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ORIGINAL ARTICLE

Color Stability, Surface Roughness, and Microhardness of Resin-Based Composites After Immersion in Beverages Commonly Consumed by Children or Accelerated Artificial Aging

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ABSTRACT
Objective: To evaluate the color stability, surface roughness, and microhardness of resin-based composites (RBCs) after accelerated artificial aging (AAA) or immersion in beverages consumed by children. **Material and Methods:** Seventy specimens were prepared from each RBC (Z350-Z350, SS-Spectra Smart, AF-Admira Fusion, and EA-Estelite Asteria). Initial color, ΔE00, surface roughness, ΔRa, and microhardness, ΔKHN readings were done. Specimens were separated into five groups (n=14): AAA (300 hours) and immersion (30 minutes daily/30 days) in Coca-Cola (CC), Grape juice (GJ), Chocolate milk (CM), or distilled water (DW). After the final readings, color and microhardness data were analyzed using two-way ANOVA, Tukey, and surface roughness by Kruskal-Wallis and Dunn's test. **Results:** SS exhibited the most significant color change in AAA, which differed from CC and GJ; the minor change occurred after CM and DW, which were distinct from each other. AF did not show a difference between the treatments. All RBCs exhibited a decrease in microhardness, except for SS, after AAA and EA in CC and DW. There was no difference in the surface roughness after treatments, except for AAA, which presented a minor change for Z350 and AF, differing from the other treatments. **Conclusion:** The beverages didn't alter the surface roughness but decreased the microhardness of the RBCs, except for CC, which increased the microhardness of EA.

Keywords: Coloring Agents; Color Perception; Dental Materials.

Introduction

Resin-based composites (RBC) are widely preferred for dental restorations due to their adequate aesthetic properties, high bond strength to the tooth structure, and reduced need for sound tissue removal [1].

The properties of RBCs are directly influenced by their inorganic fillers' characteristics, particularly the fillers' size, which can impact the aesthetic outcome and durability of the restoration [2]. Nanotechnology has enabled the development of nano-sized fillers incorporated into the resin matrix to reduce the polymerization shrinkage stress and enhance these composite materials' physico-mechanical properties and aesthetics [3]. Currently, two distinct types of RBCs contain nanometric particles: nanofilled resin composites composed of particles with a nanometer size (1-100 nm) distributed throughout the resin matrix, and nanohybrid resin composites that combine nanometric particles and micro fillers (0.4-1 μm) [4].

Nanometric particles tend to agglomerate, forming larger effective particles that can affect the light transmittance through the composite material [5]. To address this issue, supra-nanofilled resin composites have been recently introduced into the market. These composites have non-agglomerated silica particles with standardized sizes in nanometric scale (100-1000 nm) [4], which enhance the optical and physico-mechanical properties of these materials [4,6]. Supra-nanofilled resin composites exhibit higher wear resistance, smoother surfaces than nanohybrid composites [6], and higher scattering and light transmittance than other RBCs [4].

Although significant improvements have been made in the composition of RBCs [7-9], changes in these materials' physical and mechanical properties may still be a concern. Color, surface roughness, and microhardness alterations can occur due to degradation of the organic matrix and filler particles caused by ultraviolet exposure, thermal changes, humidity, and incomplete material polymerization [8-11].

Dietary habits can also affect RBCs' physical and mechanical properties [8,9]. Consumption of acidic beverages may promote degradation and a softening of the resin matrix [12], which increases the surface roughness and decreases the microhardness of RBCs [13]. Rough surfaces, in turn, facilitate the deposition of pigments and biofilm accumulation and modify the light reflection, altering the color perception of the restoration [14].

Children, in particular, are more susceptible to staining of dental restorations due to their frequent consumption of acidic and colored beverages like soft drinks, fruit juices, and chocolate milk [15]. These beverages usually contain high amounts of artificial food colors to make them more appealing to consumers [16].

Existing literature on the effect of beverages frequently consumed by children and aging on the physical and mechanical properties of recently launched supra-nanofiller and nanohybrid RBCs is still limited. It is essential to conduct *in vitro* studies under controlled conditions to support the clinical application of these composite materials. Therefore, this *in vitro* study evaluated the color stability, surface roughness, and microhardness of nanofilled, supra-nanofilled, and nanohybrid RBCs after accelerated artificial aging or immersion in different beverages consumed by children. The null hypothesis tested was that there would be no alterations in the studied properties, irrespective of the RBCs or condition to which they would be subjected.

