

Effect of Different Beverages and Polishing on the Color Stability of Monolithic Zirconia: A comparison of CIELab-CIEDE2000 Formula

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ABSTRACT

Aim: This study aimed to evaluate the color stability of two high translucency monolithic zirconia materials following different polishing protocols and immersion in two commonly consumed beverages (coffee and red wine), using both the CIELab (ΔE) and CIEDE2000 (ΔE_{00}) color difference formulas.

Materials and Methods: Discs of Katana HT and GC Initial HT zirconia were assigned to four surface treatment groups (control, re-glazed, Meisinger, Optra-fine). Specimens were immersed in coffee and red wine for 28 days. L^* , a^* and b^* were recorded using a spectrophotometer, and ΔE and ΔE_{00} values were calculated. Data were analyzed with three-way ANOVA and Tukey HSD post hoc tests ($\alpha=0.05$).

Results: Zirconia brand and beverage type significantly affected color change according to both ΔE and ΔE_{00} values ($p<0.001$), with GC Initial HT exhibiting greater discoloration than Katana HT and red wine causing more pronounced staining than coffee. While the polishing procedure had a significant effect on ΔE values ($p=0.028$), no significant effect was observed for ΔE_{00} ($p=0.429$), with the re-glazed specimens showing the lowest and the Meisinger polished specimens showing the highest color change.

Conclusion: The color stability of high translucency zirconia is significantly affected by material composition and staining medium. ΔE values tend to overestimate visual color differences compared to ΔE_{00} , which better reflects human perception. Therefore, ΔE_{00} is recommended for clinical and research evaluations involving esthetic restorations. Re-glazing is advised to enhance stain resistance, particularly in patients with frequent exposure to chromogenic beverages.

Farklı İçeceklerin ve Polişajın Monolitik Zirkonya'nın Renk Stabilitesi Üzerine Etkisi: CIELab-CIEDE2000 Karşılaştırması

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ÖZET

Amaç: Bu çalışmanın amacı, iki yüksek translusent monolitik zirkonya materyalinin farklı cilalama protokolleri ve yaygın tüketilen içeceklere (kahve ve kırmızı şarap) maruz bırakılması sonrası renk stabilitelerinin CIELab (ΔE) ve CIEDE2000 (ΔE_{00}) renk farkı formülleriyle karşılaştırmalı olarak değerlendirilmesidir.

Gereç ve Yöntemler: Katana HT ve GC Initial HT olmak üzere iki farklı zirkonya diski dört yüzey işlem grubuna (kontrol, re-glaze, Meisinger, Optra-fine) ayrıldı. Numuneler kahve veya kırmızı şarapta 28 gün boyunca bekletildi. Renk değişimleri spektrofotometre ile ölçülerek ΔE ve ΔE_{00} değerleri hesaplandı. Veriler üç yönlü ANOVA ve Tukey HSD testleri ile analiz edildi ($\alpha=0.05$).

Bulgular: Zirkonya markası ve içecek türü, hem ΔE hem de ΔE_{00} değerlerine göre renk değişimini anlamlı düzeyde etkilemiştir ($p<0.001$); GC Initial HT, Katana HT'ye kıyasla daha fazla renk değişimi göstermiş ve kırmızı şarap, kahveye göre daha belirgin lekelenmeye neden olmuştur. Cilalama prosedürü ΔE değerleri üzerinde anlamlı bir etki gösterirken ($p=0.028$), ΔE_{00} değerleri açısından anlamlı bir etki gözlenmemiştir ($p=0.429$); re-glaze uygulanmış örnekler en düşük, Meisinger ile polisaj yapılan örnekler ise en yüksek renk değişimini göstermiştir.

Sonuç: Yüksek translusent zirkonyaların renk stabilitesi, malzeme bileşimi ve boyayıcı ortamdan anlamlı düzeyde etkilenmektedir. ΔE değerleri, insan algısını daha iyi yansıtan ΔE_{00} ile karşılaştırıldığında görsel renk farklarını abartma eğilimindedir. Bu nedenle, estetik restorasyonları içeren klinik ve araştırma değerlendirmelerinde ΔE_{00} kullanımı önerilmektedir. Ayrıca, özellikle kromojenik içeceklere sık maruz kalan hastalarda leke direncini artırmak amacıyla re-glaze uygulanması tavsiye edilmektedir.

