

In Vitro Color Stability Assessment of Two Clear Aligner Types

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ABSTRACT

Background and Objective: Clear aligners, widely used in orthodontic treatment, are subject to various environmental stresses that can affect their performance and esthetics. In addition, due to patient non-compliance, aligners frequently contact hot beverages such as coffee and cold beverages like cola. This study evaluates the effect of these beverages, along with artificial saliva, on the color stability of clear aligner materials.

Methods: Two types of clear aligners; Polyethylene Terephthalate Glycol (DURAN) and copolyester/thermoplastic elastomer (CAPro), were stained using artificial saliva, cola and coffee for up to 14 days. Color stability was assessed by Vita Easyshade ADVANCE 4.0 utilizing the Commission International lightening L*a*b* color scheme.

Results: Both DURAN and CAPro aligners showed significant color changes versus baseline ($p < 0.01$). For DURAN, all $\Delta E1-\Delta E1$ comparisons were significant ($p < 0.01$) except for saliva; CAPro showed significance only in coffee ($p < 0.01$). Solution-based differences at both time points were highly significant for both materials ($p < 0.001$). Solution type had the strongest impact on color stability, followed by material and duration.

Conclusions: Color stability was significantly influenced by solution type, material, and exposure time, with the solution having the strongest effect, followed by material and time. DURAN exhibits greater resistance to staining compared to CAPro, with coffee producing the most significant discoloration, followed by cola. The degree of color change intensifies with prolonged exposure.

Keywords: Color, Dental Materials, Elastomers, Removable Orthodontic Appliances, Polyethylene Terephthalates

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INTRODUCTION

The concept of clear aligners dates back to 1946 when they were first developed as tooth positioners primarily to facilitate minor tooth movements in the final phases of orthodontic treatment.¹ Clear aligners are either thermoformed or 3D-printed. Thermoplastic polymers can be classified as amorphous and semicrystalline based on their molecular structure. Amorphous polymers are made up of molecular structures that are irregularly arranged and exhibit low degree of packing, while semicrystalline polymers show both crystalline regions (uniform and densely packed) and amorphous regions.² Clear aligner materials should transmit 80% of visible light to achieve maximum clarity. For this reason, amorphous thermoplastic polymers like, polycarbonate, polyurethane and Polyethylene Terephthalate Glycol, are preferred over opaque crystalline polymers.³

Many patients seeking orthodontic treatment prefer an esthetic appliance that is both visually appealing and comfortable to wear. Consequently, clear aligners are often chosen. Aligners must retain their color stability, as any discoloration can significantly reduce their visual attractiveness.⁴ The duration before transitioning to the next set of aligners varies, typically ranging from one to two weeks.⁵ Patients are instructed to wear their aligners full time and remove them when eating and drinking anything except water. Ignoring these instructions leads to changes in the polymer composing the aligner, affecting its transparency and compromising its esthetic properties.⁶ While previous studies have assessed clear aligner color stability,

this study replicates intraoral conditions by factoring in contact time and temperature of the beverage. Furthermore, existing literature has not clarified whether staining is more significantly influenced by the aligner material or by the staining solution, leaving a critical gap in understanding the dominant factors driving these changes. Therefore, this study aims to evaluate the color stability of two clear aligner types after seven and fourteen days of in vitro aging to enhance understanding of optical changes in clear aligner therapy and provide clinically relevant insights to guide material selection and maintenance protocols.

METHODS

Study Setting

This in vitro study was conducted at Hawler Medical University, College of Dentistry in Erbil, Kurdistan-Iraq. Ethical approval was obtained from the Scientific Research Ethical Committee (Reference Number: HMUD,2425155; Date of Approval: 26/10/2024).

Sample collection

An ideal model was scanned, converted to a stereolithography file and used to print fifty resin casts. Circular sheets of DURAN and CAPro (Scheu-Dental GmbH, Iserlohn, Germany) were thermoformed into aligners using Ministar (Scheu-Dental GmbH, Iserlohn, Germany).

DURAN sheets are composed of a single layer Polyethylene Terephthalate Glycol (PETG), while CAPro sheets are composed of layer of a soft thermoplastic elastomeric layer between two hard layers of co-polyester.