Material and Methods

Experimental Design

This study presents two experimental factors: type of resin in four levels (Z350, SS, AF, EA) and protocols submitted (aging and immersion) in five levels (AAA, CC, GJ, CM, DW). The sample size (n=14) was calculated based on a pilot study comparing the means of color stability (www.openepi.com) with a statistical power of 80% and a significance level of 5%.

Seventy specimens (n=14) were prepared from each RBC (Table 1) using the incremental technique with a cylindrical Teflon matrix (12 mm in diameter x 2 mm in height). Each increment was light-cured using an LED device (Radii-Cal, SDI, Bayswater, AUS, light intensity 1200mW/cm^2) that had its intensity measured by a radiometer previously, following the exposure time recommended by the manufacturer. Since the active tip of the photoactivation is smaller than the diameter of the specimen, a central photoactivation was performed, followed by four additional light applications on the peripheral portions of the sample, ensuring that all the material was exposed to the light. Polyester strips and glass slides were not used between the device and the sample, allowing its tip to be applied at the closest distance to the polymerized material.

Finishing was performed using a cylindrical bur (Edenta AG, Au, Switzerland) at low speed and polishing with SiC papers (600-grit, 1200- and 2000-). The thickness of each specimen was checked with a digital caliper (Digimess Precision Measurement Instruments, São Paulo, SP, Brazil). Initial color, surface roughness, and microhardness readings were done.

Table 1. Materials used.

Group/ Type	Composite	Composition	Particles Size	Filler Content (vol%/wt%)	Photoinitiator System
Z350/ Nanofilled LOT NA07519 A2	Z350/3M ESPE, Sumaré, SP, Brazil	Bis-GMA/Bis-EMA, UDMA/ TEGDMA, PEGDMA, silica/zirconia	5-20 nm non-agglomerated 600-1400 nm agglomerated	59.5%/78.5%	Camphorquinone
SS/ Nanohybrid LOT 246891I A2	Spectra Smart/ Dentsply Sirona, Petrópolis, RJ, Brazil	Glass Powder, Silica, Colloidal Hydrophobic, Dimethacrylate, Benzophenone III, EDAB, FluBlau Concentrate, Camphorquinone, BHT Butylated Hydroxytoluene, Yellow Iron Oxide, Red Iron Oxide, Black Iron Oxide and Titanium Dioxide	Not available	75-77%	Camphorquinone + EDAB
AF/ Nanohybrid LOT 2141474 A2	Admira Fusion/ VOCO, Porto Alegre, RS, Brazil	Ormocer, Barium-aluminum borosilicate glass, silicon dioxide	20-40 nm	69%/84%	Camphorquinone
EA/Supra-nanofilled LOT w116 A2	Estelite Asteria/ Tokuyama, Tokyo, Japan	Bis-GMA, Bis-MPEPP, TEGDMA/UDMA, Mequinol BHT	200 nm	71%/82%	RAP technology (with camphorquinone)

Bis-GMA: Bisphenol A Glycidyl Methacrylate; UDMA: Urethane Dimethacrylate; TEGDMA: Triethylene Glycol Dimethacrylate; Bis-EMA: Bisphenol A Glycidyl Methacrylate Ethoxylated; PEGDMA: Polyethylene Glycol Dimethacrylate; BHT: Butylated Hydroxytoluene; Ormocer: Organically Modified Ceramic; Bis-MPEPP: Bisphenol A Polyethoxy Methacrylate; RAP Technology: Radical Amplified Photopolymerization initiator; EDAB: Ethyl 4-Dimethylaminobenzoate.

Color Analysis

Color readings were taken using a spectrophotometer (PCB 6807, BYK-Gardner GmbH, Geretsried, Germany) on a standard white background (White Standard Sphere for 45°, 0° Reflectance) and inside a gray box with standard illuminant D65, which simulates the spectrum of daylight.

Three readings were taken on each specimen, and the coordinates L*, a*, and b* were recorded. L* represents lightness from black to white on a scale of zero (black) to 100 (white), a* is a measure of chroma in the red-green axis, and b is a measure of chroma in the yellow-blue axis [17]. The mean values were considered as the initial color coordinates for each specimen.

