

## Assessment of Color Accuracy in A2-Shade Composite Resins Using CIEDE2000: Conventional and 3D-Printed Materials

### CIEDE2000 Kullanılarak A2 Tonundaki Kompozit Resinlerde Renk Doğruluğunun Değerlendirilmesi: Geleneksel ve 3D Baskılı Materyaller

#### ABSTRACT

**Objective:** To compare the Commission Internationale de l'Éclairage (CIE) L\*, a\*, and b\* color parameters of various three dimensional (3D)-printed and direct composite resins, all labeled with the A2 shade, and to evaluate whether their color differences ( $\Delta E_{00}$ ) relative to the VitaPan Classical A2 shade tab reference remain within clinically acceptable thresholds.

**Materials and Method:** Three direct resin composites and two ceramic-filled 3D-printed crown resins were evaluated. For each material, six disc-shaped specimens (10 mm × 2 mm) were fabricated, all corresponding to the Vita A2 shade. Color measurements were obtained using a spectrophotometer within the CIE L\*a\*b\* color space. Color differences relative to the VitaPan Classical A2 shade tab were calculated employing the CIEDE2000 formula ( $\Delta E_{00}$ ). Statistical analyses were conducted using one-way ANOVA, followed by Bonferroni and Games-Howell post hoc tests ( $p < 0.05$ ).

**Results:** Significant differences were observed among the materials with respect to L\*, a\*, b\*, and  $\Delta E_{00}$  values ( $p < 0.001$ ). Crowntec exhibited the highest L\* value, whereas Charisma Smart demonstrated the highest a\* value. Charisma Smart, Crowntec, and Permanent Crown presented higher b\* values compared to Estelite Sigma Quick and Filtek Z250. Although Filtek Z250 and Estelite Sigma Quick displayed comparable  $\Delta E_{00}$  values, only Filtek Z250 remained below the clinical acceptability threshold ( $\Delta E_{00} < 1.8$ ), indicating an acceptable color match with the VitaPan Classical A2 shade tab.

**Conclusion:** Resin-based materials labeled as A2 showed significant differences in L\*, a\*, b\*, and  $\Delta E_{00}$  values, indicating that the A2 shade label does not ensure an acceptable color match with the VitaPan Classical A2 shade tab, as only Filtek Z250 exhibited  $\Delta E_{00}$  values below the threshold for acceptability.

**Key Words:** Three-Dimensional Printing, Composite Resins, Color, VitaPan Classical A2, CIEDE2000; Dental Materials.

#### ÖZ

**Amaç:** Bu çalışma, tümü A2 tonuyla etiketlenmiş çeşitli üç boyutlu (3B) baskılı ve direkt kompozit rezinlerin Commission Internationale de l'Éclairage (CIE) L\*, a\* ve b\* renk parametrelerini karşılaştırmayı ve VitaPan Classical A2 referans standardına göre renk farklılıklarının ( $\Delta E_{00}$ ) klinik olarak kabul edilebilir eşik değeri içinde kalıp kalmadığını değerlendirmeyi amaçlamıştır.

**Gereç ve Yöntemler:** Üç direkt kompozit rezin ve iki seramik dolgulu 3B baskılı kuron rezini değerlendirilmiştir. Her malzeme için, Vita A2 tonuna karşılık gelen altı adet disk şeklinde numune (10 mm × 2 mm) üretilmiştir. Renk ölçümleri, CIE L\*a\*b\* renk uzayında bir spektrofotometre kullanılarak elde edildi. VitaPan Classical A2 standardına göre renk farklılıkları, CIEDE2000 formülü ( $\Delta E_{00}$ ) kullanılarak hesaplandı. İstatistiksel analizler tek yönlü ANOVA kullanılarak gerçekleştirilmiş, ardından Bonferroni ve Games-Howell post hoc testleri uygulanmıştır ( $p < 0,05$ ).