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INTRODUCTION

In recent years, patient expectations for indirect restorations have grown substantially. This heightened demand has accelerated the clinical acceptance of metal free fixed restorations, largely because of their excellent biocompatibility, chemical and chromatic stability, low surface roughness, and superior esthetic performance.¹ Parallel to this trend, CAD (Computer-Aided Design), CAM (Computer-Aided Manufacturing) systems have advanced rapidly, enabling clinicians to mill uniform, defect free blocks and deliver highly aesthetic restorations in a single appointment.² Contemporary CAD-CAM blocks encompass glass ceramics, resin based composites, hybrid ceramics, and zirconia.^{2,3} Among these, zirconia based materials are particularly noteworthy for their outstanding biocompatibility, favorable mechanical properties, and promising esthetic potential. Over three successive generations, manufacturers have refined zirconia ceramics, offering a spectrum of formulations that differ in composition, strength, translucency (ranging from low to ultra-high), and shade configuration (monochromatic, pre-shaded, or multilayered).²⁻⁴

Multiple variables like ceramic thickness, intrinsic translucency, and the shade of the luting cement can influence the definitive color of an indirect restoration.^{5,6} Beyond these material related factors, the surface finishing and polishing regimen plays a critical role.⁷ Inadequately finished porcelain exhibits micro irregularities that scatter light irregularly, producing perceptible discoloration.^{8,9} As chromatic stability is a primary determinant of long-term clinical success, manufacturers now offer an array of finishing and polishing systems, including silicone-rubber wheels and pastes, aluminium-oxide abrasive discs, and surface protective varnishes.¹⁰ Several studies,^{7,8,11,12} indicates that when glazing or polishing is performed under optimal conditions, the clinical longevity and color stability of porcelain restorations are significantly improved.

Daily dietary intake exposes the oral environment to a broad spectrum of foods and beverages that differ in volume, chroma,

temperature, and chemical composition.^{13,14} Among these exposures, beverages are particularly influential, as their chromogenic pigments and pH altering properties can destabilise the color of aesthetic restorations, leading to clinically perceptible discoloration. Drinks such as coffee, tea, red wine, and cola introduce complex staining agents that interact variably with restorative materials.^{15,16} Consequently, beverage exposure is a critical extrinsic determinant of porcelain color stability, with the extent of chromatic change depending on both the beverage type and the duration of contact. Long-term or repeated immersion can produce measurable shifts from the restoration's baseline shade.^{11,17,18}

The CIE L*a*b* color system rooted in the trichromatic theory that visual perception relies on three retinal receptors, remains a principal framework for quantifying color. Within this system, the color-difference metric ΔE expresses the magnitude of perceived disparity between two specimens.¹⁹ Because dentistry treats color as an objective parameter rather than a subjective impression, standardised color spaces and metrics are indispensable for assessing the optical performance of restorative materials. Among the most widely adopted models, the Munsell system characterises hue, value, and chroma, whereas CIELab locates color along the L* (lightness), a* (red-green), and b* (yellow-blue) axes.¹⁹ ΔE is a unit used to quantify color differences between two shades. This term is mainly used in dentistry and other esthetic related disciplines to evaluate the color compatibility of restorations with natural teeth. The calculation of ΔE is performed using a color system.^{19,20} Nevertheless, ΔE does not account for the human eye's non linear response to chromatic variation. To remedy this limitation, the CIE introduced the CIEDE2000 (ΔE_{00}) equation, an improved metric derived from CIELAB coordinates that compensates for perceptual non-uniformities and is now the recommended standard for evaluating color differences.²¹ Within the CIELab and CIEDE2000 color systems, chromatic discrepancies are quantified with the ΔE and ΔE_{00} formulas, respectively. Although ΔE_{00} correlates more closely with human visual perception, ΔE remains the preferred metric in

clinical dentistry because of its computational simplicity and widespread familiarity.¹⁹ In practical terms, ΔE thresholds of 1.2 and 2.7 have been proposed for 50% perceptibility and acceptability, respectively, whereas the corresponding ΔE_{00} thresholds are 0.8 and 1.8.²¹

Consequently, accurate intraoral shade selection and meticulous communication with the laboratory are essential for ensuring the final restoration falls within these clinically acceptable limits.

Table 1. Instructions and manufacturer information of polishing procedures.

Group	Material	Manufacturer	Instruction
Katana HT	High-translucency yttria-stabilized zirconia (Y-TZP)	Kuraray Noritake Dental, Kurashiki, Japan	
GC Initial Zirkonia Disk HT	High-translucency yttria-stabilized zirconia (Y-TZP)	GC Corporation, Tokyo, Japan	
Control	IPS Ivocolor Glaze Paste	Ivoclar Vivadent AG, Schaan, Liechtenstein	-
Re-Glaze	IPS Ivocolor Glaze Paste	Ivoclar Vivadent AG, Schaan, Liechtenstein	-
Meisinger	Meisinger Luster Extraoral Twist Kit	Hager & Meisinger, Neuss, Germany	Respectively; green-blue-red-yellow rubbers without water cooling
OptraFine	OptraFine Assortment Kit	Ivoclar Vivadent AG, Schaan, Liechtenstein	blue-dark blue under water cooling after OptraFine HP Polishing Paste (Ivoclar Vivadent AG) without water cooling