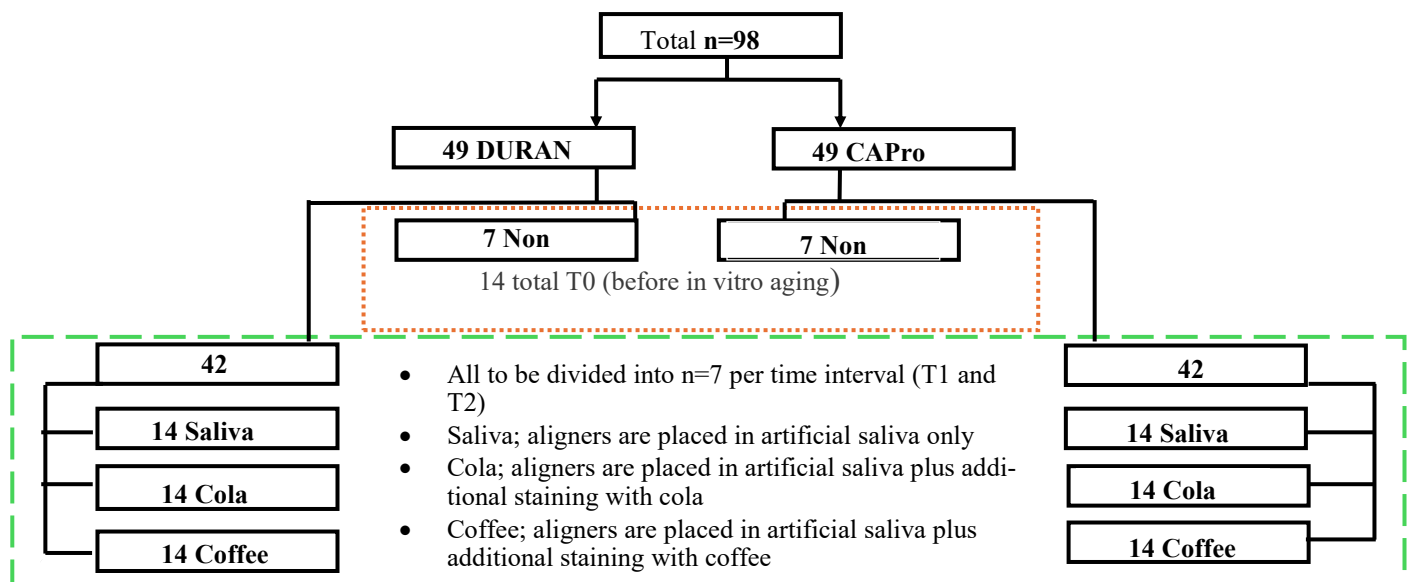


Figure 1. Diagram showing study design and coding of samples

Both sheets have a thickness of 0.75 mm. The required sample size was calculated using G-power software (V.3.1.9.7, Kiel, Germany), which indicated that a minimum of 90 samples was necessary to achieve a significance level of alpha equal to 5% and power equal to 95%.

For this study, twenty-five sheets of each material type were thermoformed, and the resulting aligners were cut with scissors between the central incisors to prevent heat-induced deformation.⁷ This process yielded 100 potential samples of which 98 were used. Sample coding and study design are illustrated in Figure 1

Methodology

Fourteen specimens (n = 14) were used for baseline evaluation, with seven samples of each material assessed for optical properties before aging. The remaining samples (n = 84) were immersed in artificial saliva (modified Carter’s solution) and incubated at 37 °C for 22 hours per day up to two

weeks, randomly distributed into six glass jars (14 per jar, 150 mL artificial saliva each). Samples belonging to the T1 group were removed from the jars after seven days, whereas samples in the T2 group remained for fourteen days. To simulate daily aligner removal during meals, samples were taken out of the incubator for two hours daily and stored at room temperature.⁸ During this period, they were stored in a dry and dark environment to minimize extrinsic color change.⁴ Additional staining procedures with cola and coffee were performed three times per day in a one to one ratio,⁹ with each immersion lasting three minutes in a water bath maintained at 37 °C using two containers of artificial saliva (75 mL each). Figure 2 shows the overall in vitro aging protocol. This aging approach was selected to replicate real-life conditions, ensuring the staining process holds clinical relevance. Additional staining procedure is illustrated in Figure 3.

