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Comparative effects of bubble tea and black tea on the color stability of nanofilled and microhybrid composite resins over time

Bubble tea ve siyah çayın farklı kompozit rezinlerin renk stabilitesi üzerindeki etkilerinin karşılaştırmalı analizi

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ABSTRACT
Aim: This study evaluates the effect of bubble tea and black tea on the color stability of composite resins.
Methods: Composite resin specimens (6×2 mm) [Enamel Plus HRi (HRi), Filtek Universal Restorative (FU), and G-ænial Anterior (GC)] were prepared (n = 90). A spectrophotometer was used to record baseline color values. The specimens in each composite resin group were randomly divided into three subgroups and submerged in bubble tea, black tea, and, as a control, distilled water (n = 10). Color measurements were conducted at three time points: a baseline before immersion (t0), after 24 hours (t1), and 28 days (t2) of storage in different immersion media. The color change (ΔE00) values for the specimens were computed using the CIEDE2000 color difference equation. The ΔE00 values were assessed based on the 50/50% perceptibility and acceptability thresholds. Data were analyzed using two-way ANOVA and Tukey HSD test for pairwise comparisons ($p < 0.05$).
Results: Both bubble tea and black tea caused color changes exceeding the acceptability threshold in all composite materials at 24 hours and 28 days. The ΔE00 values of all composites increased significantly between these two time points ($p < 0.001$). No significant differences were observed among the composites in ΔE00 values over 24 hours ($p > 0.05$). After 28 days in black tea, FU exhibited significantly higher ΔE00 values compared to GC and HRi ($p < 0.05$). In contrast, HRi demonstrated significantly lower discoloration than FU and GC following 28 days of immersion in bubble tea ($p < 0.05$).
Conclusion: Bubble tea and black tea induced discoloration above the acceptable threshold in the tested composite materials. Prolonged immersion time increased the color change in all materials. Although short-term immersion revealed no material-dependent differences, long-term color stability differed depending on the composite resin and the immersion medium employed.
Keywords: Color; composite dental resin; tea

ÖZ
Amaç: Bu çalışmanın amacı, bubble tea ve siyah çayın farklı kompozit rezinlerin renk stabilitesi üzerindeki etkisini değerlendirmektir.
Yöntemler: Enamel Plus HRi (HRi), Filtek Universal Restorative (FU) ve G-ænial Anterior (GC) kompozit rezinlerinden disk şeklinde (6 × 2 mm) örnekler hazırlanmıştır (n = 90). Başlangıç renk ölçümleri bir spektrofotometre kullanılarak yapılmıştır Her kompozit grubu bubble tea, siyah çay ve kontrol grubu olarak distile suda bekletilmek üzere rastgele üç alt gruba ayrılmıştır (n = 10). Renk ölçümleri, bekletme öncesinde (t0), 24 saat sonra (t1) ve 28 gün sonra (t2) spektrofotometre kullanılarak gerçekleştirilmiştir. Renk değişimi (ΔE00) değerleri CIEDE2000 renk farkı formülü kullanılarak hesaplanmış ve %50/50 algılanabilirlik ile kabul edilebilirlik eşiklerine gore değerlendirilmiştir. Veriler two-way ANOVA ve Tukey HSD testleri kullanılarak analiz edilmiştir ($p < 0,05$).
Bulgular: Bubble tea ve siyah çay, tüm kompozit materyallerde hem 24 saat hem de 28 günlük değerlendirme sürelerinde kabul edilebilirlik eşiğinin üzerinde renk değişimine neden olmuştur. Tüm kompozitlerde ΔE00 değerleri zamanla anlamlı şekilde artmıştır ($p < 0,001$). 24 saatlik bekleme periyodunda kompozitlerin ΔE00 arasında anlamlı bir fark gözlenmemiştir ($p > 0,05$). 28 gün sonunda siyah çayda bekletilen ornekler arasında FU'nun ΔE00 değeri, GC ve HRi'ye kıyasla anlamlı derecede daha yüksek bulunmuştur ($p < 0,05$). Ayrıca, bubble tea icinde 28 gun bekletilen HRi örneklerinin ΔE00 değerleri, FU ve GC'ye gore anlamlı düzeyde daha duşük olarak saptanmıştır ($p < 0,05$).
Sonuç: Bubble tea ve siyah çay, incelenen kompozit rezinlerde klinik olarak kabul edilemez düzeyde renklenmeye yol açmıştır. Solüsyonlarda bekletme süresinin uzaması, tüm materyallerde renk değişimini artırmıştır. Kısa süreli bekletmelerde materyaller arasında fark gözlenmezken, uzun süreli maruziyet sonucu meydana gelen renk değişimi kullanılan kompozit türüne ve bekletme ortamına bağlı olarak farklılık göstermiştir.
Anahtar Sözcükler: Çay; kompozit dental rezin; renk