**Bulgular:** L\*, a\*, b\* ve  $\Delta E_{00}$  değerleri açısından malzemeler arasında önemli farklılıklar gözlemlenmiştir ( $p < 0,001$ ). Crowntec en yüksek L\* değerini gösterirken, Charisma Smart en yüksek a\* değerini göstermiştir. Charisma Smart, Crowntec ve Permanent Crown, Estelite Sigma Quick ve Filtek Z250'ye kıyasla daha yüksek b\* değerleri sergilemiştir. Filtek Z250 ve Estelite Sigma Quick benzer  $\Delta E_{00}$  değerleri sergilemiş olsa da, sadece Filtek Z250 klinik kabul edilebilirlik eşliğinin altında kalarak ( $\Delta E_{00} < 1,8$ ), VitaPan Classical A2 tonuyla kabul edilebilir bir renk uyumu olduğunu göstermiştir.

**Sonuç:** A2 olarak etiketlenen rezin bazlı malzemeler L\*, a\*, b\* ve  $\Delta E_{00}$  değerlerinde önemli farklılıklar göstermiştir. Bu, A2 renk etiketinin VitaPan Classical A2 rengiyle kabul edilebilir bir renk uyumu sağlamadığını göstermektedir, çünkü sadece Filtek Z250 kabul edilebilirlik eşliğinin altında  $\Delta E_{00}$  değerleri sergilemiştir.

**Anahtar Kelimeler:** Üç Boyutlu Yazıcı, Kompozit Resinler, Renk, VitaPan Klasik A2, CIEDE2000, Dental Materyaller.

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## INTRODUCTION

Currently, for teeth exhibiting substantial material loss, research efforts concentrate on improving the optical properties of direct composites and resin-based permanent restorations fabricated through three-dimensional (3D) printing, while considering both structural integrity and aesthetic requirements. The clinical application of these advanced materials is particularly prominent in the restoration of teeth with extensive structural damage, especially those that have undergone endodontic treatment. The restoration of teeth following root canal treatment presents a complex clinical challenge, as the long-term success of treatment is significantly influenced by the quality and integrity of the coronal restoration, which often surpassing the procedural success of the root canal treatment itself (1). Beyond mechanical durability, aesthetic outcomes critically depend on the restorative material's ability to mask discolored dentin or internal stains resulting from endodontic treatment; this ability is intrinsically linked to the material's optical properties (2). Therefore, the restorative material must not only provide adequate structural reinforcement to withstand occlusal forces but also maintain a stable and optimized color profile to ensure seamless esthetic integration. Precise and objective characterization of the initial  $L^*$ ,  $a^*$ , and  $b^*$  color coordinates of the materials under investigation is essential for predicting both the aesthetic prognosis and overall treatment success, particularly in patients with structurally compromised dentition (3). The color of natural teeth or restorations is quantitatively characterized using the parameters of the CIE-Lab color space (Commission Internationale de l'Éclairage, 1971), which comprise  $L^*$  (lightness),  $a^*$  (chroma along the red-green axis), and  $b^*$  (chroma along the yellow-blue axis) (4). In 2001, the CIE introduced the CIEDE2000 color difference formula to enhance the accuracy of correlating perceived and measured color differences, thereby addressing the limitations inherent in the CIE  $L^*a^*b^*$  system established in 1976 (5, 6). The determination of color difference relies on the visual perception of changes in an object's color values and the assessment of color changes that affect esthetic appearance. The color difference value at which 50% of observers perceive a visible change is defined as the 50% perceptibility threshold. Similarly, the color difference value considered clinically acceptable by 50% of observers is termed the 50% acceptability threshold (7). Spectrophotometry remains the gold standard for the precise and reproducible measurement of color parameters and serves as a fundamental basis for evaluating color matching capabilities and long-term color stability (8, 9).