A Constant state of aligners 22 hours per day, up to 2 weeks

B Additional staining procedure of aligners 3 times per day for 3 minutes

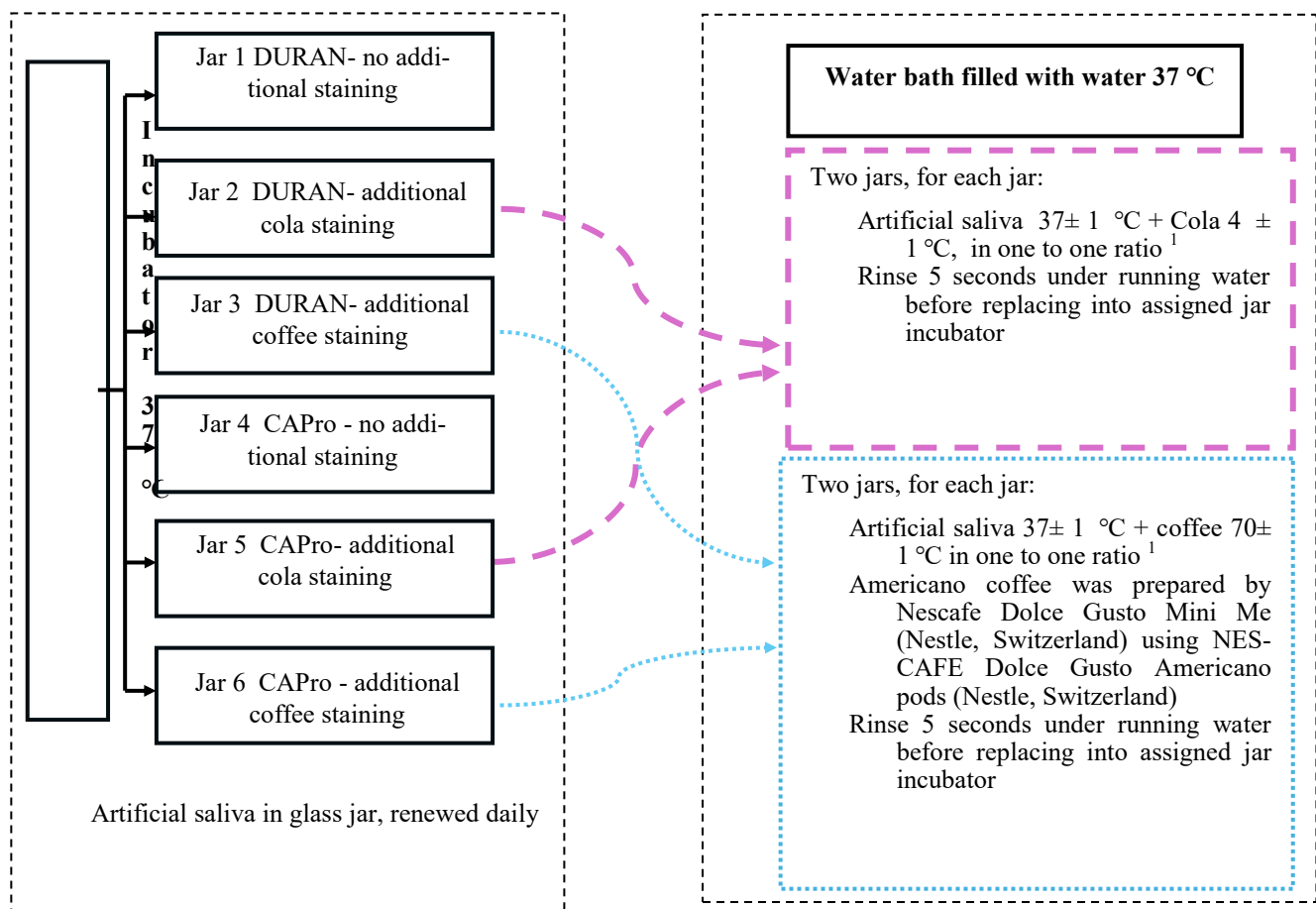


Figure 2. In vitro aging of samples A Constant state B Additional staining procedure



Figure 3. Additional staining procedure (1) Two jars with artificial saliva in water bath (2) Cola freshly taken out of fridge (3) Additional staining in progress (4) Samples placed back into its assigned jar (5) Jars placed back into incubator (6) Freshly Americano coffee brewed with Dolce Gusto Mini Me

Measurement protocol

Vita Easyshade Advance 4.0 (Vita Zahnfabrik, Germany) measured aligner color change at T0 (baseline before in vitro aging), T1 (after 7 days), and T2 (after 14 days) on a white sheet to prevent color absorption.¹ Each time point had its own dedicated sample set. The spectrophotometer was calibrated prior to each measurement. Measurements were conducted under identical lighting,

with a standardized setup using two central incisor teeth models, made with palfique universal flow medium A2 (Tokuyama Dental, Japan), as background reference. The optical tip was pressed vertically against the central incisors' flat labial surface, with three readings averaged per sample. The measurement protocol to ensure consistent color analysis is shown in Figure 4.