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INTRODUCTION

Resin-based composite materials have become one of the most frequently preferred restorative options in modern dental practice, owing to their favorable aesthetic characteristics and broad clinical applicability (1). For an aesthetic restorative material to be considered successful, it should closely mimic the natural tooth structure by maintaining intrinsic properties such as color, translucency, surface texture, and resistance to extrinsic staining over a prolonged service period, in addition to providing an accurate initial color match at the time of placement (2). However, despite ongoing improvements in composite resin formulation and advances in manufacturing technologies, achieving predictable long-term color stability continues to pose a significant clinical challenge for both clinicians and researchers. Color deterioration of composite restorations not only compromises the aesthetic outcome but may also reduce patient satisfaction, frequently necessitating either repair or complete replacement of the affected restoration, which in turn results in additional chairside time and increased treatment costs (1,3).

The discoloration of composite resin materials is a multifactorial phenomenon that is governed by a complex interplay of both intrinsic and extrinsic factors, making it one of the most commonly reported clinical complications associated with direct aesthetic restorations (3,4). Intrinsic factors primarily involve physicochemical alterations within the resin matrix, whereas extrinsic factors are mainly related to surface adsorption or absorption of staining agents, commonly associated with dietary habits and tobacco use (4). Numerous studies have demonstrated that frequently consumed drinks, such as black tea, coffee, carbonated soft drinks, and red wine, contribute to varying levels of discoloration in tooth-colored restorative materials (4,5).

Among extrinsic factors, dietary habits have received considerable attention in the literature due to their direct and repeated contact with restorative surfaces in the oral environment. The modern diet includes a wide variety of pigmented foods and beverages that are consumed on a daily basis, and the cumulative exposure of composite restorations to these chromogenic agents over months and years represents a clinically significant challenge. Understanding how specific dietary components interact with different composite formulations is therefore essential for predicting the long-term aesthetic performance of these materials.

The color stability of composite resins is impacted by a complex interplay of both material-related and environmental factors. Material composition plays a pivotal role, with the resin matrix type, filler characteristics (including size, content, loading percentage, morphology, and surface properties), degree of monomer conversion, and the matrix's hydrophilicity significantly affecting susceptibility to discoloration (6-8). The resin matrix, particularly when containing hydrophilic monomers such as triethylene glycol dimethacrylate (TEGDMA), exhibits increased water sorption capacity, which serves as a medium for chromogen penetration (6, 9). Although filler particles themselves do not absorb water into their bulk, they can contribute to surface water adsorption, with a higher resin-to-filler ratio leading to increased water uptake and potential weakening of the resin-filler interface (6). This weakened interface may result in microcrack formation and interfacial gaps through swelling and plasticizing effects, facilitating stain penetration and subsequent discoloration (6,7). Recent studies have demonstrated that nanofilled composites, despite their smaller particle size, providing smoother surfaces, may paradoxically exhibit greater susceptibility to certain staining agents due to their larger surface area available for chromogen adsorption, while their performance varies depending on the specific material composition and staining medium (10,11).

While the staining effects of traditional beverages such as coffee, black tea, and red wine on composite resins have been thoroughly documented in the dental literature, the rapid evolution of global dietary trends has introduced a range of novel beverages whose chromogenic potential remains largely unexplored. Many of these newer beverages feature complex formulations combining multiple colorants, acidic components, and sugar-based additives, which may interact with composite resin surfaces through mechanisms that differ from those of conventional staining agents. In particular, the synergistic effects of multiple chromogenic compounds present within a single beverage have not been adequately addressed, as most existing studies have focused on beverages containing a predominant staining agent rather than complex mixtures. This gap in the literature highlights the need to extend staining research beyond well-established beverages to include contemporary dietary trends that are increasingly prevalent in daily consumption patterns. Failure to account for these emerging beverages in dental materials research may result in an incomplete understanding of the clinical staining risks that patients face, ultimately limiting the ability of clinicians to provide evidence-based guidance on dietary habits following restorative treatment.