The field of restorative materials is undergoing rapid technological advancements, particularly with the emergence of high-performance permanent composite resins fabricated through additive manufacturing. Although direct resin composites have traditionally served as the primary materials for intraoral restorations, the new generation of 3D-printed resins offers distinct structural and compositional advantages. Therefore, a systematic and quantitative comparison of the fundamental intrinsic color parameters ( $L^*$ ,  $a^*$ , and  $b^*$ ) between these two categories of restorative materials is essential for evidence-based clinical decision-making. The materials selected for this study represent a comprehensive range of both conventional and advanced restorative solutions, which differ fundamentally in their manufacturing processes and compositions. Light-cured direct resin composite materials comprise a polymer matrix reinforced with various inorganic filler systems; the specific size, refractive index, and distribution of these filler particles significantly influence the material's optical properties by affecting light scattering and absorption. These factors ultimately determine the material's final CIE  $L^*$ ,  $a^*$ , and  $b^*$  color parameters, as well as its translucency (10, 11). In contrast, ceramic-filled permanent crown 3D-printed resins exhibit a high degree of polymerization conversion, elevated ceramic filler loading, and low water absorption. These characteristics are specifically engineered to enhance mechanical strength and long-term color stability compared to traditional composites. A limited number of studies in the literature have compared the differences in the CIE  $L^*$ ,  $a^*$ , and  $b^*$  color parameters of resin-based restorative materials fabricated using various techniques and evaluated whether their optical properties are clinically acceptable. The purpose of this in vitro study was to compare the CIE  $L^*$ ,  $a^*$ , and  $b^*$  color coordinates of conventional and 3D-printed resin-based restorative materials labeled as A2 shade and to evaluate their color differences ( $\Delta E_{00}$ ) relative to the VitaPan Classical A2 shade reference using the CIEDE2000 formula, with interpretation based on the established acceptability threshold under standardized experimental conditions. The null hypothesis posited that resin-based restorative materials designated with the same shade (A2) would not differ in their CIE  $L^*$ ,  $a^*$ , and  $b^*$  color parameters, and that the color differences ( $\Delta E_{00}$ ) relative to the VitaPan Classical A2 shade tab would remain within clinically acceptable thresholds.

The minimum specimen size for one-way analysis of variance (ANOVA) was calculated using G\*Power 3.1.9.7 software. With a Type I error rate ( $\alpha$ ) of 0.05, power of 0.95, and an effect size (Cohen's  $f$ ) of 1.31 from Melara et al. (12), the analysis indicated 20 specimens (4 per group) were sufficient. However, this study used six specimens per group ( $n=6$ ) to ensure adequate power.

Table 1 ( $n=6$ ) presents the composition of packable composites and additive manufacturing resins, all in Vita A2 shade. Estelite Sigma Quick (Tokuyama, Tokyo, Japan), Charisma Smart (Heraeus Kulzer, Hanau, Germany), and Filtek Z250 (3M-ESPE, St Paul, MN, USA) were molded into 10 mm diameter, 2 mm thick silicone molds, placed between glass slides with semi-transparent Mylar strips. Specimens were light-cured for 10 seconds at a 1 mm distance using a high-power LED unit (Ba International Ultimate Base 290, BA International, Northampton, UK) with 3000 mW/cm<sup>2</sup> intensity and 380–500 nm wavelength.

Additively manufactured disc-shaped specimens (10 mm diameter, 2 mm thick) were digitally designed using ExoCAD GmbH software (Darmstadt, Germany). A 2 mm specimen thickness was selected to minimize background-related influences on color measurements, particularly those associated with material translucency. Crowntec specimens (Saremco print CROWNTEC, A2; Saremco Dental AG, Rebstein, Switzerland) were fabricated using an Asiga MAX UV printer (Asiga, Alexandria, NSW, Australia). After printing, residual material was removed with isopropyl alcohol, and cured in an Otofash G171 device (NK Optik GmbH, Baierbrunn, Germany). Permanent Crown specimens (Permanent Crown Resin, Formlabs, Somerville, MA, USA) were fabricated using a Form 3 printer (Formlabs), washed in isopropyl alcohol tank (Form Wash, Formlabs), and cured in a FormCure device (Formlabs). Support structures were removed with a cut-off disk.

All specimens were sequentially sanded under water using 600-, 800-, 1000-, and 1200-grit silicon carbide papers and subsequently polished using a 3M™ Sof-Lex™ Diamond Polishing System (3M ESPE, Seefeld, Germany). Polishing was performed with diamond-impregnated spirals for 20 seconds per spiral using a slow-speed handpiece under water cooling (hand-polishing technique).