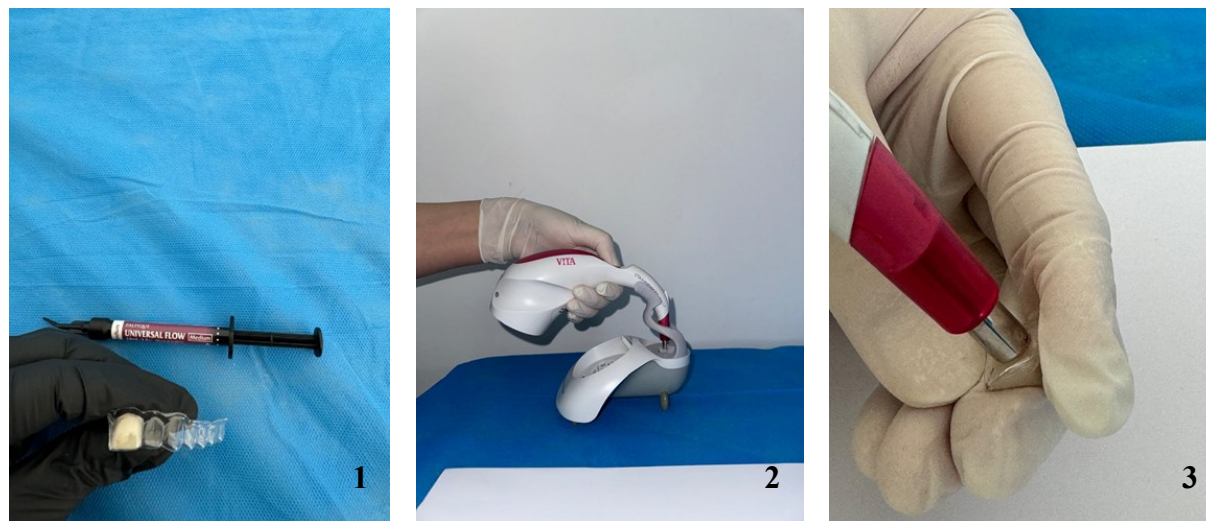


Figure 4. Measurement protocol for consistent color analysis (1) Background reference made by flowable composite (2) Calibration before each measurement (3) Placement of the optical tip against the aligner with the background reference in place

Color change was measured using the Commission Internationale de l'Eclairage L*a*b* color system, where L* represents lightness (+ bright, - dark), a* represents red (+) green (-) scale and b* yellow (+) to blue (-) scale. Color change is calculated between T0-T1($\Delta E1$) and T0-T2 ($\Delta E2$). ΔE values were calculated as: $\Delta E = [(\Delta L)^2 + (\Delta a)^2$

$+ (\Delta b)^2]^{1/2}$ where ΔL , Δa and Δb represent differences between baseline and stained samples in saliva, cola or coffee solution. To evaluate clinical relevance, ΔE values were converted to National Bureau of Standards (NBS) units using the formula $NBS = \Delta E \times 0.92$ (Table 1).

Table 1. National Bureau of Standard Ratings

National Bureau of Standards (NBS) units	Description of Color Changes
0.0-0.5	Trace: Extremely slight change
0.5-1.5	Slight: Slight change
1.5-3.0	Noticeable: Perceivable
3.0-6.0	Appreciable: Marked change
6.0-12.0	Much: Extremely marked change
12.0 or more	Very much: Change to other color

Statistical analysis

Statistical analysis was conducted by R (version 4.4.2; R Foundation for Statistical Computing, Vienna, Austria), SPSS (version 29; IBM Corp., Armonk, New York, United States), and GraphPad Prism (version 10; GraphPad Software, San Diego, California, United States). The Shapiro–Wilk test was applied to assess normality of ΔE values across all material, solution, and time groups. Homogeneity of variances was ex-

amined using Levene’s test. As all p-values exceeded 0.05, the assumptions for parametric testing were met. Independent t-tests compared color changes (ΔE) at different time points, one-sample t-tests determined if ΔE values significantly deviated from baseline and ANOVA to compared between solutions. Bonferroni post hoc tests were performed for DURAN and CAPro to identify which staining solutions contributed to significant changes in ΔE . A three-way ANOVA examined

the effects of material, solution and time on color stability. Chi-square tests analyzed categorical perceptual color changes.

RESULTS

Shapiro–Wilk tests confirmed normal distribution for all ΔE datasets across material, solution, and

time groups. Homogeneity of variance was also verified as shown in Table 2, with all p-values exceeding 0.05, indicating equal variances. Therefore, the assumptions for parametric analysis were met, and parametric tests were appropriate for addressing the study objectives.

Table 2. Test of Homogeneity Outputs Between Groups for Both Materials

Material	ΔE	Levene Statistic	df1	df2	P-Values
DURAN	$\Delta E1 (T0 - T1)$	0.276	2	18	0.762
	$\Delta E2 (T0 - T2)$	0.357	2	18	0.705
CAPro	$\Delta E1 (T0 - T1)$	2.709	2	18	0.094
	$\Delta E2 (T0 - T2)$	1.144	2	18	0.341

Assessment of staining solutions and color stability over time

The study assessed the progression and intensity of staining by analyzing ΔE values. Comparisons were made across two timeframes (T1 and T2) against the baseline using a one-sample t-test,

within each material over different time intervals using independent t-tests and between solutions through one-way ANOVA. Table 3 shows the descriptive statistics which reveal clear trends in color change associated with the type of material, the staining solution and exposure time.

Table 3. Color Change (ΔE) Between Time Points and Statistical Comparison for DURAN and CAPro Across Solutions

Material	Solutions	$\Delta E1 (T0 - T1)$	$\Delta E2 (T0 - T2)$	T-test for $\Delta E1$ and $\Delta E2$
		Mean \pm SD (p-value)	Mean \pm SD (p-value)	T-value (p-value)
DURAN	Saliva (n = 7)	0.075 \pm 0.053 (0.009)	0.103 \pm 0.062 (0.004)	- 0.913 (0.379)
	Cola (n = 7)	0.284 \pm 0.071 (< 0.001)	0.425 \pm 0.077 (< 0.001)	-3.55 (0.004)
	Coffee (n = 7)	0.380 \pm 0.091 (< 0.001)	0.570 \pm 0.066 (< 0.001)	-4.460 (0.001)
	ANOVA Test (p-value)	31.353 (< 0.001)	84.233 (< 0.001)	
CAPro	Saliva (n = 7)	0.304 \pm 0.126 (0.001)	0.326 \pm 0.116 (< 0.001)	-0.339 (0.741)
	Cola (n = 7)	0.322 \pm 0.119 (< 0.001)	0.467 \pm 0.133 (< 0.001)	-2.135 (0.054)
	Coffee (n = 7)	0.651 \pm 0.057 (< 0.001)	0.910 \pm 0.177 (<0.001)	-3.680 (0.003)
	ANOVA Test (p-value)	24.180 (< 0.001)	(< 0.001)	