The mechanism of beverage-induced staining in composite resins is multifactorial, involving both the chemical composition of the beverage and its interaction with the restorative material. Chromogenic beverages contain various staining agents, including tannins (polyphenolic compounds), melanoidins, anthocyanins, and other chromophores, which penetrate the resin matrix through water-mediated diffusion processes (10, 11). These compounds differ in their molecular size and polarity, which in turn affects their ability to infiltrate and become entrapped within the polymer network of the composite. Coffee, one of the most extensively studied beverages, induces discoloration through multiple mechanisms: melanoidins (brown-colored high-molecular-weight nitrogenous compounds produced during roasting), tannins, and caffeine all contribute to staining by deeply penetrating the composite matrix (11, 12). Tea-induced discoloration is primarily attributed to the sorption of tannins, which are anionic polyphenolic compounds capable of forming stable complexes within the resin structure (10,11). The specific type of tea also appears to influence the degree of staining, as variations in tannin concentration and composition among different tea varieties may result in differing levels of discoloration. The pH of beverages also plays a critical role in the staining process; acidic beverages can contribute to surface degradation by roughening the resin surface, indirectly facilitating stain retention and chromogen adsorption (10). This surface alteration creates micro-irregularities that serve as additional sites for pigment accumulation, further accelerating the discoloration process. Furthermore, the duration and frequency of exposure to chromogenic beverages significantly influence the degree of discoloration, with extended immersion periods correlating with increased color change values (9,12).

Bubble tea, which originated in East Asia, is a tea-based beverage flavored with milk or fruit and supplemented with toppings such as tapioca pearls or jelly. The beverage is typically shaken to create a characteristic frothy texture (13). The composition of bubble tea is notably complex, as it combines multiple potential chromogenic components including tea-derived tannins, artificial or natural colorants from fruit flavorings, and sugar-based additives that may collectively interact with restorative dental materials. Since its emergence in Taiwan during the 1980s, bubble tea has gained widespread global recognition and popularity, particularly among younger populations, evolving beyond a simple beverage into a cultural phenomenon that influences modern lifestyle trends (14). This growing consumption pattern among adolescents and young adults, who represent a significant proportion of patients receiving aesthetic composite restorations, underscores the clinical importance of investigating its potential staining effects. Given its increasing consumption worldwide, evaluating the potential impact of bubble tea on the color stability of restorative materials has become clinically relevant. A comprehensive understanding of the effects of commonly consumed beverages on the color stability of composite resins is essential for clinicians when selecting appropriate restorative materials for their patients (15).

The degree of discoloration is affected by several factors, including the type of restorative material, its chemical composition, surface characteristics, and the staining potential of the immersion medium (15). Despite the rapidly growing global consumption of bubble tea, particularly among younger populations, no studies have been identified in the literature that specifically investigate its effects on the color stability of composite resins. Therefore, the present study aimed to evaluate the effects of bubble tea and a widely consumed beverage, black tea, on the color stability of composite resins with different structural characteristics. It was hypothesized that (1) the tested composite resins would demonstrate color changes within clinically acceptable limits following immersion in bubble tea and black tea, regardless of immersion duration, and (2) no significant differences would be observed in color change among the different composite resins when immersed in their respective solutions.

MATERIAL AND METHODS

Three different commercially available composite resin restorative materials (Shade A2) [Filtek Universal Restorative (3M, St. Paul, MN, USA); G-ænial Anterior (GC, Tokyo, Japan); Enamel Plus HRi (Micerum, Avegno, Italy)] were evaluated in the present study. The composite resin materials and soft drinks used in this study are presented in Table 1.