All specimens were prepared by a single operator, and dimensional accuracy was verified using a digital caliper (Absolute Digimatic, Mitutoyo, Japan). The specimens were then stored in distilled water for 24 hours to allow completion of polymerization and rehydration.

A spectrophotometer (VITA Easyshade® V; VITA Zahnfabrik, Bad Säckingen, Germany) measured color properties under a D65 light source against a neutral gray background. Color measurements of the specimens and the VitaPan Classical A2 reference shade tab were performed three times using the same protocol, and the arithmetic mean of the readings was recorded as the CIE L\*, a\*, and b\* coordinates, which quantify perceptible color differences. Here, L\* indicates lightness (higher values are lighter), a\* the red-green axis (positive for red, negative for green), and b\* the yellow-blue axis (positive for yellow, negative for blue). Color differences were calculated using the CIEDE2000 metric ( $\Delta E_{00}$ ), comparing each specimen to the VitaPan Classical reference via the  $\Delta E_{00}$  formula (5):

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

The CIEDE2000 (1:1:1) color difference formula, with parametric factors  $k_L$ ,  $k_C$ , and  $k_H$  set to 1, was used to calculate color change ( $\Delta E_{00}$ ). A 50% perceptibility threshold was set at 0.8, and a 50% acceptability threshold at 1.8. Color changes with  $\Delta E_{00}$  values  $\geq 1.8$  were considered clinically unacceptable (7).

L\*, a\*, b\*, and  $\Delta E$  values were compared across groups. All variables exhibited skewness and kurtosis values within  $\pm 2$ , meeting the normality assumption, so one-way ANOVA was conducted. When significant differences were identified, the Bonferroni post-hoc test was used if the homogeneity of variances assumption was met; otherwise, the Games-Howell post-hoc test was applied (SPSS v29.0, IBM Corp., Armonk, NY, USA). Statistical significance was set at  $p < 0.05$  for all analyses.

**Table 1.** Composition of the materials employed.

Brand Information	Composition
<b>Estelite® Sigma Quick</b>	<u>Matrix:</u> Bis-GMA, TEGDMA <u>Fillers:</u> Pre-polymer (particle size 2 µm), silicon-zirconia- particles (particle size 0.2 µm), 82 wt. %
<b>Charisma Smart</b>	<u>Matrix:</u> Bis-GMA, TEGDMA <u>Fillers:</u> Silicon dioxide (particle size 0.02-0.07 µm), barium glass, aluminum, fluoride (particle size 0.02-2 µm), %58-60 wt. %
<b>Filtek Z250</b>	<u>Matrix:</u> BisGMA, BisEMA, UDMA, TEGDMA <u>Fillers:</u> Zirconia, silica (particle size 0.6 µm), 82 wt. %
<b>Crowntec</b>	<u>Matrix:</u> Esterification products of 4,4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, initiators <u>Fillers:</u> Inorganic silica fillers, 30–50 wt. % (particle size 0.7 µm)
<b>Permanent Crown</b>	<u>Matrix:</u> 4,4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, methyl benzoylformate, diphenyl (2,4,6-trimethyl benzoyl) <u>Fillers:</u> Inorganic fillers, 30–50 wt. % (particle size 0.7 µm)

Abbreviations used in the table: Bis-GMA: Bisphenol A-glycidyl methacrylate, TEGDMA: Triethylene glycol dimethacrylate, Bis-EMA: Ethoxylated bisphenol A glycol dimethacrylate, UDMA: Urethane dimethacrylate.

