical analysis

Data were initially assessed for normality using the Shapiro-Wilk test. Subsequently, the data were analyzed using a three-way mixed ANOVA, with brand (Vittra APS [FGM], Herculite Précis [Kerr], and Harmonize [Kerr]) and opacity (enamel, dentin, and incisal/translucent) as between-subject factors, and time (30, 60, and

90 days) as the within-subject factor. Main effects, two-way interactions, and the three-way interaction among these factors were examined.

When statistically significant differences were identified, Bonferroni post hoc tests with an adjusted significance level ($\alpha = 0.025$) were applied. The overall level of significance was set at 5% ($\alpha = 0.05$).

Statistical analyses were performed using IBM SPSS Statistics software (version 31.0.1.0).

RESULTS

According to the three-way mixed ANOVA, statistically significant differences were observed among brands, resin types, and aging times ($p < 0.05$).

The analysis of the color stability of the resin composites using the ΔE_{00} and ΔE_{ab} measurement systems provided detailed insights into the performance of the materials according to brand, resin type, and artificial aging time [Table III and Table IV].

In general, all composites evaluated showed clinically perceptible color changes ($\Delta E_{00} > 2.25$) after artificial aging. These changes occurred for all resin types and brands.

The results obtained using the ΔE_{00} and ΔE_{ab} measurement systems showed a similar behavior pattern, which reinforces the reliability of the data. However, the absolute ΔE_{ab} values were consistently higher than those of ΔE_{00} for the same specimens and evaluation times. Despite these numerical differences, the performance order among the brands and resin types was maintained on both scales (Tables III and IV).

Table III - Mean and Standard Deviation (s) Values of ΔE_{00} by Resin Type, Resin, and Time

Resin type	Resin	ΔE_{00} 30 days	ΔE_{00} 60 days	ΔE_{00} 90 days
Enamel	Vittra APS	2.89 ± 0.84 ^{aA}	5.09 ± 1.77 ^{aA}	5.12 ± 1.62 ^{aA}
	Herculite Précis	1.69 ± 0.86 ^{aA}	2.51 ± 1.15 ^{bA}	3.49 ± 1.10 ^{bcA}
	Harmonize	1.96 ± 1.02 ^{aA}	5.06 ± 1.31 ^{aA}	4.42 ± 1.18 ^{acA}
Dentin	Vittra APS	2.99 ± 1.78 ^{aA}	6.75 ± 2.75 ^{aB}	4.03 ± 1.20 ^{aBc}
	Herculite Précis	4.69 ± 2.73 ^{bB}	4.19 ± 2.83 ^{bB}	7.59 ± 1.24 ^{bB}
	Harmonize	6.14 ± 2.38 ^{cB}	6.22 ± 2.18 ^{aB}	6.54 ± 1.69 ^{cB}
Incisal/ Translucent	Vittra APS	3.85 ± 1.60 ^{aA}	4.77 ± 2.20 ^{aA}	4.82 ± 1.77 ^{aAc}
	Herculite Précis	3.71 ± 1.06 ^{aB}	4.41 ± 0.76 ^{aB}	3.92 ± 1.12 ^{aA}
	Harmonize	2.31 ± 0.53 ^{bA}	2.17 ± 0.73 ^{aB}	2.84 ± 0.73 ^{bc}

Table IV - Mean and Standard Deviation (s) Values of ΔE_{ab} by Resin Type, Resin, and Time

Resin type	Resin	ΔE_{ab} 30 days	ΔE_{ab} 60 days	ΔE_{ab} 90 days
Enamel	Vittra APS	3.26 ± 1.27^{aA}	6.21 ± 2.25^{aA}	6.50 ± 1.62^{aA}
	Herculite Précis	2.42 ± 1.01^{bA}	4.26 ± 1.40^{bA}	4.67 ± 1.16^{bA}
	Harmonize	2.71 ± 1.06^{aA}	5.83 ± 1.42^{aA}	4.73 ± 1.26^{bA}
Dentin	Vittra APS	3.66 ± 1.50^{aB}	7.27 ± 2.19^{aB}	4.70 ± 1.14^{aB}
	Herculite Précis	5.05 ± 2.37^{bB}	5.24 ± 2.21^{bB}	8.11 ± 1.03^{bB}
	Harmonize	6.52 ± 1.74^{cB}	6.33 ± 1.78^{aB}	6.84 ± 1.78^{cB}
Incisal/ Translucent	Vittra APS	4.63 ± 1.33^{aA}	6.18 ± 1.80^{aA}	5.94 ± 1.70^{aA}
	Herculite Précis	4.12 ± 0.76^{aB}	5.11 ± 0.89^{aB}	4.71 ± 1.01^{aA}
	Harmonize	3.13 ± 0.63^{bA}	3.07 ± 0.59^{bB}	3.45 ± 0.62^{bA}

Color stability was significantly influenced by the resin brand. The Vittra APS (FGM) group showed the highest mean ΔE_{00} values at 60 and 90 days, suggesting lower color stability over time (Table III).