Sample preparation

Sample size calculation was carried out with G*Power software (version 3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Germany). A priori power analysis for one-way ANOVA involving three groups was conducted using an effect size of f = 0.60, α = 0.05, and statistical power of 0.80. The results demonstrated that at least 10 specimens per group were required, resulting in a total of 90 specimens for all experimental conditions (3 composite resins × 3 immersion media × n = 10). Ninety cylindrical composite resin specimens, each measuring 6 mm in diameter and 2 mm in height, were prepared for the study (n = 10 per group). Specimen fabrication was performed using bilateral open Teflon molds. A glass plate was placed against the bottom surface to achieve a flat base, and the top surface was lined with celluloid tape followed by a second glass plate to obtain a uniformly smooth surface finish. Prior to light curing, the glass plate covering the top surface was removed. The light-curing unit tip was positioned perpendicular to the specimen surface in direct contact with the Mylar strip. Specimens were polymerized using a light-emitting diode (LED) curing device (Elipar S10; 3M ESPE, St. Paul, MN, USA), delivering a light intensity of 1200 mW/cm² over a wavelength range of 430-480 nm. FU and GC were cured for 10 seconds; HRi for 40 seconds, following manufacturer's instructions. Each specimen was cured solely from the top surface. The unmeasured bottom surfaces of the specimens were numbered to guarantee that the same surface was evaluated consistently throughout the study. Thereafter, the surface of each sample was wet-ground sequentially using silicon carbide abrasive papers with decreasing grit sizes (400, 600, 800, 1000, 2000) under water cooling for 60 seconds per grit size. Specimens within each composite resin group were randomly allocated into three subgroups (n = 10) and stored in one of the following media: bubble tea (Popping Bubble tea, Strawberry & Lemonade with Green Tea, BobaCO, Türkiye), black tea (Earl Grey Black Tea, Twinings of London, Poland), or distilled water. The composite samples were stored in lightproof containers at 37 °C for 28 days. The immersion media were refreshed every other day to avoid bacterial contamination. Samples were carefully blotted dry after being rinsed with distilled water for ten seconds prior to measurement. Color measurements were taken at three specified time points: initially before immersion (t_0), after 24 hours (t_1), and after 28 days (t_2) of storage in different immersion media.

Color measurement

The color of each specimen was measured with a clinical spectrophotometer (VITA Easyshade; VITA Zahnfabrik, Bad Sackingen, Germany). Before each measurement session, the device was calibrated following the manufacturer's recommended calibration protocol to ensure measurement reliability and consistency throughout the study. Each specimen was placed on a white background surface, and the spectrophotometer probe tip was carefully positioned perpendicular to the center of the specimen to ensure standardized and repeatable measurements. The measurement process was repeated three times for each disc, and the L*, a*, and b* values were recorded to determine the mean. All colorimetric measurements were carried out according to the Commission Internationale de l'Eclairage (CIE) L*, a*, b* color space system, employing a standardized D65 lighting and a white background as the reference surface. Color change values (ΔE_{00}) of the samples were determined by applying the CIEDE2000 color difference formula:

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

In this equation, ΔL', ΔC', and ΔH' correspond to the differences in lightness, chroma, and hue components, respectively. The weighting functions SL, SC, and SH are incorporated to adjust the total color difference relative to the location of the color difference pair within the L', a', and b' coordinate system. The parametric factors kL, kC, and kH allow modification of the formula for particular experimental setups. The RT term serves as a rotation function that compensates for the interaction between chroma and hue differences, particularly in the blue region of the color space (16). Obtained ΔE_{00} values were evaluated against the 50:50% perceptibility and acceptability thresholds as reference criteria. According to previously established guidelines, the 50:50% perceptibility threshold (PT) corresponds to a ΔE_{00} value of 0.8, indicating the point at which color differences become visually detectable by half of the observers. The 50:50% acceptability threshold (AT) is set at a ΔE_{00} value of 1.8, representing the level at which color changes are deemed clinically unacceptable by half of the observers. This methodology facilitates a standardized evaluation of color differences, considering both perceptible and acceptable thresholds (17).

Statistical analysis

Normality of the data was verified through the Shapiro-Wilk test. A two-way ANOVA was then carried out to examine how the immersion medium (bubble tea, black tea, distilled water) and composite resin type (FU, GC, HRi) influenced ΔE_{00} values, incorporating the time point (24 hours vs. 28 days) as a within-subject factor. Post-hoc pairwise comparisons were conducted using the Tukey HSD test. The threshold for statistical significance was established at $p < 0.05$, and all analyses were conducted using the SPSS Statistics for Windows (Statistical Package for the Social Sciences package program version 31.0, IBM Corp., Armonk, NY, USA).