Surface Roughness Analysis

Surface roughness was measured using a rugosimeter (Model SJ-201P, Mitutoyo Corp., Tokyo, Japan). Three readings were taken (long = 5 mm, cutoff = 0.8 mm; speed = 0.25 mm/s) on each specimen at different locations: in the center and 1 mm from the middle on each side. The mean value of these three measurements was considered as the initial surface roughness value.

Microhardness Analysis

Knoop microhardness (KHN) readings were taken using a microhardness tester (HMV-2, Shimadzu Corp., Kyoto, Japan), with a pyramid-shaped diamond indenter applied with a vertical static load of 50 g, for 15 seconds. After measuring the largest diagonal of the indention, the data were calculated by using the formula: $KHN = 1.451\ F/d^2$, where F is the applied force and d is the length of the largest diagonal in the indentation.

Three measurements were obtained for the surface roughness analysis, as described. The mean value of these three readings was considered as the initial microhardness value. After the initial readings, the specimens were randomly separated (n = 14) into five groups: subjected to accelerated artificial aging, immersion in Coca-Cola, grape juice, chocolate milk, or distilled water (control), totaling 280 specimens.

Accelerated Artificial Aging (AAA)

Specimens subjected to accelerated artificial aging (Comexim Matérias Primas Ltda., São Paulo, SP, Brazil) were placed in a chamber where they were submitted to repeated cycles of exposure to UV-B light with radiation concentrated between 280 and 320 nm at 50 °C for four hours, followed by a water vapor condensation step at 50 ° for four hours, following the ASTM-G154-16 standard [18]. The specimens were submitted to AAA for 300 hours, representing one year of natural aging.

Immersion in the Beverages

The pH of the immersion liquids was measured using a pH meter (Simpla PH140, Akso Produtos Eletrônicos Ltda., São Leopoldo, RS, Brazil), and it was performed in triplicate. Specimens assigned to these groups were immersed in their respective solutions (Coca-Cola (CC) (Coca-Cola Company, São Paulo, SP, Brazil), Grape juice (GJ) (Kapo, Coca-Cola Company, São Paulo, SP, Brazil), Chocolate milk (CM) (Toddynho, PepsiCo do Brazil Ltda., São Paulo, SP, Brazil), or distilled water (DW) for 30 min at 37 °C. Subsequently, the specimens were rinsed with distilled water and remained in distilled water at 37 °C. This cycle was repeated for 30 days [19].

Final Analysis

After AAA and immersion in the solutions, final color, surface roughness, and microhardness readings were performed, as previously described. Color alteration (ΔE_{00}) was calculated using the following formula:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right) + \left(\frac{\Delta C'}{k_c S_c}\right) + \left(\frac{\Delta H'}{k_H S_H}\right) + R_T \frac{\Delta c'}{k_c S_c}\frac{\Delta H'}{k_H S_H}}$$

Where ΔL', ΔC,' and ΔH' are the differences in brightness, chroma, and hue between two specimens, and R_T (rotation function) is a function that explains the interaction between chroma and hue differences in the blue region. S_L, S_C, and S_H are the weighting functions for the luminance, chroma, and hue components. K_L, K_C, and

K_H are the parametric factors according to different visualization parameters that were defined as 1. ΔE_{00} was compared with the acceptability (1.8) and perceptibility (0.8) thresholds [20].

Surface roughness alteration (ΔRa) was calculated as the difference between the final and initial mean value using the formula $\Delta Ra = Ra_f - Ra_i$, where Ra_f represents the final surface roughness and Ra_i, the initial surface roughness. ΔRa was compared with the surface roughness thresholds for bacterial plaque retention (0.2 µm) [21].

Microhardness alteration (ΔKHN) was determined by the difference between the final and the initial measurements using the formula: $\Delta KHN = KHN_f - KHN_i$, where KHN_f is the final microhardness, and KHN_i is the initial microhardness.

Statistical Analysis

Data were tested for normality using Shapiro-Wilk's test ($p<0.05$) to assess their distribution. Color and microhardness alteration data exhibited a normal distribution and were analyzed using two-way ANOVA and Tukey's test ($p<0.05$). Surface roughness alteration data did not follow a normal distribution and were analyzed using Kruskal-Wallis and Dunn's test ($p<0.05$).

Results

pH values

pH values of the solutions were 2.55 for CC, 3.02 for GJ, 6.29 for CM, and 6.2 for DW.