Single factor assessment

For DURAN, minimal color change occurred in saliva ($\Delta E1 = 0.075 \pm 0.053$, $\Delta E2 = 0.103 \pm 0.062$), stabilizing over time ($t = -0.913$, $p = 0.379$). Cola-induced discoloration increased significantly ($\Delta E1 = 0.284 \pm 0.071$, $\Delta E2 = 0.425 \pm 0.077$) and compounded over time ($t = -3.550$, $p = 0.004$). Coffee caused the highest ΔE ($\Delta E1 = 0.380 \pm 0.091$, $\Delta E2 = 0.570 \pm 0.066$), showing progressive staining ($t = -4.460$, $p = 0.001$). ANOVA confirmed significant solution-based differences at both time points ($F = 31.353$, $p < 0.001$ for $\Delta E1$; $F = 84.233$, $p < 0.001$ for $\Delta E2$). CAPRO showed a greater degree of discoloration

compared to DURAN in all solutions. In saliva, $\Delta E1 = 0.304 \pm 0.126$, $\Delta E2 = 0.326 \pm 0.116$, stabilizing over time ($t = -0.339$, $p = 0.741$). Cola showed moderate staining ($\Delta E1 = 0.322 \pm 0.119$, $\Delta E2 = 0.467 \pm 0.133$), with borderline significance between $\Delta E1$ and $\Delta E2$ ($t = -2.135$, $p = 0.054$). Coffee caused severe staining ($\Delta E1 = 0.651 \pm 0.057$, $\Delta E2 = 0.910 \pm 0.177$), with significant ΔE progression ($t = -3.680$, $p = 0.003$). ANOVA results confirmed significant solution-based effects ($F = 24.180$, $p < 0.001$ for $\Delta E1$; $F = 31.269$, $p < 0.001$ for $\Delta E2$). The pairwise comparison between solutions was examined in Table 4 and Figure 5.

Table 4. Pairwise Comparison Test with Bonferroni Method

Material	ΔE	Solutions		Mean Difference (I-J)	SE	P-Value	95% Confidence Interval	
							Lower Bound	Upper Bound
DURAN	$\Delta E1 (T0 - T1)$	Saliva	Cola	-0.20819	0.03929	< 0.001	-0.3119	-0.1045
			Coffee	-0.30432	0.03929	< 0.001	-0.4080	-0.2006
		Cola	Coffee	-0.09612	0.03929	0.075	-0.1998	0.0076
	$\Delta E2 (T0 - T2)$	Saliva	Cola	-0.32131	0.03676	< 0.001	-0.4183	-0.2243
			Coffee	-0.46618	0.03676	< 0.001	-0.5632	-0.3692
		Cola	Coffee	-0.14487	0.03676	0.003	-0.2419	-0.0478
CAPRO	$\Delta E1 (T0 - T1)$	Saliva	Cola	-0.01858	0.05623	1.000	-0.1670	0.1298
			Coffee	-0.34754	0.05623	< 0.001	-0.4959	-0.1991
		Cola	Coffee	-0.32895	0.05623	< 0.001	-0.4773	-0.1806
	$\Delta E2 (T0 - T2)$	Saliva	Cola	-0.14081	0.07717	0.254	-0.3445	0.0629
			Coffee	-0.58466	0.07717	< 0.001	-0.7883	-0.3810
		Cola	Coffee	-0.44385	0.07717	< 0.001	-0.6475	-0.2402