## RESULTS

As presented in Table 2, ANOVA revealed statistically significant differences in L\* values among the materials tested ( $F = 35.983$ ,  $p < 0.001$ ). Subsequent post hoc comparisons using the Games–Howell test demonstrated that Crowntec exhibited significantly higher L\* values than all other materials. Additionally, Permanent Crown showed significantly higher L\* values than all materials except Crowntec, whereas Filtek Z250 had significantly higher L\* values than Estelite Sigma Quick. Significant differences in a\* values were observed among the materials ( $F = 51.462$ ,  $p < 0.001$ ; Table 2). Games–Howell post hoc analyses indicated that Charisma Smart exhibited significantly higher a\* values compared to Crowntec, Filtek Z250, and Permanent Crown. Furthermore, both Estelite Sigma Quick and Permanent Crown demonstrated significantly higher a\* values than Crowntec and Filtek Z250. Significant differences in b\* values were observed among the study groups ( $F = 251.068$ ,  $p < 0.001$ ; Table 2). Bonferroni post hoc tests revealed that Charisma Smart, Crowntec, and Permanent Crown exhibited significantly higher b\* values compared to Estelite Sigma Quick and Filtek Z250. Statistically significant differences in  $\Delta E$  values were observed among the materials tested ( $F = 67.597$ ,  $p < 0.001$ ; Table 2). Post hoc analysis using the Games–Howell test indicated that Crowntec exhibited significantly higher  $\Delta E$  values compared to Estelite Sigma Quick, Filtek Z250, and Permanent Crown. Additionally, Charisma Smart and Permanent Crown demonstrated significantly higher  $\Delta E$  values than Estelite Sigma Quick and Filtek Z250. Importantly, only Filtek Z250 presented  $\Delta E_{00}$  values below the clinical acceptability threshold of 1.8, whereas all other materials exceeded this threshold.

## DISCUSSION

The null hypothesis of this study posited that resin-based restorative materials designated with the same shade (A2) would exhibit no significant differences in their CIE L\*, a\*, and b\* color parameters, and that the color differences ( $\Delta E_{00}$ ) relative to the VitaPan Classical A2 shade tab would remain within clinically acceptable thresholds. However, the present findings led to the rejection of this null hypothesis, as significant differences in color coordinates and clinically unacceptable  $\Delta E_{00}$  values were identified in the majority of the materials tested. In this study, the color matching of various resin-based materials in the A2 shade was evaluated using the CIEDE2000 ( $\Delta E_{00}$ ) color difference formula. According to the acceptability threshold proposed by Paravina et al.,  $\Delta E_{00}$  values exceeding 1.8 indicate color differences that may be considered clinically unacceptable under standardized experimental conditions, although clinical acceptability may vary depending on restorative context (7). Based on this criterion, notable differences in color matching performance were observed among the materials tested. Filtek Z250 ( $\Delta E_{00} = 1.57 \pm 0.13$ ) remained below the acceptability threshold, indicating an acceptable color match with the VitaPan Classical A2 reference shade tab, whereas Estelite Quick, Charisma Smart, Permanent Crown, and Crowntec exhibited  $\Delta E_{00}$  values exceeding this limit. These findings are consistent with previous reports demonstrating that resin-based materials labeled with the same VitaPan Classical shade frequently fail to reproduce the optical characteristics of the corresponding shade tab (14).

**Table 2.** Comparison of different values between different study groups.

	Charisma Smart	Crowntec	Estelite Quick	Filtek Z250	Permanent Crown	F	p
<b>L</b>	78.37±2.38 <sup>AB</sup>	84.59±0.29 <sup>D</sup>	76.56±1.48 <sup>A</sup>	80.14±0.95 <sup>B</sup>	81.84±0.70 <sup>C</sup>	35.983	< 0.001
<b>a</b>	1.26±0.10 <sup>C</sup>	0.00±0.06 <sup>A</sup>	1.13±0.39 <sup>BC</sup>	0.23±0.25 <sup>A</sup>	1.09±0.07 <sup>B</sup>	51.462	< 0.001
<b>b</b>	28.51±0.58 <sup>B</sup>	28.44±0.71 <sup>B</sup>	21.03±1.16 <sup>A</sup>	20.67±0.63 <sup>A</sup>	29.47±0.30 <sup>B</sup>	251.068	< 0.001
<b><math>\Delta E</math></b>	4.69±0.55 <sup>BC</sup>	5.36±0.24 <sup>C</sup>	2.79±0.96 <sup>A</sup>	1.57±0.13 <sup>A</sup>	4.83±0.17 <sup>B</sup>	67.597	< 0.001

Data were analyzed using one-way ANOVA followed by Bonferroni or Games–Howell post hoc tests ( $p < 0.05$ ). Different superscript letters indicate statistically significant differences.