Color Analysis

A comparison of color alteration (ΔE_{00}) among the groups is presented in Figure 1. SS exhibited color alterations above the acceptability threshold after immersion in CC, GJ, and AAA, different from the other conditions that caused color alterations within the perceptibility threshold after Immersion in CC and AAA, resulting in similar ($p>0.05$) color alterations that were higher ($p<0.05$) than those observed in the other conditions. Immersion in CM and DW resulted in the lowest ($p<0.05$) color alterations, with no difference ($p>0.05$) between them.

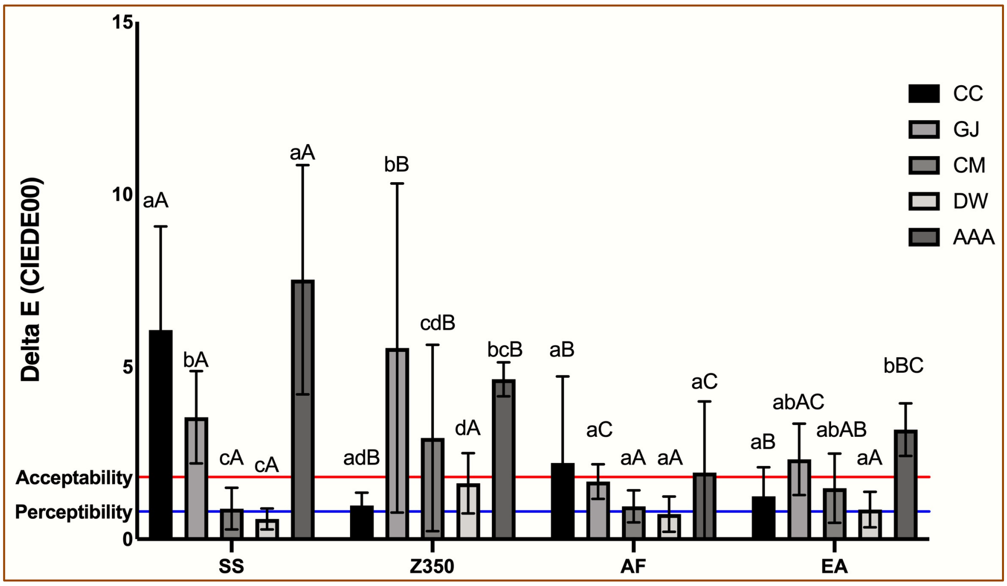
Irrespective of the condition, Z350 presented color alterations above the perceptibility threshold. Additionally, after immersion in GJ, CM, and AAA, those alterations exceeded the acceptability threshold. Immersion in GJ caused the highest color alteration, different ($p<0.05$) from all the other conditions, except after AAA, which showed similar ($p>0.05$) results. Immersion in CC resulted in the lowest color alteration, different ($p<0.05$) from immersion in GJ and AAA but similar ($p>0.05$) to the other conditions. After immersion in CM, the color alteration was similar ($p>0.05$) to those obtained after the other conditions, except after immersion, GJ demonstrated a different ($p<0.05$) result. Z350 presented lower ($p<0.05$) color alteration after immersion in DW than after immersion in GJ and AAA.

The tested conditions for AF were insignificant ($p>0.05$). Immersion in GJ, CM, and DW caused color alterations below the acceptability threshold, with immersion in DW even revealing color alteration within the perceptibility threshold. However, after immersion in CC and after AAA, the results exceeded the acceptability threshold.

EA showed the highest color alteration after AAA, different ($p<0.05$) from those obtained after immersion in CC and DW. There were no differences ($p>0.05$) among the other comparisons. All the conditions caused color alterations above the perceptibility threshold, except after immersion in DW. Moreover, immersion in GJ and AAA produced color alterations above the acceptability threshold.

After immersion in CC, SS had higher ($p<0.05$) color alteration than the other RBCs, which showed no differences ($p>0.05$) among them. After immersion in GJ, Z350 showed the highest color alteration, different ($p<0.05$) from all the other RBCs. SS had higher ($p<0.05$) color alteration than AF but similar ($p>0.05$) to EA, which also showed similar ($p>0.05$) results to AF. When immersed in CM, Z350 showed higher ($p<0.05$) color alteration than SS and AF but similar ($p>0.05$) to EA. There was no difference among the other RBCs ($p>0.05$).