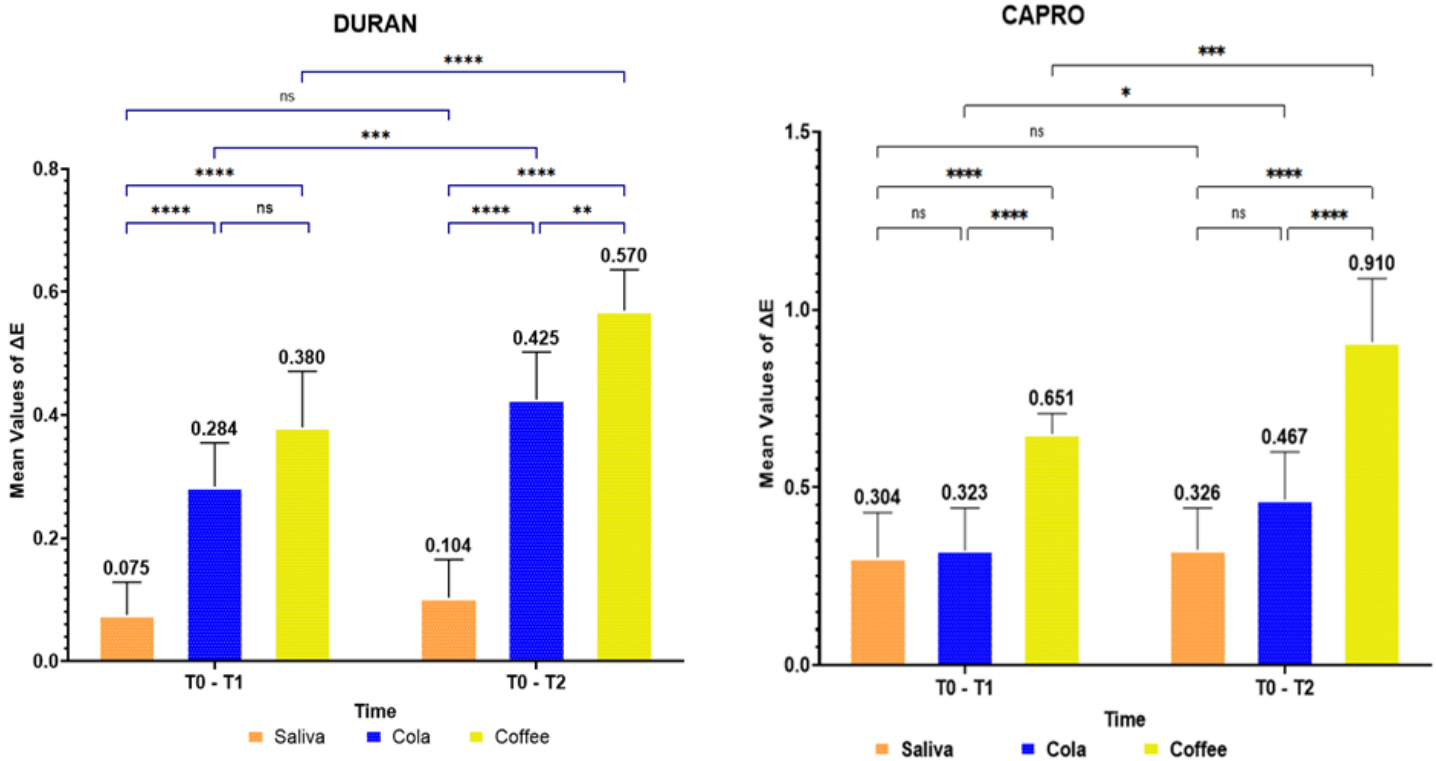


Figure 5. Error Bar chart illustration of color change assessment for DURAN and CAPRO

For DURAN, the difference of mean values of all the pairs turned out to be significant except changes between cola and coffee groups in ΔE1 and changes from ΔE1 to ΔE2 for saliva group. For CAPRO, the mean values of all the pairs differed significantly, except between solutions such as saliva versus cola at both time periods and the changes from ΔE1 to ΔE2 for the saliva group.

Multiple Factor Evaluation on color change

Three-way ANOVA in Table 5 revealed significant effects for Material ($F = 72.663$, p -value < 0.001 , partial $\eta^2 = .502$), Solution ($F = 122.140$, p -value < 0.001 , partial $\eta^2 = 0.772$), and Time ($F =$

34.133 , p -value < 0.001 , partial $\eta^2 = 0.322$) on the dependent variable ΔE. This showed that each component affects ΔE separately. Solution was the most important factor in color change, with the biggest effect size, followed by material and time. The Material × Solution interaction was the most significant of the interaction effects (p -value < 0.001 , partial $\eta^2 = 0.256$), followed by Solution × Time interaction ($p = 0.002$, partial $\eta^2 = 0.157$). The three-way interaction Material × Solution × Time ($p = 0.756$) and the Material × Time interaction ($p = 0.626$), however, were not significant.

Table 5. Three-Way ANOVA Results for the Effects of Material, Solution, and Time on Color Change (ΔE)

Source	F - Value	P-Value	Partial Eta Squared
Intercept	1287.842	< 0.001	0.947
Material	72.663	< 0.001	0.502
Solution	122.140	< 0.001	0.772
Time	34.133	< 0.001	0.322
Material * Solution	12.375	< 0.001	0.256
Material * Time	0.239	0.626	0.003
Solution * Time	6.697	0.002	0.157
Material * Solution * Time	0.281	0.756	0.008
R Squared = .844 (Adjusted R Squared = .820)			

National Bureau of Standard ratings

All DURAN samples in the ΔE1 interval showed only trace color changes, making a chi-square test inappropriate due to the lack of variance. In contrast, five out of seven CAPro samples in coffee

showed slight changes, while all other CAPro samples exhibited extremely slight color changes. Unlike DURAN, coffee significantly influenced CAPro's early discoloration, as confirmed by a chi-square test ($\chi^2 = 14.677, p = 0.001$) (Table 6).