Although the VitaPan Classical shade guide is a visual reference and does not share the same optical structure as resin-based restorative materials, it remains the most widely used shade system in clinical dentistry. Restorative materials labeled with VitaPan Classical shades implicitly claim correspondence to this reference. Previous studies have consistently shown that polymerized resin composites exhibit notable color differences relative to their corresponding VitaPan Classical shade tabs, even when evaluated using spectrophotometric methods and the CIEDE2000 formula (9, 13, 14). Therefore, in the present study, the VitaPan Classical A2 shade tab was used as a reference benchmark to assess the deviation of materials marketed as A2, rather than to imply optical equivalence. Notably, Filtek Z250 and Estelite Sigma Quick exhibited comparable  $\Delta E_{00}$  values and demonstrated less deviation from the VitaPan Classical A2 shade tab relative to the other materials tested. This finding may be attributed to their relatively lower  $b^*$  values, which diminished the influence of yellowness on the overall color difference. In contrast, Crowntec displayed the highest  $\Delta E_{00}$  values among all materials evaluated. This pronounced color discrepancy can be explained by a combination of optical factors, including an elevated  $b^*$  value that increased yellowness, alongside a high  $L^*$  value and a low  $a^*$  value, which collectively shifted the color toward a lighter, greener, and cooler appearance. The interaction of these parameters likely acted synergistically to produce a substantial deviation from the VitaPan Classical A2 reference shade tab, highlighting the multifactorial nature of color mismatch in resin-based restorative materials. Although derived from an *in vitro* model, the observed  $\Delta E_{00}$  differences exceeded commonly used acceptability thresholds, suggesting potential clinical relevance. Sulaiman et al. reported that several contemporary resin-based materials exceeded clinically acceptable  $\Delta E_{00}$  thresholds even prior to aging, with microhybrid and bioactive materials demonstrating particular susceptibility to color change (15). Furthermore, recent studies on universal- and single-shade composites have indicated that acceptable shade integration is highly dependent on the specific material and cannot be generalized across different formulations (16, 17). In this context, the elevated  $\Delta E_{00}$  values observed for most materials in the present study suggest potential limitations when these materials are employed in highly esthetic regions without the implementation of additional shade-matching strategies. The present study revealed statistically significant differences in the CIE  $L^*$ ,  $a^*$ , and  $b^*$  coordinates among resin-based restorative materials nominally classified as A2. Kim and Park reported that, within the same A-shade category, resin composites from different product lines exhibit considerable variations in lightness and chromatic coordinates, which do not consistently correspond to the VitaPan Classical shade ordering (9, 13). These findings corroborate the current