RESULTS

Mean and standard deviation values of ΔE_{00} for the restorative materials across the different immersion solutions are summarized in Table 2. According to two-way ANOVA, the immersion medium exerted a statistically significant influence on ΔE_{00} values ($p < 0.001$), while material type also demonstrated a significant effect ($p = 0.003$). However, no statistically significant interaction was observed between the immersion medium and material type ($p = 0.483$).

An analysis of the color change of FU, GC, and HRi immersed in distilled water over time revealed no significant differences between the 24-hour and 28-day intervals ($p = 0.532$, $p = 0.576$, $p > 0.05$). At the 24-hour mark, both FU and GC exhibited color change rates exceeding the AT; however, after 28 days, the ΔE_{00} value for Filtek decreased below the AT ($\Delta E_{00} < 1.8$). The ΔE_{00} values for HRi remained within the AT at both time points. Furthermore, the ΔE_{00} values for GC at 24 hours and 28 days were significantly higher than those for FU and HRi ($p < 0.05$).

Both black tea and bubble tea caused discoloration above the AT in all composite samples across both time periods. The ΔE_{00} values of all composites demonstrated a significant increase between 24 hours and 28 days of storage ($p < 0.001$). No notable differences in ΔE_{00} values were observed among the composites during the 24-hour storage period ($p > 0.05$). Among the composites immersed in black tea for 28 days, the ΔE_{00} value of FU was higher than that of GC and HRi ($p < 0.05$). Furthermore, the ΔE_{00} value recorded for HRi specimens stored in bubble tea at the 28-day time point was significantly lower compared to those obtained for FU and GC ($p < 0.05$) (Figure 1).

DISCUSSION AND CONCLUSION

The present study investigated the effect of bubble tea, a beverage that has experienced a notable surge in popularity in recent years, particularly among younger consumer groups, and black tea on the color change of three different composite resin restorative materials. Despite the widespread consumption of bubble tea globally, its potential chromogenic effect on dental restorative materials has received limited attention in the literature, highlighting the need for further investigation in this area. The tested composites exhibited a color change exceeding the AT following immersion in both bubble tea and black tea. A statistically significant difference in the rate of color change was observed between 24 hours and 28 days of immersion in both tea solutions ($p < 0.001$). No significant difference was identified between the ΔE_{00} values of the composites immersed in both solutions after 24 hours ($p > 0.05$), whereas significant differences were noted on day 28 ($p < 0.05$). Based on these findings, the first hypothesis proposing that the composite resins would exhibit color change within the acceptability threshold following immersion in bubble tea and black tea, and that immersion duration would have no influence on the magnitude of color change, was rejected. The null hypothesis stating that the composite resins would exhibit similar color change rates regardless of the immersion solution was partially accepted.

This study assessed the impact of bubble tea and black tea on the color stability of composite resins, employing distilled water as a control. The immersion of samples in solutions for 24 hours was reported to simulate the effect equivalent to one month of clinical aging, while 28 days corresponds to approximately 2.5 years. The equivalence between immersion time and clinical aging is based on the assumption that continuous exposure to staining solutions in vitro simulates intermittent but repeated exposure in the oral environment. It has been suggested that 24 hours of continuous immersion may correspond to approximately one month of clinical exposure, considering that beverages are typically consumed for short periods throughout the day. Accordingly, extended immersion periods, such as 28 days, have been used to simulate long-term clinical aging in accelerated in vitro conditions (1,3,9,18). In the present investigation, the specimens were immersed in the solutions for 28 days, with color evaluations conducted at 24 hours and after 28 days, following the initial measurements. Spectrophotometers, colorimeters, or digital cameras have been employed to assess color alterations in dental materials (19). Spectrophotometers have been accepted as a reliable method for the quantitative evaluation of dental materials' coloration (20,21). This technique measures the quantity and spectral composition of light reflected from an object and translates it into numerical data (19). In this study, color measurements were obtained using the VITA Easyshade spectrophotometer (VITA Zahnfabrik), a widely recognized device reported to have an agreement rate of 96.4% and an accuracy rate of 92.6% (22). To assess color variations, the American Dental Association recommends the use of the CIE L*, a*, b* (Commission Internationale de l'Éclairage L*, a*, b*) measurement system. This system is optimal for identifying subtle color discrepancies and is widely used in dentistry (20,21). The CIELAB methodology is derived utilizing the ΔE_{ab} formula, which computes the L*, a*, and b* color-difference values for various materials. In the current investigation, the CIEDE2000 (ΔE_{00}) formula, introduced in 2001 and recognized for its superior sensitivity compared with the CIELAB (ΔEab) formula, was adopted to quantify color differences (23). It is also worth noting that the selection of an appropriate color difference formula is of particular importance when evaluating subtle chromatic changes in dental materials. While the traditional CIELAB formula has been widely used in earlier studies, it has been criticized for its non-uniform perceptual scaling, which may lead to inconsistent interpretation of color differences across different regions of the color space. The CIEDE2000 formula addresses these limitations by incorporating corrections for lightness, chroma, and hue weighting, as well as an interactive term that accounts for the interaction between chroma and hue differences in the blue region. Consequently, the use of the CIEDE2000 formula in the present study allows for a more perceptually accurate and clinically meaningful assessment of color changes compared to studies that have relied solely on the CIELAB system.