This study extends beyond most studies in the literature by simultaneously analysing how four polishing protocols and two commonly consumed beverages interact to affect two monolithic zirconia materials. Its principal novel contribution is the dual assessment of color change using both the CIELab (ΔE) and CIEDE2000 (ΔE_{00}) metrics, with results interpreted against established perceptibility and acceptability thresholds. This paired evaluation offers clinicians concrete, comparable evidence for deciding which formula should serve as their reference standard. This study aims to quantitatively assess whether the color stability of two high translucency monolithic zirconias is altered by (i) four common finishing and polishing protocols and (ii) immersion in coffee or red wine, using both CIELab (ΔE) and CIEDE2000 (ΔE_{00}) color difference formulas. The null hypothesis of this study is that neither the type of zirconia material, the finishing and polishing procedure, the beverage, nor their interactions have a significant effect on the mean ΔE or ΔE_{00} values.

MATERIAL AND METHODS

High-translucency monolithic zirconia blocks, Katana HT (Kuraray Noritake Dental, Kurashiki, Japan) and GC Initial Zirkonia Disk HT (GC Corporation, Tokyo, Japan), were

selected as the substrate materials. An a priori power analysis performed using G*Power v3.0.10 ($f = 0.40$, power = 0.95, $\alpha = 0.05$) indicated that a minimum of seven specimens per experimental cell was required. Accordingly, 64 discs of each material ($n = 64$), resulting in a total of 128 specimens, were milled using a CAD/CAM system. Prior to densification, the green state discs were ground unidirectionally for 15 seconds under a constant hand pressure of 10 N using silicon carbide papers with grit sizes of 600, 800, and 1200 (Struers A/S, Ballerup, Denmark).²² Katana specimens were sintered in a Tegra Speed furnace (Teknik Dental, Istanbul, Turkey) at 1515 °C with a holding time of 90 minutes, followed by cooling to 800 °C. GC specimens were sintered in the same furnace according to the manufacturer's recommendations: heating to 1000 °C for 2 hours, ramping to 1450 °C over 4.5 hours, holding at 1450 °C for 2 hours, and cooling to 1000 °C. After sintering, all specimens had final dimensions of 15 mm in diameter and 1.2 mm in thickness, which were verified using a digital micrometer (Table 1).

A thin glaze layer (IPS Ivocolor Glaze Paste, Ivoclar-Vivadent) was applied to the occlusal surface of each disc and fired in a Vacumat 6000 MP furnace (VITA Zahnfabrik; drying 403 °C, closing delay 6 min, heating rate 45 °C min⁻¹, peak 710 °C, vacuum released at

450 °C). To standardize the surface condition prior to the application of different polishing protocols, the initial glaze layer was intentionally removed. This procedure was performed to eliminate the potential masking effect of the original glaze and to ensure that all specimens started from a comparable surface state, allowing a reliable evaluation of the independent effects of re-glazing and mechanical polishing procedures on color stability. To remove glaze layer, a 100 µm diamond bur (Komet Z877K; Ø 5 mm, L 11 mm) mounted in a laboratory handpiece was run at 10 000 min⁻¹ under constant pressure; a new bur was used for every group.. Discs were then randomised into four study groups:

1. Control – glazed, no further treatment.
2. Re-glaze – surface abrasion followed by re-glazing.
3. Meisinger – surface abrasion plus polishing with Meisinger Luster Extraoral Twist kit (Hager & Meisinger, Neuss, Germany).
4. Optra-fine – surface abrasion plus polishing with Optra-fine kit and paste (Ivoclar-Vivadent, Schaan, Liechtenstein).

Baseline color coordinates were recorded using a spectrophotometer in “single-tooth” mode (VITA Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany) against a neutral gray background with the following CIELab coordinates: $L = 50.2$, $a = 0.1$, and $b^* = -0.3^{**}$. All color measurements were performed under dry conditions, with the specimens placed directly on the background surface, and no coupling medium was used during the measurements. Specimens were immersed for 28 days in one of two freshly prepared beverages: coffee (2 g of Nescafé Classic dissolved in 150 mL of boiling distilled water; pH = 5.50) or red wine (DLC Öküzgözü 2009; pH = 3.28). To ensure that only one surface was exposed to the staining solutions, the nontreated (intaglio) surfaces of the specimens were embedded in modeling wax, leaving the treated surfaces fully exposed to the beverages throughout the immersion period. All specimens were stored at a constant temperature of 37 °C to simulate oral conditions. The beverage solutions were renewed every 24 hours under identical conditions to minimize

variations in concentration and temperature during the aging process. No chemical stabilizers or oxidation–reduction agents were added to the solutions. After each 24-hour immersion cycle, the specimens were removed from the beverages, rinsed thoroughly with distilled water to eliminate residual staining agents, and gently air-dried. At the end of the 28-day immersion period, final color measurements were obtained under standardized conditions.