Herculite Précis (Kerr) showed the lowest mean values in most groups, especially in the enamel shade (3.49 ± 1.10 at 90 days), indicating the best chromatic performance and higher color stability (Table III).

The Harmonize (Kerr) resin had an intermediate performance, with greater changes in the dentin and enamel shades (6.54 ± 1.69 and 4.42 ± 1.18 , respectively, at 90 days), but with a favorable performance in the incisal/translucent shade (2.84 ± 0.73 , at 90 days) (Table III).

The opacity of the resin directly influenced the color stability of each brand [Tables III and IV]. The dentin shade showed the greatest color change (mean value of 6.05 at 90 days) compared to the enamel and incisal/translucent shades (mean values at 90 days of 4.34 and 3.89, respectively). Therefore, the latter two shades generally demonstrated greater color stability than the other shades.

Different lowercase letters within the same column indicate significant differences between brands, for the same resin type and aging period. Different uppercase letters within the same column indicate significant differences between resin types, for the same brand and aging period.

DISCUSSION

The null hypothesis was rejected, as opacity significantly influenced color stability, in interaction with resin brand and aging time.

The results obtained using both ΔE formulas demonstrated that color changes were clinically perceptible for all resins and opacities at all evaluation times.

Evaluations using the ΔE_{00} and ΔE_{ab} formulas showed similar trends in color changes among the groups. However, the absolute ΔE_{ab} values, although reflecting the same behavior observed with ΔE_{00} , were consistently higher. This difference between the formulas can be partially attributed to the fact that ΔE_{00} incorporates perceptual corrections through weighting functions related to lightness (SL), chroma (SC), and hue (SH), thereby providing a closer approximation to human visual perception. Consequently, ΔE_{00} values tend to be more clinically relevant, showing approximately 95% agreement with visual assessments, whereas ΔE_{ab} , which does not account for these perceptual weightings, achieves about 75% agreement [19]. ΔE_{ab} assumes uniform color perception throughout the color space, a limitation overcome by ΔE_{00} , which adjusts color difference values according to the position of the sample within the color space, aligning them with visual perception and allowing color differences to be interpreted in relation to perceptibility and acceptability thresholds [19–20].

All experimental groups showed ΔE_{00} values higher than the clinical acceptability threshold of 2.25 after aging time (90 days), indicating color changes that would be visually perceptible and clinically unacceptable. This limit was established through studies that related instrumental measurements of color differences to visual assessments performed by human observers, defining the perceptibility and acceptability thresholds as $\Delta E_{00} = 1.3$ and 2.25, and $\Delta E_{ab} = 1.8$ and 3.3, respectively [23–25]. Therefore, regardless of the color difference

formula used, the results of the present study exceeded the limits of clinical acceptability.

Brand analysis performed by ANOVA ($p < 0.05$) revealed significant differences in color stability, with Vittra APS resin exhibiting the greatest color changes in the enamel and incisal/translucent shades at 90 days (Tables III and IV). This performance may be associated with two main factors: the APS photoinitiator system and the presence of hydrophilic monomers, which increase water sorption and susceptibility to hydrolytic degradation [26]. Water absorption, in addition to promoting hygroscopic expansion, facilitates the diffusion of colorants into the resin matrix, thereby intensifying chromatic changes [26–27]. This effect is exacerbated in formulations with lower inorganic filler content, which increases water uptake [27–28], and with a more permeable organic matrix, as observed for Vittra APS, which presents a lower filler content than Herculite Précis (Kerr).

In contrast, Herculite Précis (Kerr) exhibited the best color stability in most groups, with significantly lower color changes than the other materials in the enamel and dentin shades at the 60-day evaluation. Its nanohybrid composition, characterized by a high and uniform distribution of inorganic fillers and a lower content of hydrophilic monomers in the resin matrix, results in reduced water sorption and, consequently, greater surface integrity, decreasing the likelihood of color alteration [27–28]. These findings are supported by Prodan et al. [6], who associated higher filler content and opacity with reduced chromatic change.

The Harmonize resin, which uses ART (Adaptive Response Technology) with spherical nanoparticles, showed intermediate stability but good performance in the incisal/translucent shade. This configuration contributes to lower surface irregularity and higher effective filler content, reducing discoloration compared with conventional materials [29]. However, shades with higher chromas, such as dentin and enamel, showed a greater propensity for perceptible color changes over time.