In this study, distilled water induced a color change in all composite materials. After 28 days, the color change rates of HRi and FU remained within the AT, whereas GC exceeded it. Notably, GC demonstrated greater color variation than the other composites during both immersion periods. The color changes recorded in the distilled water group, which surpassed the acceptability threshold for GC at both time points and for FU at the 24-hour measurement, can likely be explained by intrinsic water sorption mechanisms rather than extrinsic chromogen absorption. It has been stated that the water diffusion into the resin matrix induces plasticization of the polymer network and elution of residual monomers, both of which alter the optical properties of the composite in the absence of staining agents (6,7). All composite materials immersed in bubble tea and black tea for 24 hours exhibited color changes exceeding AT, according to the present findings. Furthermore, the ΔE_{00} values of these materials increased significantly after a period of 28 days ($p < 0.001$). These findings are in agreement with previous studies investigating the effects of black tea on the coloration of composite materials (1,3,15,24). Several studies have shown that black tea induces a color change above AT, and that the rate of coloration is proportional to the duration in the coloring solution (1-3,24). Since no studies on bubble tea were found in the current literature, a direct comparison was not possible. The pronounced staining observed with bubble tea can be attributed to its complex composition (3,5,25,26). Beyond the tea base, bubble tea contains multiple chromogenic components, including fruit flavorings, milk derivatives, and notably, black carrot juice concentrate used as a natural colorant. The combination of tannins from the tea base, acidic fruit components (citric acid), and anthocyanins from black carrot may contribute to the observed staining. Furthermore, the acidic nature of the beverage (pH 3–4) might facilitate surface softening of the resin matrix, thereby enhancing chromogen penetration. The black carrot juice concentrate may also have a contributory role in the coloration. It should also be considered that the staining behavior of composite resins in the oral environment is not solely determined by the chromogenic potential of the beverage itself, but also by the dynamic interaction between the beverage and the restoration surface over time. Factors such as the viscosity of the beverage, the contact time during each consumption episode, and the buffering capacity of saliva all play a role in modulating the extent of chromogen adsorption. In vitro immersion models, by design, eliminate the protective role of the salivary pellicle and the mechanical cleansing effect of mastication and tongue movement, which may result in an overestimation of staining compared to clinical conditions. Nevertheless, such models remain valuable for establishing relative comparisons between materials and staining agents under controlled and reproducible conditions.

Table 1. The composite resin materials and soft drinks.

	Product	Manufacturer	Chemical composition	Classification	Batch number
Composite resin restorative materials	Filtek Universal Restorative (FU)	3M, St. Paul, MN, USA	AUDMA, AFM, Diuretane-DMA, and 1,12-dodecane-Dimethacrylate. Filler: silica (20nm), zirconia (4 to 11nm), YbF_3 (100nm) Filler weight/Volume: 76.5%/58.4%	Nanofilled	NF18742
	G-ænial Anterior (GC)	GC, Japan	UDMA, dimethacrylate co-monomers, Silica, fumed silica, pre-polymerized fillers (silica, strontium and lanthanoid fluoride) (16-17 µm) Filler weight/Volume: 76%/63%	Microhybrid	2012252
	Enamel Plus HRi (HRi)	Micerium, Avegno, Italy	Diuretane-DMA, Bis-GMA, 1,4-1,4-butanedioldimethacrylate; Glass filler, Nano zirconium oxide particles (0,7 µm-0,04 µm) Filler weight/Volume: 75%/53%	Microhybrid	2017003643
Soft drinks	Popping Bubble tea Strawberry&Lemonade with Green Tea	BobaCO, Türkiye	Water, Sugar, Fructose-Glucose Syrup, Maltodextrin, Fruit juice concentrates (Lemon, apple), Green tea extract %0.3, Flavorings, Stabilizers (Calcium chloride, calcium lactate), Acidity regulator (Citric acid), Thickeners (Xanthan gum, sodium carboxymethyl cellulose, sodium alginate), Antioxidant (Ascorbic acid), Black carrot juice concentrate.		4M31H02A
	Earl Grey Black Tea	Twinings of London, Poland	Black tea, Bergamot flavoring (3%)		737309