CIELab color difference was calculated as

$\Delta E_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ where ΔL^* , Δa^* , and Δb^* are the differences in lightness, green-red, and blue-yellow coordinates, respectively where ΔL^* , Δa^* , and Δb^* denote lightness, green-red, and blue-yellow differences, respectively.^{23,24} CIEDE 2000 color difference was determined by

$\Delta E_{00} = [(\Delta L'/K_L S_L)^2 + (\Delta C'/K_C S_C)^2 + (\Delta H'/K_H S_H)^2 + RT(\Delta C'/K_C S_C)(\Delta H'/K_H S_H)]^{1/2}$ where ΔL_0 , ΔC_0 , and ΔH_0 are the differences in lightness, chroma, and hue between the two specimens that were compared. S_L , S_C , and S_H are the weighting functions for the lightness, chroma, and hue components, respectively. K_L , K_C , and K_H are the parametric factors to be adjusted according to different viewing parameters. In the current study, K_L , K_C , and K_H were set to 1.²⁵

Normality and homoscedasticity were confirmed by Shapiro–Wilk and Levene tests ($\alpha = 0.05$). A three-way ANOVA evaluated the effects of zirconia material (Katana, GC), polishing procedure (Control, Re-glaze, Meisinger, Optra-fine) and beverage (wine, coffee) on both ΔE and ΔE_{00} . Significant main or interaction terms were explored with Tukey’s HSD post-hoc test. Statistical significance was set at $p < 0.05$.

RESULTS

Table 2 presents the mean and standard deviation values of color changes measured using the CIEDE2000 (ΔE_{00}) and CIELab (ΔE_{ab}) color difference formulas for all study groups. For ΔE_{00} , three-way ANOVA revealed that material type ($F = 76.239$; $p < 0.001$) and beverage type ($F = 62.230$; $p < 0.001$) significantly affected color change, whereas the polishing procedure alone did not show a

significant main effect ($p = 0.429$). However, significant interaction effects were observed for material $\times$ polishing procedure ($p = 0.008$),

material $\times$ beverage ($p < 0.001$), and material $\times$ polishing procedure $\times$ beverage ($p = 0.001$) (Table 3).

Table 2. ΔE_{00} and ΔE values after beverage immersion and distribution of all study groups according to clinical acceptability thresholds

Material	Polishing	Beverage	ΔE_{00} (Mean $\pm$ SD)	ΔE (Mean $\pm$ SD)
GC	Control	Coffee	$2.59 \pm 0.83^*$	$3.31 \pm 1.02^*$
GC	Control	Wine	$4.13 \pm 3.60^*$	$4.33 \pm 3.38^*$
GC	Re-glaze	Coffee	$2.87 \pm 1.58^*$	$3.71 \pm 2.05^*$
GC	Re-glaze	Wine	$2.59 \pm 1.61^*$	$3.79 \pm 2.56^*$
GC	Meisinger	Coffee	$4.56 \pm 0.09^*$	$5.65 \pm 0.03^*$
GC	Meisinger	Wine	$2.95 \pm 0.60^*$	$4.52 \pm 0.89^*$
GC	OptraFine	Coffee	$2.86 \pm 0.93^*$	$3.49 \pm 1.20^*$
GC	OptraFine	Wine	$2.89 \pm 1.01^*$	$4.35 \pm 1.47^*$
Katana	Control	Coffee	0.76 ± 0.28	1.18 ± 0.58
Katana	Control	Wine	0.94 ± 0.41	1.81 ± 0.59
Katana	Re-glaze	Coffee	0.50 ± 0.11	0.83 ± 0.21
Katana	Re-glaze	Wine	$2.65 \pm 0.94^*$	$3.94 \pm 1.45^*$
Katana	Meisinger	Coffee	0.84 ± 0.57	1.41 ± 0.88
Katana	Meisinger	Wine	$2.13 \pm 0.36^*$	$3.60 \pm 0.88^*$
Katana	OptraFine	Coffee	0.81 ± 0.36	1.70 ± 1.10
Katana	OptraFine	Wine	$2.60 \pm 0.53^*$	4.61 ± 0.21

Indicates clinically unacceptable value ($\Delta E > 2.7$, $\Delta E_{00} > 1.8$).