Immersion in DW resulted in a similar color alteration ($p>0.05$) among the RBCs. After AAA, SS showed the highest color alteration, different ($p<0.05$) from all the other RBCs. AF had the lowest color alteration, different ($p<0.05$) from SS and Z350 but similar ($p>0.05$) to EA. Z350 presented a similar ($p>0.05$) color alteration to EA.



Different lowercase letters indicate significant differences between the tested conditions (AAA or immersion in the beverages) within the identical RBC; Different uppercase letters indicate significant differences between the RBC when submitted to the same condition ($p<0.05$); 2-way ANOVA, Tukey's test.

Figure 1. Comparison (means) of color alteration (ΔE) among the groups.

Microhardness Analysis

A comparison of microhardness alteration (ΔKHN) among the groups can be observed in Table 2. Negative values were observed for all the groups, indicating a decrease in microhardness, except for SS after AAA and EA after immersion in CC, DW, and AAA.

After immersion in CC, AF presented the highest ΔKHN after immersion in CC, which differed from all the other RBCs ($p<0.05$). When immersed in GJ, SS exhibited the highest ΔKHN, different ($p<0.05$) from all the other RBCs. After immersion in CM, EA revealed lower ($p<0.05$) ΔKHN values than SS and Z350 but similar ($p>0.05$) to AF. Following immersion in DW, Z350 presented higher ($p<0.05$) ΔKHN values than EA but similar ($p>0.05$) to SS and AF. After AAA, SS and EA presented lower ($p<0.05$) ΔKHN values than Z350 and AF, with no difference ($p>0.05$) between the former or between the latter. There were no differences ($p>0.05$) among the other comparisons.

Regarding SS, immersion in GJ and CM caused higher ($p<0.05$) ΔKHN values than the other conditions. Z350 showed higher ($p<0.05$) ΔKHN values after AAA than after the different conditions, except after immersion in CM, which demonstrated similar (p>0.05) ΔKHN values. For AF, AAA and immersion in CC produced higher (p<0.05) ΔKHN values than immersion in DW. EA showed different (p<0.05) ΔKHN values after AAA and after immersion in GJ. No differences were found among the other comparisons (p>0.05).

Table 2. Comparison of microhardness alteration (ΔKHN).

Groups*	SS Mean (SD)	Z350 Mean (SD)	AF Mean (SD)	EA Mean (SD)
CC	-0.6 (7.7)^{aA}	-2.3 (4.2)^{aA}	-7.8 (4.5)^{bA}	0.7 (4.9)^{aAB}
GJ	-9.5 (4.7)^{aB}	-3.6 (8.4)^{bA}	-3.4 (4.4)^{bAB}	-3.1 (2.9)^{bA}
CM	-7.8 (8.2)^{aB}	-7.2 (6.8)^{aAB}	-5.9 (5.1)^{abAB}	-0.7 (2.5)^{bAB}
DW	-1.6 (3.3)^{abA}	-5.9 (4.6)^{aA}	-1.4 (4.7)^{abB}	2.1 (2.6)^{bAB}
AAA	2.6 (4.1)^{aA}	-12.6 (8.6)^{bB}	-7.4 (5.3)^{bA}	4.2 (4.5)^{aB}

*2-way ANOVA; Tukey's test; Lowercase letters within the same row and uppercase letters within the same column indicate statistically significant differences (p<0.05).

Surface Roughness Analysis

A comparison of surface roughness alteration (ΔRa) among the groups can be observed in Table 3. All the groups presented ΔRa values below the established threshold for bacterial plaque retention, except for SS and EA after AAA. Regardless of the tested condition, no differences (p>0.05) were found among the RBCs, except after AAA, where SS and EA demonstrated higher (p<0.05) ΔRa values than Z350 and AF, with no difference (p>0.05) between the former or the between the latter. SS and EA displayed higher ΔRa values after AAA than after the other conditions. Z350 exhibited higher ΔRa values after AAA than after immersion in DW. There were no differences (p>0.05) among the different comparisons.

Table 3. Comparison (medians and limits from lower to upper) of surface roughness alteration (ΔRa).