AUDMA: Aromatic urethane dimethacrylate; AFM: Addition-Fragmentation monomer; diuretane-DMA: Diuretane- dimethacrylate; YbF3: Ytterbium tri fluoride; UDMA: Urethane dimethacrylate; Bis-GMA: Bisphenol A-glycidyl methacrylate.

The present study found no statistically significant differences in color change among the composite materials immersed in bubble tea and black tea after 24 hours. At 28 days, however, the ΔE_{00} value of FU in black tea exceeded those of GC and HRi, while in the bubble tea group, the ΔE_{00} values of FU and GC were higher than that of HRi. The color stability of composite resins is strongly influenced by their composition, particularly the relative proportions of the organic matrix and filler content (3). In addition to filler content, filler particle size has been reported to affect the color change of composite resins (26-28). Although composites with smaller filler particles are often considered less susceptible to external staining, nanohybrid composites with smaller fillers may present a larger surface area for stain adsorption, thereby increasing the risk of discoloration (15,26,28). In the present study, FU, a nanofilled composite, exhibited the greatest discoloration in black tea, whereas GC and FU showed greater discoloration than HRi in bubble tea. These findings are consistent with previous reports indicating that nanofilled composites are more prone to discoloration than nanohybrid and microhybrid composites (25,29,30). Nevertheless, both filler size and filler content should be considered when evaluating color stability (5). Compared with FU, GC contains prepolymerized fillers, which may be more susceptible to discoloration, whereas HRi incorporates glass filler particles. The inherent resistance of glass fillers to water absorption may explain the superior color stability observed for HRi (27). Additionally, given the high water absorption capacity of silane, the silanization of inorganic fillers may also contribute to composite discoloration (1,31). Beyond filler characteristics, the resin matrix composition also plays a crucial role in color stability. Hydrophilic monomers such as TEGDMA, which may be present in varying proportions among the tested composites, can increase water sorption and subsequently facilitate chromogen uptake. The degree of conversion and residual monomer content following polymerization may

Table 2. The mean and standard deviations of DE_{00} values

Immersion	Material	24 hours	28 days	p-Value
Distilled water	FU	1.9 ± 0.7 [a]	1.5 ± 0.9 [a]	p = 0.532
	GC	3.5 ± 1.0 [b]	3.1 ± 1.2 [b]	p = 0.576
	Hri	1.2 ± 0.6 [a]	1.2 ± 0.6 [a]	p > 0.05
Black Tea	FU	5.4 ± 2.1 [a]	12.2 ± 1.7 [a]	p < 0.001
	GC	6.2 ± 0.9 [a]	9.6 ± 0.7 [b]	p < 0.001
	Hri	5.8 ± 1.5 [a]	9.4 ± 1.2 [b]	p < 0.001
Bubble Tea	FU	8.7 ± 0.8 [a]	14.7 ± 1.7 [a]	p < 0.001
	GC	9.4 ± 1.6 [a]	16.0 ± 2.6 [a]	p < 0.001
	Hri	6.9 ± 1.0 [a]	10.4 ± 4.9 [b]	p < 0.001

FU: Filtek Universal Restorative; GC: G-ænial Anterior; HRi: Enamel Plus HRi. (ΔE_{00} values of restorative materials after immersion in water, black tea, and bubble tea at two time points. Superscript lowercase letters indicate statistical differences between materials within each immersion solution (i.e., comparisons are made separately for distilled water, black tea, and bubble tea) based on two-way ANOVA ($p < 0.05$). p-values in the last column (p-Value) indicate statistical differences between time points within each material and immersion condition.