Table 3. ΔE_{00} values according to three-way ANOVA test

ΔE_{00} (CIEDE 2000)				
	df	Mean Square	F	Sig.
Material	1	77.979	76.239	0.000
Polishing procedure	3	0.948	0.926	0.429
Beverage	2	63.650	62.230	0.000
Material*polishing procedure	3	4.133	4.041	0.008
Material*Beverage	2	20.187	19.737	0.000
Polishing procedure*Beverage	6	1.714	1.676	0.130
Material*Polishing procedure*Beverage	6	3.959	3.871	0.001

The mean ΔE_{00} was 1.40 ± 0.79 for Katana and 3.18 ± 1.59 for GC; thus, GC discs underwent markedly greater color change than Katana discs ($p < 0.001$). Red wine resulted in greater color change (2.61 ± 1.66) compared with coffee (1.97 ± 1.15) ($p < 0.001$). Among the polishing procedures, the highest mean value was observed in the Meisinger group (2.62 ± 1.83) and the lowest in the Re-Glaze group (2.15 ± 1.32), although the difference was not statistically significant ($p = 0.429$). The highest ΔE_{00} value was observed in the GC–

Meisinger–coffee group (4.56 ± 0.09), whereas the lowest was recorded in the Katana–re-glaze–coffee group (0.50 ± 0.11).

For ΔE values, beverage ($F = 88.868$; $p < 0.001$), material ($F = 54.614$; $p < 0.001$), and polishing procedure ($p = 0.028$) showed significant main effects. Significant interactions were also observed for material $\times$ polishing ($p = 0.008$), material $\times$ beverage ($p < 0.001$), and polishing $\times$ beverage ($p = 0.026$), while the three-way interaction was borderline significant ($p = 0.057$) (Table 4).

Table 4. ΔE values according to three-way ANOVA test

	ΔE (CIEDE2000)			
	df	Mean Square	F	Sig.
Material	1	83.820	54.614	0.000
Polishing procedure	3	4.765	3.104	0.028
Beverage	2	136.392	88.868	0.000
Material*Polishing procedure	3	6.226	4.057	0.008
Material * Beverage	2	25.240	16.446	0.000
Polishing Procedure*Beverage	6	3.775	2.460	0.026
Material*Polishing procedure*Beverage	6	3.202	2.087	0.057

GC Initial HT demonstrated higher mean ΔE values (4.15 ± 2.05) than Katana HT (2.39 ± 1.35) ($p < 0.001$). Wine (3.87 ± 2.14) led to a more pronounced color loss than coffee (2.66 ± 1.63) ($p < 0.001$). The highest ΔE value occurred in the GC–Meisinger–coffee subgroup (5.65 ± 0.03), while the lowest was observed in the Katana–re-glaze–coffee subgroup (0.83 ± 0.21).

DISCUSSION

The aim of this study was to evaluate the color stability of two high translucency monolithic zirconia materials following different finishing and polishing protocols and immersion in two commonly consumed beverages using both CIELab (ΔE) and CIEDE2000 (ΔE_{00}) color difference formulas. By assessing color changes against clinically accepted perceptibility and acceptability thresholds, the study sought to provide a dual metric comparison that would guide clinicians in selecting both material and surface treatment protocols to optimize esthetic outcomes. The null hypothesis of this study was partially rejected. Statistical analyses revealed that both zirconia material and beverage type significantly influenced color changes in both ΔE and ΔE_{00} measurements. While the polishing procedure did not independently affect ΔE_{00} values, it showed a significant effect on ΔE results. In particular, the three-way ANOVA results demonstrated that not only the main effects of material and beverage, but also their interactions with the finishing and polishing protocols, had a significant impact on color stability. This finding indicates a complex interplay among these factors in determining color stability. Therefore, the results should be interpreted primarily at the subgroup level rather than solely based on the overall mean

values of individual factors.

The findings of this study revealed that the type of zirconia material had a statistically significant effect on color stability, with GC Initial HT zirconia showing higher ΔE and ΔE_{00} values compared to Katana HT after immersion in staining solutions. This result suggests that microstructural differences between brands, such as the proportion of cubic and tetragonal phases, coloring techniques, and translucency levels, play a pivotal role in discoloration susceptibility. Supporting this, Saker et al.²⁶ emphasized that the surface finish interacts with the material's inherent characteristics to influence its optical durability, with higher translucency zirconia being more vulnerable to staining despite its esthetic benefits. This aligns with our study's finding that GC Initial HT, presumably exhibiting higher translucency, was more prone to color change than Katana HT. Additionally, Abdelhafez et al.¹⁵ found material specific differences in response to common beverages, where zirconia's composition and surface characteristics modulated its susceptibility to discoloration, reinforcing the role of brand specific microstructure in clinical performance.

Our results indicated that the type of beverage significantly influenced the extent of color change in both zirconia materials tested, with red wine inducing markedly higher ΔE and ΔE_{00} values compared to coffee. This difference can be attributed to the more aggressive chemical composition of red wine, which includes low pH organic acids, ethanol, and high concentrations of anthocyanins—pigments with a well-documented affinity for ceramic surfaces. The acidic nature of red wine ($pH \approx 3.28$) is particularly relevant, as it can

compromise the surface integrity of glazed or polished restorations, increasing surface roughness and facilitating pigment penetration. In contrast, coffee, with a relatively higher pH (5.5) and a simpler molecular pigment profile, showed a lower staining potential. These findings are consistent with those of Abounassif et al.²⁷, red wine was consistently the most chromogenic beverage, producing the greatest ΔE_{00} shifts across various zirconia types and surface treatments. Their data revealed that specimens exposed to red wine not only showed higher color change but also crossed the clinical acceptability threshold more frequently than those immersed in coffee. Furthermore, the study by Saker et al.²⁶ confirmed that color stability of zirconia is beverage dependent, with red wine exerting the strongest staining effect regardless of the polishing method applied. Notably, samples that underwent mechanical adjustment prior to re-glazing or polishing still demonstrated perceptible discoloration following immersion in red wine, underlining the beverage's potent chromogenic capacity.