Groups*	SS	Z350	AF	EA
CC	0.025 (-0.04 – 0.27)^{aA}	0.025 (-0.03 – 0.09)^{aAB}	0.025 (-0.03 – 2.31)^{aA}	0.01 (-0.06 – 0.05)^{aA}
GJ	0.03 (-0.03 – 0.08)^{aA}	0.015 (-0.06 – 0.1)^{aAB}	0.015 (-0.13 – 0.06)^{aA}	0.015 (-0.09 – 0.07)^{aA}
CM	-0.01 (-0.16 – 0.06)^{aA}	0.03 (-0.02 – 0.08)^{aAB}	0.015 (-0.08 – 0.08)^{aA}	0.03 (-0.05 – 0.26)^{aA}
DW	0.01 (-0.05 – 0.06)^{aA}	-0.01 (-0.07 - 0.07)^{aA}	0 (-0.06 – 0.11)^{aA}	0.015 (-0.09 – 0.04)^{aA}
AAA	0.24 (0.09 – 0.53)^{aB}	0.035 (0.01 – 0.17)^{bB}	0.01 (-0.06 – 0.1)^{bA}	0.705 (0.5 – 1.17)^{aB}

*Kruskal-Wallis test; Dunn's test; Lowercase letters within the same row and uppercase letters within the same column indicate statistically significant differences (p<0.05).

Discussion

This study evaluated the color stability, surface roughness, and microhardness of nanofilled, supra-nanofilled, and nanohybrid RBCs after accelerated artificial aging or immersion in different beverages commonly consumed by children. The null hypothesis tested was that there would be no alterations in the studied properties, irrespective of the RBCs or condition to which they would be subjected. Based on the results of this study, the null hypothesis was rejected since these conditions significantly altered all the evaluated properties of the RBCs.

RBCs' physical and mechanical properties can be influenced by various factors, including exposure to ultraviolet (UV) light, temperature changes, and humidity [22,23]. After AAA, all the tested RBCs exhibited clinically unacceptable color changes, which suggests that the materials were susceptible to color alterations when exposed to adverse conditions.

One factor contributing to the discoloration of RBCs is the photoinitiation system. All the RBCs evaluated in the present study contain camphorquinone (CQ) as a photoinitiator that, under heat or UV light, causes a yellowish of the composite material [21]. In addition, residual unreacted monomers after polymerization cause a more intense yellow color [21].

Changes in the resin matrix's chemical composition can also significantly impact the color stability of RBCs [21]. The organic phase of most RBCs consists of dimethacrylate monomers, including triethylene glycol dimethacrylate (TEGDMA), Urethane dimethacrylate (UDMA), and bisphenol A glycidyl methacrylate (Bis-GMA). Prolonged exposure to UV light, humidity, and temperature variations can cause the degradation of these monomers, resulting in decreased color stability over time [24]. RBCs containing TEGDMA are particularly susceptible to water absorption, which can exacerbate this degradation process. In contrast, RBCs containing UDMA and Bis-EMA, like Z350, are less prone to hydrolytic degradation [25].

Furthermore, the degradation of dimethacrylate monomers caused by exposure to UV light or water can induce physical alterations in RBCs, such as wear and the formation of microcracks, subsequently leading to an increase in the surface roughness of these materials [26]. AAA caused the highest surface roughness alterations (ΔRA) in all the RBCs, except for AF, with ΔRA values for SS and EA surpassing the threshold for plaque accumulation. However, the ΔRA value of Z350 did not exceed this threshold, which can be attributed to the presence of Bis-EMA. Bis-EMA is a hydrophobic monomer with excellent hydrolytic degradation resistance [27].

In turn, surface roughness of dental materials can also affect the perception of color. Surface roughness significantly affects how light interacts with the surface [26]. Rough surfaces cause light to scatter and reflect in multiple directions, which can alter the perception of color [28]. Therefore, the presence of dimethacrylate monomers in the composition of Z350, EA, and SS (although the manufacturer does not provide the specific composition information) can explain the color and surface roughness alterations observed in the present study.

On the other hand, AF stands out from the other RBCs as it belongs to the category of Organically Modified Ceramics (Ormocer). It comprises inorganic-organic copolymers and does not contain conventional dimethacrylates like Bis-GMA. Compared to traditional methacrylate-based composites, AF has a smaller amount of organic resin [29]. In line with the present study, previous research has shown that AF exhibits higher color stability than other resin-based composites [30,31]. Furthermore, in this study, AF demonstrated color alteration that was very close to the clinically acceptable limit. This can be attributed to its lower organic matrix content and higher inorganic filler content, reducing water sorption, low water solubility, and low abrasion rate [32].