also influence susceptibility to staining, as incomplete polymerization creates pathways for stain penetration. Another factor that warrants consideration is the potential influence of surface finishing and polishing protocols on the color stability of composite resins. In the present study, specimens were fabricated against a Mylar strip, which produces the smoothest possible surface but does not reflect the clinical reality where restorations typically undergo contouring and polishing procedures. Surface roughness resulting from clinical finishing has been shown to increase the susceptibility of composite resins to extrinsic staining by creating micro-irregularities that promote chromogen retention. Therefore, the staining patterns observed in this study may differ from those encountered in clinical practice, where surface texture varies depending on the finishing protocol employed. Future investigations comparing the staining behavior of composites with different surface treatments would provide additional clinically relevant information.

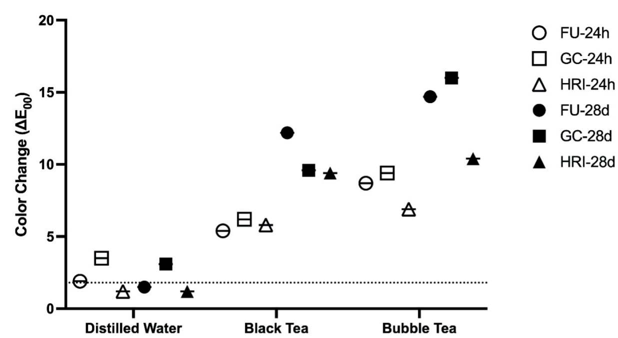

Figure 1. Color change among the materials at 24 hours and 28 days. FU: Filtek Universal Restorative; GC: G-ænial Anterior; HRi: Enamel Plus HRi. ΔE_{00} values of restorative materials after immersion in water, black tea, and bubble tea at two time points.

As with all in vitro studies, this research has certain inherent limitations. The oral environment differs from laboratory conditions in multiple aspects, and this variability should be considered when interpreting the clinical relevance of the findings. In vitro models cannot fully replicate the complex conditions of the oral cavity, where factors such as salivary enzymes, dietary habits, pH changes, and mechanical abrasion may significantly influence color stability. In the current study, the use of a static immersion model without thermal cycling or brushing simulation represents an additional limitation, as intraoral conditions are inherently dynamic. Therefore, the results should be interpreted with caution in terms of their clinical relevance. Future studies incorporating in vivo conditions or more comprehensive simulation models would provide a more accurate assessment of material performance. Moreover, commercially available canned bubble tea was used to standardize immersion protocols; however, bubble tea prepared in cafés and restaurants varies considerably in flavor composition and colorant content. Further studies investigating different types and preparations of bubble tea may provide more comprehensive insights into their potential staining effects on composite restorations.

The findings of this study have important implications for clinical practice. Clinicians should counsel patients, particularly younger populations who frequently consume bubble tea, about the potential for visible discoloration of composite restorations over time. Given that this demographic tends to have heightened aesthetic expectations, early awareness of staining risks may help manage patient expectations and reduce the need for premature restoration replacement. While all tested composites demonstrated susceptibility to staining from both beverages, the material-dependent differences observed at longer exposure periods suggest that composite selection may play a role in long-term aesthetic outcomes. Therefore, clinicians should take into account not only the initial color-matching performance of a composite but also its resistance to chromogenic challenge when planning restorations for patients with high beverage consumption habits. Regular professional maintenance, including polishing procedures, may be beneficial for patients who regularly consume chromogenic beverages. Such routine surface refinishing procedures could contribute to recovering the optical characteristics of the restoration and prolonging the interval before discoloration reaches a clinically unacceptable level. Furthermore, patient education regarding dietary habits and their impact on restoration longevity should be incorporated into treatment planning, especially for anterior restorations where esthetics are of primary concern. In this context, providing patients with specific guidance on the staining potential of popular beverages, including bubble tea, may contribute to improved long-term satisfaction with aesthetic restorative treatments.

Both bubble tea and black tea caused clinically unacceptable color changes in all composite resins tested under in vitro conditions. The magnitude of discoloration increased significantly with extended immersion time, with all composites showing greater color changes after 28 days compared to 24 hours. Although no statistically significant differences were detected among the composite resins at the 24-hour immersion period, material-dependent variations emerged at the 28-day time point, indicating that both the type of immersion medium and the particular composite resin material played a role in determining the extent of color change.

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