A review of the literature reveals no clear consensus on how finishing and polishing protocols affect the color stability of zirconia ceramics. Whereas several authors have reported statistically significant inter protocol differences, especially between glazed and mechanically polished surfaces²⁷⁻³⁰, other investigations have found no such effect.^{4,31,32} In this study, although the polishing protocol did not show a statistically significant main effect on ΔE_{00} values, it significantly affected ΔE results. This discrepancy may reflect the ΔE_{00} formula's enhanced sensitivity to perceptual differences and its relative robustness against overestimation of minor variations. Among the four tested protocols, the Meisinger polished group exhibited the highest degree of color change, whereas the re-glazed group consistently showed the lowest values in both metrics. This suggests that mechanical polishing, despite being practical in clinical settings, may not restore the same level of surface smoothness or glaze like integrity, making the surface more receptive to staining agents. It is well documented that surface roughness plays a direct role in stain

accumulation; even microscopic grooves can harbor chromogenic compounds, leading to increased discoloration over time. Re-glazing, on the other hand, creates a uniform, glassy barrier that enhances stain resistance. Accordingly, interpreting polishing methods or materials solely based on their overall mean values may be misleading, as the magnitude and clinical relevance of color change depend largely on the specific combination of material, surface treatment, and staining medium.

Consistent with previous studies, this study's statistical analysis uncovered multiple significant two-way and three-way interactions in both the ΔE_{00} and ΔE datasets.^{4,27} These findings demonstrate that color stability is not solely dependent on individual factors but on how these variables interact. This supports the notion of a synergistic effect: a more stain prone material, when polished inadequately and exposed to a chromogenic beverage, undergoes amplified color degradation. These complex interactions highlight the importance of adopting a holistic approach in restorative treatment planning, one that considers not only the material and finishing method but also the patient's dietary habits and oral environment. For instance, although the polishing procedure did not demonstrate a significant main effect on ΔE_{00} values, its influence became evident when evaluated in combination with material type and beverage. Specifically, higher color change values observed in certain GC subgroups, such as the Meisinger-coffee combination, indicate that the effect of polishing cannot be interpreted independently from the material-beverage interaction. This finding highlights the importance of interaction-based interpretation when evaluating color stability outcomes.

In the current study, both the CIELab (ΔE) and CIEDE2000 (ΔE_{00}) formulas were employed to assess the extent of color change in monolithic zirconia samples, enabling a dual evaluation approach aligned with international recommendations. Consistent with the findings of Paravina et al.²¹, our results confirmed that ΔE values were systematically higher than ΔE_{00} values across nearly all groups. While this discrepancy is mathematically expected due to the perceptual adjustments built into the ΔE_{00}

formula, its clinical implications are significant. For example, in several subgroups, particularly the GC–Meisinger–coffee and GC–Optra–fine–wine combinations, ΔE values exceeded the clinical acceptability threshold of 2.7, suggesting a potentially unacceptable color shift. However, the corresponding ΔE_{00} values for these same groups remained below or near the 1.8 acceptability threshold, indicating that the perceived color difference might still fall within clinically tolerable limits. This divergence underscores the importance of metric selection when interpreting color stability data. The ΔE formula, although widely used for its computational simplicity, may exaggerate the visual impact of subtle color changes, potentially leading clinicians to overestimate the esthetic failure risk. In contrast, the ΔE_{00} formula incorporates human perceptual non linearity, weighting differences in lightness, chroma, and hue according to their visibility, and thus offers a more realistic representation of what patients actually perceive. Accordingly, our study supports the growing consensus in the literature that ΔE_{00} should be prioritized in research and clinical reporting where perceptual accuracy is critical. However, given that ΔE continues to be the default reference in many clinical tools and laboratory workflows, presenting both metrics, as done here, provides a comprehensive framework for evaluating and communicating color stability outcomes in zirconia restorations.