Table 6. Color Change Distribution Categories (ΔE1: T0–T1) by Material and Solution

Materials	Solutions	Trace: Extremely slight change	Slight: Slight change	Chi-square (p-value)
DURAN	Saliva	7	0	NA
	Cola	7	0	
	Coffee	7	0	
CAPRO	Saliva	7	0	14.677 (0.001)
	Cola	7	0	
	Coffee	2	5	

Chi-square analysis of ΔE2 in Table 7 shows that cola and saliva groups exhibited only trace color changes, while coffee caused a noticeable shift, six of seven DURAN samples showed slight changes ($\chi^2 = 19.386, p < 0.001$). Similarly, CA-

Pro displayed distinct transitions: all coffee samples had mild alterations ($\chi^2 = 20.306, p < 0.001$), saliva samples showed only trace changes, and cola samples had a mix (5 trace, 2 slight).

Table 7. Color Change Distribution Categories (ΔE2: T0–T2) by Material and Solution

Materials	Solutions	Trace: Extremely slight change	Slight: Slight change	Chi-square (p-value)
DURAN	Saliva	7	0	19.386 (p < 0.001)
	Cola	7	0	
	Coffee	1	6	
CAPRO	Saliva	7	0	20.306 (p < 0.001)
	Cola	5	2	
	Coffee	0	7	

DISCUSSION

Clear aligners' transparency significantly contributes to their widespread appeal and popularity. Maintaining color stability is fundamental to the esthetic quality and patient satisfaction of orthodontic aligners.³ Although patients are advised to remove their aligners when eating or drinking anything other than water to prevent staining, many fail to follow this recommendation. A considerable proportion continue to eat and drink with their aligners in place, which affects their transparency and diminishes their esthetic appeal.⁶

This study evaluated discoloration patterns in two aligner materials, DURAN and CAPro, when exposed to artificial saliva, cola, and coffee over

time. CAPro clear aligners are made up of a polymer blend consisting of three layers, inner thermoplastic elastomer layer with two layers of a copolyester according to their manufacturer, while DURAN aligners are made up of PETG. PETG is a non-crystalline co-polyester, comprised of 1,4-cyclohexane two methanol (CHDM), ethylene glycol (EG) and terephthalic acid (TPA).²

To simulate real intraoral conditions, an in vitro aging protocol was used in which samples remained in artificial saliva for 22 hours daily and were exposed to cola and coffee three times per day. For the additional staining procedure, a water bath set at 37 °C was used to replicate the thermal environment of the oral cavity. Although coffee

was initially prepared at 70 °C to reflect typical Americano preparation, this temperature does not persist intraorally; hot beverages rapidly cool toward oral temperatures. Placing the coffee in the 37 °C water bath allowed it to equilibrate to physiologic levels, ensuring realistic thermal exposure. The same principle applied to cola: although consumed cold, it warms quickly once in the mouth. Placing the cola in the water bath prevented artificially low exposure temperatures and more accurately reflected the transient warming that occurs during actual beverage intake.

The present data showed a statistically significant difference in color stability between the two aligner materials, DURAN and CAPro. CAPro material had a higher mean ΔE value than DURAN, signifying increased discoloration. The results indicated that DURAN demonstrated enhanced resistance to stains and superior color stability compared to CAPro under the evaluated conditions. The type of material used in the manufacturing of clear aligners significantly impacts their color stability. PETG aligners are more resistant to stains and chemical alterations due to their molecular structure.³ Olteanu et al.,¹ found that CAPro stains more than PETG aligners. This is consistent with previous studies indicating that PETG material exhibits lower polarity, attributed to the presence of '-COO-' and 'C-O-C' surface groups. As a result, its tendency to adsorb pigments is reduced.¹⁰ Fourier Transform Infrared Spectroscopy analysis of CAPro aligners showed they have outer PETG layers and polyurethane-based center. The spectra of these aligners closely resemble PETG only aligners,¹¹ but the outer PETG layer in CAPro does not prevent discoloration to the same extent, potentially due to polyurethane-based components within its structure. Previous studies have reported that polyurethane content increases water absorption¹² allowing for greater stain pigment adsorption and adhesion.^{6,13} This is supported by studies who report greater water absorption and discoloration of Zendura FLX (composed of PETG outer layers and polyurethane-based centers)¹¹ compared to PETG only aligners.^{14,15} ClearCorrect aligners with a PETG outer layer exhibit better stain resistance than Invisalign aligners with outer polyurethane layer,^{3,6} this indicates that PETG contributes to improved color stability.