Opacity directly impacted color stability. The dentin shade, characterized by higher pigmentation and opacity, exhibited greater color changes, with statistically significant differences across all brands at the 90-day evaluation. This behavior may be attributed to its lower translucency, which limits light diffusion and may favor the perception of localized degradation processes. As emphasized

by Prodan et al. [6], higher opacities reduce the aesthetic impact of water sorption.

Color stability is a multifactorial phenomenon determined by both intrinsic and extrinsic factors [6–8]. In the present study, which employed artificial aging exclusively in distilled water, the findings suggest that intrinsic factors of the composites, particularly the composition of the organic matrix and filler particles, play a predominant role in maintaining esthetics over time. Discoloration may occur due to oxidation of the organic matrix components or water absorption, which can trigger degradation of the resin phase, debonding of filler particles, hydrolytic degradation of the inorganic phase, and changes in the refractive index of the material [26]. Studies have shown that water absorption increases as the inorganic filler content decreases, rendering the matrix more susceptible to the diffusion of colorants [1,2,8]. Alencar et al. [27] highlighted that water sorption facilitates the penetration of colorants into the organic phase, intensifying material darkening. Therefore, the increase in ΔE values observed may be attributed both to the hydrophilic nature of the matrix, which favors the diffusion of pigment molecules, and to the structural characteristics of the composites, including filler particle size, distribution, and content.

Clinical implications and study limitations

The findings of this study have direct implications for clinical practice. The selection of resin type (incisal/translucent, dentin, or enamel) and brand may significantly affect the esthetic longevity of restorations, particularly in anterior regions when layering techniques are employed [30]. These results are clinically relevant, as they assist clinicians in selecting the most appropriate resin composite opacity to optimize color stability over time. It is also worth noting that, in stratified composite restorations, dentin-shade increments are typically covered by an enamel-shade layer, which in the present study showed comparatively greater color stability; therefore, intrinsic color changes occurring in the internal dentin layer may have a more limited impact on the overall esthetic appearance of the restoration, a clinical scenario that was not directly evaluated in this *in vitro* model. Moreover, improved long-term color stability may reduce the need for restoration replacement for esthetic reasons alone, helping to minimize the repeated restorative cycle and preserve healthy

dental structure, in line with the principles of minimally invasive dentistry.

As an *in vitro* study, the results may not fully reflect the complex conditions of the oral environment, which include variations in temperature, pH, abrasion, and exposure to different staining agents. The methodological decision to use distilled water alone for aging was intended to ensure controlled conditions and to standardize the analysis of the intrinsic color stability of the resins. However, this approach limits the extrapolation of the findings to extrinsic pigmentation processes that occur in the oral environment, where staining is a clinically relevant factor. Future studies may complement these findings by evaluating the behavior of different resins in various staining solutions over longer periods to provide a more comprehensive assessment of material staining resistance, as well as the effectiveness of polishing protocols in controlling pigmentation. Additionally, although the irradiance was not verified with a radiometer, the same curing unit, curing time, and standardized curing protocol were applied to all specimens, ensuring identical polymerization conditions and minimizing variability among the experimental groups.

CONCLUSION

Based on the results of this study, it can be concluded that the color stability of resin composites is significantly influenced by resin type, opacity, and aging time, with a statistically confirmed three-way interaction among these factors. Clinically, enamel and translucent/incisal resins, particularly formulations with higher filler content, exhibit better chromatic stability and, therefore, may be preferentially considered when long-term esthetic maintenance is a primary objective.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author's Contributions

FCPG, LFC, JPAC: Conceptualization. FCPG, LFC, JPAC, JMSM: Methodology. AAL: Statistical Analysis. FCPG, DBPM: Validation. JPAC, FCPG: Investigation. JPAC, JMSM, AAL: Data Curation. LFC, FCPG, JPAC: Writing – Original Draft

Preparation. JPAC, FCPG, DBPM: Writing–Review & Editing. FCPG, LFC, DBPM: Supervision. FCPG, LFC: Project Administration. LFC, FCPG: Funding Acquisition.

Conflict of Interest

The authors declare no conflicts of interest.

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Regulatory Statement

This study was conducted in accordance with the relevant institutional guidelines. Ethics committee approval was not required for this study, as it was an *in vitro* study that did not involve human subjects.

Statement of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Claude (Anthropic) for text review and reference organization. After using this tool, the authors have reviewed and edited the content appropriately and take full responsibility for the content of the publication.

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