Combining this inorganic-organic matrix and a high concentration of filler particles contributes superior physical properties to methacrylate-based composite resins [32]. This is likely why AF showed similar ΔRA after all the tested conditions, below the threshold to prevent biofilm accumulation, and exhibited lower surface roughness alteration than EA and SS after AAA.

Exposure to UV light, temperature changes, and humidity fluctuations can degrade the resin matrix of RBCs, leading to the plasticization of the material. The energy from UV radiation can break down the polymer chains in RBCs and release free radicals; temperature variations can accelerate detrimental chemical reactions within the resin matrix, and water absorption may lead to plasticization of the resin matrix, softening the RBC [33]. However, the effects of these environmental conditions may vary depending on the composition of each RBC [34]. The microhardness of all the RBCs decreased after AAA, except for SS and EA.

The microhardness of RBCs is influenced by the degree of crosslinking achieved during polymerization [34]. A higher degree of conversion of monomers to polymers results in a denser and more rigid polymer network, leading to increased microhardness [34]. EA uses an innovative initiator system called RAP (Rapid

Amplified Photopolymerization) that works with CQ to decrease the curing time [35]. In addition to containing CQ, SS uses benzophenone as a photoinitiator and ethyl 4-dimethylaminobenzoate as a co-initiator (activated at 361 nm and 375nm, respectively). This combination can improve the properties of SS by increasing the reactivity of the photosensitizer and facilitating a faster polymerization reaction [36,37].

In addition, in this study, the RBCs were exposed to UV light and temperature, two forms of energy that allow for complete material polymerization [38]. Thus, the composition of SS and EA, along with the post-photopolymerization phenomenon, could have increased the microhardness of these materials.

Frequently consumed acidic and colored beverages can also cause significant alterations in the properties of composite materials. In our study, color alterations were clinically acceptable after immersion in distilled water. However, when immersed in CC, both SS and AF exhibited color alterations surpassing the acceptability threshold. SS and AF are nanohybrid materials that combine nanoparticles and microfillers. According to Demirci et al. [39], nanohybrid composites have lower surface smoothness than nanofiller composites. Rough surfaces are more prone to pigment deposition, which can alter the color of the restoration [14].

After immersion in GJ, SS also displayed clinically unacceptable color alteration. CC and GJ, in addition to being colored beverages, are also acidic, which can exacerbate the color alterations in RBCs. The acidic pH of these beverages can degrade and soften the organic matrix of the composite material, as observed in the present study, increasing the surface roughness. Acidic solutions can also accelerate chemical reactions, such as the oxidation of unreacted methacrylate monomers, which contribute to color alterations in the material [40]. CC was responsible for the highest color alteration as it was the most acidic solution, capable of significantly altering the color of AF. The presence of nanohybrid fillers and methacrylates in SS would explain the results obtained with this RBC, which differs from AF, a nanohybrid material free of methacrylates.

In contrast, nanofiller composites demonstrate superior color stability owing to their higher filler content [39]. The hydrophobic nature of these filler particles leads to lower water absorption, resulting in lower hydrolytic degradation and, consequently, decreased discoloration [41]. Furthermore, incorporating smaller filler particles guarantees the proper distribution of the particles within the resin matrix, preventing their release during polishing or wear, thereby obtaining a compact and smooth surface [41].

Both Z350 and EA, despite being nanofiller composites, showed clinically unacceptable color alterations after immersion in GJ, with Z350 demonstrating the highest alteration. Moreover, only Z350 presented color alteration above the acceptability threshold after immersion in CM among the tested RBCs. In a previous study conducted by Fontes et al. [42], GJ also produced the highest color alteration in Z350 compared to other immersion solutions, possibly due to the low pH of the beverage, which led to degradation and staining of the RBC [42]. CC has a lower pH than GJ and did not cause the exact color change. This can be explained by the fact that GJ may have caused more remarkable color alteration due to the presence of phenolic compounds and tannins in grapes. Hydrophilic dimethacrylate monomers in both RBCs can justify our results [24,40,41].