In light of these findings, the choice of color difference formula is not merely a methodological consideration but a clinically impactful decision. The CIELab (ΔE) system remains widely used in dental laboratories and spectrophotometric devices due to its computational simplicity and long standing familiarity. However, it does not account for the nonlinear nature of human color perception, often exaggerating minor chromatic variations that may not be clinically relevant.^{21,33} In contrast, the CIEDE2000 (ΔE_{00}) system incorporates perceptual weighting functions for lightness, chroma, and hue differences, offering a more accurate reflection of what the human eye can perceive.^{21,33} Therefore, in high esthetic demand cases, particularly anterior restorations,

ΔE_{00} provides a more clinically meaningful assessment of color stability. Conversely, in routine monitoring or situations where device interfaces default to ΔE , this traditional metric may still serve a pragmatic role for quick evaluations. Our findings support the recommendation that both ΔE and ΔE_{00} should be reported in tandem, as this dual metric approach enables a more comprehensive and clinically grounded evaluation of color changes in zirconia based restorations. This study has some limitations. Since it was conducted in vitro, it does not fully reflect the real conditions in the mouth, such as saliva, chewing forces, and temperature changes. The 28 day immersion period simulates aging but may not directly represent long term clinical exposure. Surface roughness (Ra) and glaze layer thickness were not measured in the present study. In addition, microstructural characteristics such as phase composition and translucency parameters were not directly evaluated. As these parameters may influence staining susceptibility, future studies are recommended to include microstructural characteristics and surface roughness analyses and standardized evaluation of glaze layer thickness to support and expand the present findings. Also, only two types of zirconia and two beverages were tested, so the results may not apply to all materials or dietary habits. Lastly, surface roughness was not measured, which could have helped explain the staining differences. Future studies should include more materials, beverages, and in vivo conditions for a more comprehensive evaluation.

CONCLUSION

Within the limitations of this in vitro study, the color stability of high-translucency monolithic zirconia was significantly influenced by the zirconia brand and the type of staining beverage, whereas the effect of polishing protocol depended on the color-difference metric employed. The dual-metric assessment demonstrated that ΔE values were consistently higher than ΔE_{00} values, highlighting the importance of metric selection when interpreting color changes. Considering the study findings, re-glazing procedures demonstrated more favorable color stability and

may be preferred in high-esthetic-demand areas. Additionally, zirconia materials exhibiting lower susceptibility to discoloration, such as Katana HT in the present study, may be more suitable for patients with frequent consumption of chromogenic beverages such as coffee or red wine. In such individuals, surface treatment protocols that enhance surface integrity may provide more favorable color stability outcomes. Future in vivo studies incorporating salivary dynamics, masticatory forces, and extended aging periods are warranted to validate and expand upon these results.

Ethical Approval

Ethical approval was not required for this study as no human or animal materials were used.

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Conflict of Interest

The authors deny any conflicts of interest related to this study.

Author Contributions

Design: NKA, NY, Data collection or access: NKA, Analysis and comments: NKA, Literature search: NKA, NY, Writing: NKA.

REFERENCES

1. Acar NK, Sengul F, Bardakci E, Celikel P. Assessing the accuracy, reliability, quality, and readability of artificial intelligence chatbots in patient education: insights from zirconia crowns. *BMC Oral Health*. 2026;26:502.
2. Spitznagel F, Boldt J, Gierthmuehlen P. CAD/CAM ceramic restorative materials for natural teeth. *J Dent Res*. 2018;97:1082-91.
3. Skorulska A, Piszko P, Rybak Z, Szymonowicz M, D et al. Review on polymer, ceramic and composite materials for cad/cam indirect restorations in dentistry—Application, mechanical characteristics and comparison. *Mater*. 2021;14:1592.
4. Lassila L, Uctasli MB, Wada K, Vallittu PK, et al. Effect of different beverages and polishing techniques on colour stability of CAD/CAM composite restorative materials. *Biomater Invest Dent*. 2024;11:40591.
5. Van Zeghbroeck L. CAD/CAM treatment for the elderly—a case report. *Gerodontology*. 2012;29:e1176-79.
6. Pecho OE, Ghinea R, Ionescu AM, Cardona JC, et al. Optical behavior of dental zirconia and dentin analyzed by Kubelka–Munk theory. *Dent Mater*. 2015;31:60-7.
7. Ozdogan A, Kaya N. Effectiveness and safety of bleaching agents on lithium disilicate glass ceramics. *J Dent Res Dent Clin Dent Prospects*. 2022;16:251–7.
8. Kim I-J, Lee Y-K, Lim B-S, Kim C-W. Effect of surface topography on the color of dental porcelain. *J Mater Sci: Mater Med*. 2003;14:405-9.
9. Abu-Obaid Aa, AlMawash A, Alyabis N, Alzaaqa N. An in vitro evaluation of the effect of polishing on the stainability of different CAD/CAM ceramic materials. *Saudi Dent J*. 2020;32:135-41.
10. Kiliç Avşar M, Bolayir G, Saygin A, Ulucan MÇ. Investigation of colour and surface changes of ceramic CAD/CAM blocks with different surface treatments after immersion to different beverages. *J Aust Ceram*. 2022;58:901-11.
11. Sarac D, Sarac YS, Yuzbasioglu E, Bal S. The effects of porcelain polishing systems on the color and surface texture of feldspathic porcelain. *J Prosthet Dent*. 2006;96:122-28.
12. Preston J. Perspectives in dental ceramics. *Quintessence*; 1988:331-43.
13. Sağlam G, Cengiz S. The Evaluation of the Effect of Coffee Staining and 16% Carbamide Peroxide Bleaching on the Color Change of Chairside CAD/CAM Ceramics. *J Dent Mater Tech*. 2021;10
14. Priya KS, Kumar MP, Krishna VP, Lakshmaiah P, et al. Effect of Acidic Agents on Microhardness and Surface Morphology of Two Metal Ceramic Materials: An In Vitro Study. *J Contemp Dent Pract*. 2019;20:1329-34.