While our results diverge from a limited number of previous studies, such as Staderini et al.,¹⁶ they remain broadly consistent with the majority of exist-

ing literature. For instance, Staderini et al.¹⁶ reported that PETG (Erkodur) exhibited approximately twice the optical density of TPU (F22) at baseline, indicating greater transparency in TPU. These findings align with those of Lombardo et al.⁹ and Cremonini et al.,¹⁷ all of which utilized F22 clear aligners and reported superior optical stability in polyurethane-based systems compared to PETG. In the latter two studies, All In aligners, composed of PETG,¹⁸ showed inferior color stability compared with Invisalign (polyurethane). This suggests that brand-specific formulation and manufacturing processes may significantly affect performance, even among aligners made from the same base material. Additionally, although Fourier Transform Infrared Spectroscopy confirmed material equivalence between CA Pro+ and Zendura FLX, their optical properties differ notably. Scheu CA Pro+ exhibits higher baseline transmittance than Zendura FLX, yet after exposure to a staining solution, it shows a greater percentage change. This implies that Zendura FLX retains its transparency more effectively under simulated staining conditions.¹⁹

Among the staining solutions tested in the present study, coffee led to the greatest discoloration across both materials, followed by cola and artificial saliva. The low polarity yellow pigment composition of coffee and its tendency to slowly penetrate organic substrates¹ contributes to notable color shifts, consistent with previous studies on clear aligner staining.^{1,3,13,14,20,21} Cola-induced staining is moderate but displayed an increasing trend over time, particularly in DURAN. The brown coloration of cola is attributed to the presence of caramel, which serves as a coloring agent in carbonated beverages. The acidity of these solutions facilitates physical and chemical surface alterations, enhancing stain adherence.¹ Research indicates that elevated temperatures increase water permeability in materials. After consuming hot beverages or food, oral cavity temperatures can exceed 57°C, requiring several minutes to normalize.¹¹ This prolonged heat exposure enhances pigment penetration, leading to deeper staining. In addition, the difference in staining ability between cola and coffee may be due to the high polarity of Coca-Cola, which likely diminishes its absorption capacity and reduces its ability to adhere to the material's surface, making it more easily removed during rinsing.²² When patients consistently remove their aligners while eating and drinking, there is a noticeable, though not statistically significant, pattern

of increased absorbance and decreased transmittance.²³ In our study both Duran and CAPro showed an extremely slight, but measurable color shift in saliva, which remains unchanged over time. This suggests initial discoloration occurs but stabilizes without further degradation.

The frequency and duration of clear aligner contact with staining agents may affect pigmentation. Increasing staining duration results in greater color changes in samples.^{1,3,4,13,14,21,24,25} In the present study, prolonged exposure to cola and coffee worsened color change in both DURAN and CAPro, but with the change between $\Delta E1$ and $\Delta E2$ for cola in the CAPro aligners not being statistically significant.

Three-way ANOVA conducted in the current study confirmed that material type, staining solution and time all independently significantly affected ΔE values, with solution type being the strongest determinant, followed by material and time. The Material \times Solution interaction was the most significant of the interaction effects, indicating that the impact of solutions on color stability varies according to the material. The effect of solutions on color change changes with time, as seen by the substantial Solution \times Time interaction. The three-way interaction Material \times Solution \times Time and the Material \times Time interaction, however, are not significant, this indicates that time did not differentially impact materials either alone or in combination with two other factors at the same time.

The findings of this study hold clinical significance, as maintaining patient compliance with aligner removal during meals and beverages continues to be a persistent challenge. Although staining levels in the study were categorized as "extremely slight" to "slight" using NBS ratings, exposure could eventually compromise aligner esthetics. Šimunović et al.³ observed marked changes in ClearCorrect aligners, likely due to differing methodologies. Their study submerged aligners in staining solutions for seven days without artificial saliva, while the current study simulated real-life conditions with daily artificial saliva incubation and brief staining exposures. PETG aligners showed a slight color change (NBS 1.38) after two weeks of coffee exposure,²¹ exceeding our findings, possibly due to prolonged staining and lack of rinsing, all of which may have amplified discoloration. Interestingly, another study found that aligners immersed in artificial saliva

exhibited an NBS value of 2.23,²⁰ exceeding that observed for coffee exposure. This stands in contrast to our findings, where aligners stored solely in artificial saliva, without interaction with cola or coffee, showed only minimal color variation. This discrepancy may be attributed to the fact that the referenced study did not consider the temperature of the staining solutions and conducted measurements without placing tooth models behind the aligners.

The findings of this study support several clinical recommendations, including selecting low-permeability polymers, educating patients on the staining effects of pigmented and hot beverages, and maintaining regular cleaning protocols to reduce plaque and pigment accumulation. Future research should further refine in vitro models by incorporating masticatory forces, enzymatic activity, and microbiological factors, and should also explore the optical behavior of emerging 3D-printed aligner materials. In-vivo studies remain essential to validate laboratory outcomes and to better understand aligner performance under real physiological conditions.

CONCLUSION

Material type, staining solution and exposure time each had a significant impact on color stability, with solution type being the most influential factor, followed by material and time. CAPro clear aligners made up of copolyester/thermoplastic elastomer are more susceptible to staining compared to DURAN clear aligners made up of PETG. Among beverages, coffee is the most potent staining solution followed by cola and artificial saliva. Among time intervals, exposure to staining agents up to fourteen days is more evident compared to seven days.

Conflict of Interest

The authors declare no conflicts of interest.

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