Nonetheless, EA contains monodispersing supra-nano spherical fillers that improve its physical and mechanical properties [4,6]; probably, for this reason, immersion in CM was not significant for this material. The uniform size and shape of the filler particles in EA enhance its wear resistance and prevent discoloration of the material [43]. In a study by Gurgan et al. [44], the authors found that EA exhibited lower surface roughness and color change than other nanofilled RBCs.

However, in the present study, the greatest changes in surface roughness are not associated with the most significant color changes of the composites after immersion in different solutions, as reported by Yildiz et al. [45]. Immersion in the tested solutions caused similar surface roughness alterations in all the RBCs within the clinically acceptable threshold for bacterial adhesion. Moreover, the surface roughness alterations were similar among the RBCs, probably due to comparable filler size and load [32].

As mentioned earlier, surface roughness is not the only factor contributing to color change. Changes in the chemical composition of the RBCs through hydrolysis could have caused the discoloration observed in the RBCs evaluated in the present study [24,40,41].

Concerning the microhardness of the RBCs, their immersion in the tested solutions decreased microhardness, except for EA after immersion in DW and CC. Water absorption can have a detrimental effect on the microhardness of RBCs [46]. Water absorption can lead to material swelling and residual monomers' release. This process disrupts the polymeric chains within the resin matrix, weakening the material and decreasing its mechanical properties [46]. Acidic and carbonated beverages can also affect the microhardness of RBCs by causing surface erosion and dissolution, which soften the resin matrix [47]. Moreover, these beverages can dissolve the filler particles within RBCs, causing them to leach out of the material [47]. As a result, the structural integrity of the RBC is compromised, reducing its microhardness [47].

Several factors influence the microhardness of RBCs, among which the fillers' type, shape, and size play a significant role [48]. Regarding EA, our findings can be explained by the specific characteristics of its fillers. EA contains spherically shaped silica-zirconia fillers that contribute to its increased hardness and lower solubility [48]. In addition, incorporating RAP technology in EA provides a high degree of conversion, which leads to high microhardness values [35].

Although EA did not exhibit a reduction in microhardness after immersion in CC and DW, the results were similar to those of the other RBCs. Duration and frequency of exposure to low-pH beverages are essential factors in determining their impact on the surface hardness of RBCs [47].

The physical and mechanical properties of RBCs are influenced by a variety of factors, including extrinsic factors such as artificial food colors, the pH of the beverages, the frequency and duration of exposure to acidic and colored beverages, as well as environmental conditions like UV-light, temperature changes, and humidity fluctuations. In addition, intrinsic factors, such as the composition of the resin matrix and fillers, also play a significant role in determining the performance of RBCs.

In vitro studies offer advantages in terms of time and cost compared to *in vivo* studies. However, *in vitro* studies also have inherent limitations. While these in vitro studies aim to simulate *in vivo* conditions, the methods employed can sometimes be more aggressive than what occurs in clinical scenarios. Additionally, the complex oral environment cannot be fully replicated *in vitro*. Another limitation of the study was that the authors believe changes are related to yellowness. However, despite evaluating all the CIE color axes, presenting all the values here was impossible.

In the present study, distilled water was used as a storage solution. Nonetheless, immersion in saliva could have produced different results since saliva contains enzymes and ions that could affect the properties of the RBCs tested [49]. However, it is essential to consider the clinical applicability of the study, particularly regarding children's consumption of beverages. Given the restorative material and the frequency of beverage intake, dentists must conduct regular check-ups of the patient, especially considering the reduction in the microhardness of the composites. Further studies, both *in vitro* and *in vivo*, are necessary to fully understand the long-term impact of these factors on the properties of RBCs, providing valuable insights for their practical application in dental practice.

Conclusion

The composition influences resin-based composites' physical and mechanical properties. Exposure to UV light, temperature changes, and humidity led to clinically unacceptable color changes in all composites, along with surface roughness alterations surpassing the bacterial plaque retention threshold. Additionally, these conditions increased the microhardness of dimethacrylate-based composites such as Spectra Smart and Estelite Asteria.

Among beverages commonly consumed by children, Coca-Cola caused clinically unacceptable color changes in nanohybrid composites Spectra smart and Admira Fusion, while Chocolate milk affected nanofilled composite Z350. Grape juice caused color changes in all composites except in the organically modified ceramic Admira Fusion. While the beverages did not significantly alter surface roughness, they did decrease the microhardness of the composites overall, except for Coca-Cola, which increased the microhardness of Estelite Asteria.

Authors' Contributions

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

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