15. Abdelhafez MHA, Abu-Eittah MRH. Effect of Common Staining Beverages on Color Stability of Polymer-infiltrated Ceramics and Extra Translucent Zirconia: An In Vitro Study. *J Contemp Dent Pract*. 2024;25:411-16.
16. Ozkanoglu S, Akin E. Evaluation of the effect of various beverages on the color stability and microhardness of restorative materials. *Niger J Clin Pract*. 2020;23:322-28.
17. Sarıkaya I, Yerliyurt K, Hayran Y. Effect of surface finishing on the colour stability and translucency of dental ceramics. *BMC oral health*. 2018;18:1-8.
18. Saba DA, Salama RA, Haridy R. Effect of different beverages on the color stability and microhardness of CAD/CAM hybrid versus feldspathic ceramic blocks: An in-vitro study. *Future Dent J*. 2017;3:61-6.
19. Joiner A. Tooth colour: a review of the literature. *J Dent*. 2004;32:3-12.
20. Pekkan G, Pekkan K, Bayindir BÇ, Özcan M, et al. Factors affecting the translucency of monolithic zirconia ceramics: A review from materials science perspective. *Dent Mater J*. 2020;39:1-8.
21. Paravina RD, Ghinea R, Herrera LJ, Bona AD et al. Color difference thresholds in dentistry. *J Esthet Restor Dent*. 2015;27:1-9.
22. Mohammadi-Bassir M, Babasafari M, Rezvani MB, Jamshidian M. Effect of coarse grinding, overglazing, and 2 polishing systems on the flexural strength, surface roughness, and phase transformation of yttrium-stabilized tetragonal zirconia. *J Prosthet Dent*. 2017;118:658-65.
23. Colorimetry C. official recommendations of the International Commission on Illumination. Publication CIE No 152. 1986
24. Standard C. Colorimetry-part 4: CIE 1976 L* a* b* colour space. International Standard. 2007:2019-06.
25. Luo MR, Cui G, Rigg B. The development of the CIE 2000 colour-difference formula: CIEDE2000. *Color Research & Application: Endorsed by Inter-Society Color Council, The Colour Group (Great Britain), Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, The Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de la Couleur*. 2001;26:340-50.
26. Saker S, Özcan M. Effect of surface finishing and polishing procedures on color properties and translucency of monolithic zirconia restorations at varying thickness. *J Esthet Restor Dent*. 2021;33:953-63.
27. Abounassif FM, Alfaraj A, Gadah T, Yang CC, et al. Color stability of precolored and extrinsically colored monolithic multilayered polychromatic zirconia: Effects of surface finishing and aging. *J Prosthodont*. 2024
28. da Silva AO, Fiorin L, Faria ACL, Ribeiro RF, et al. Translucency and mechanical behavior of partially stabilized monolithic zirconia after staining, finishing procedures and artificial aging. *Sci Rep*. 2022;12:16094.
29. Yıldırım AZ, Sönmez A, Karagülleoğlu ZY, Duman AN. Yapay Yaşlandırma İşleminin Monolitik Zirkonyaların Renk Stabilitesi ve Translucensi Özelliklerine Etkileri. *Selcuk Dent J*. 2025;12:48-53.
30. Kim H-K, Kim S-H, Lee J-B, Han J-S, et al. Effect of polishing and glazing on the color and spectral distribution of monolithic zirconia. *J Adv Prosthodont*. 2013;5:296-304.
31. Soares PM, Zucuni CP, Ilha BD, Jacques LB, et al. Optical properties and color stability of a translucent zirconia: effects of finishing after grinding. *Braz Dent J*. 2024;35:e24-6094.
32. Akkal O, Yilmaz ZS. Color Changes of Restorative Materials with Different Surface Finishing Processes Applied and Kept in Different Solutions. *Int J Prosthodont Restor Dent*. 2020 Sep 1;10:115-21.
33. Lee Y-K. Comparison of CIELAB ΔE^* and CIEDE2000 color-differences after polymerization and thermocycling of resin composites. *Dent Mater*. 2005;21:678-82.