results and underscore the limitations of relying exclusively on manufacturer-designated shade labels to achieve predictable esthetic outcomes. The variation in lightness ( $L^*$ ) among the materials tested offers valuable insight into their perceived differences in brightness. Among the materials evaluated, Estelite Sigma Quick demonstrated the lowest  $L^*$  values, indicating the darkest appearance, followed by Charisma Smart. Conversely, Crowntec exhibited the highest  $L^*$  values, corresponding to the whitest and brightest appearance among the tested materials. These results suggest that, despite identical shade designations, substantial differences in perceived lightness exist, which may undermine esthetic integration when material selection relies solely on shade labeling. The significant variation in  $L^*$  values observed may be attributed to differences in filler composition, filler morphology, filler loading, and the refractive index matching between the filler and resin matrix. Kim and Park have shown that  $L^*$  values are strongly influenced by both material formulation and specimen thickness, even within the same shade designation (9). Additionally, Sulaiman et al. reported that nanofilled resin composites exhibit greater stability in lightness and translucency compared to microhybrid materials, highlighting the importance of filler technology in optical performance (15). Accordingly, materials exhibiting higher  $L^*$  values in the present study may appear clinically lighter than the intended A2 shade, potentially compromising esthetic integration (18). The observed significant differences in the  $a^*$  and, more notably,  $b^*$  coordinates suggest material-dependent chromatic variations along the red–green and yellow–blue axes. Specifically, variations along the red–green axis ( $a^*$ ) were material-dependent and influenced the perceived warmth or coolness of the restorations. Crowntec and Filtek Z250 exhibited more negative  $a^*$  values, indicating a tendency toward greener and cooler hues, whereas Charisma Smart exhibited the highest positive  $a^*$  values, corresponding to a more reddish and warmer color, followed by Estelite Sigma Quick. These shifts in  $a^*$  values may contribute to clinically perceptible hue differences, particularly in highly esthetic regions where subtle color deviations are critical. Differences along the yellow–blue axis ( $b^*$ ) were particularly pronounced and appear to play a predominant role in the overall color mismatch. Charisma Smart, Crowntec, and Permanent Crown demonstrated higher positive  $b^*$  values, indicating a more yellowish hue compared to Estelite Sigma Quick and Filtek Z250. This increased yellowness likely contributed to their greater deviation from the VitaPan Classical A2 reference shade, as  $b^*$  has been consistently identified as a primary factor influencing perceptible color differences among A-shade resin

composites (9, 18). In the present study, materials with higher positive  $b^*$  values consequently appeared more yellow than the VitaPan Classical A2 reference. This finding is further corroborated by aging studies, which have shown that increases in  $b^*$  values play a dominant role in long-term color mismatch and aesthetic degradation of resin-based materials (15, 16). All specimens were standardized to a thickness of 2 mm, thereby ensuring that the observed color differences could be primarily attributed to intrinsic material properties rather than variations in thickness. This methodological approach is substantiated by Ardu et al., who demonstrated that composite thickness significantly affects  $L^*$ ,  $b^*$ , translucency, and  $\Delta E_{00}$  values, even within identical shade designations (19). Furthermore, recent investigations into universal-shade and bulk-fill composites corroborate that optical behavior is highly dependent on thickness, largely due to alterations in light transmission and scattering (17, 20, 21). The results demonstrate that resin-based materials designated as A2 shade do not consistently achieve an accurate match with the VitaPan Classical A2 shade tab. This observation aligns with prior studies reporting variability in shade reproduction among conventional, universal-shade, and bulk-fill resin composites (17, 22). Consequently, clinicians should not depend exclusively on manufacturer shade labels, especially in the esthetic zone, but should also take into account material-specific optical properties, translucency, and employ clinical try-in procedures to ensure optimal color matching. Beyond their use as definitive crown restorations, 3D-printed permanent crown resins also have clinical applications in inlay, onlay, and endocrown restorations, particularly in teeth with extensive substance loss and/or following endodontic treatment (23). In such cases, these materials may be considered as alternatives to direct composite restorations, which motivated their inclusion in the present comparison. To the best of the authors' knowledge, there are currently no studies evaluating the use of these materials as alternatives to composite veneers or overlays in esthetic regions. Nevertheless, the present findings suggest that, when shade selection is performed using the VitaPan Classical system, careful consideration is warranted in esthetically demanding applications, as material-dependent differences in intrinsic color accuracy may influence clinical outcomes. From a clinical perspective, the intrinsic color coordinates reported in the present study should be interpreted in relation to additional variables that may influence the final appearance of restorations. Although CIE  $L^*$  reflects material lightness, translucency is more appropriately described by background-dependent parameters; nevertheless, previous studies have reported associations between translucency behavior and color coordinates, including  $L^*$ , in resin-based materials (24). Accordingly, materials with higher  $L^*$  values may be more susceptible to the influence of underlying tooth color

or luting cement shade. Moreover, the shade and opacity of luting cements have been shown to affect post-cementation  $L^*$ ,  $a^*$ , and  $b^*$  values (25-28), indicating that the color of cemented 3D-printed resin restorations may differ from their intrinsic baseline values. In contrast, layered composite restorations may still be influenced by the color of the underlying tooth structure, even in the absence of a luting cement. Accordingly, the material-dependent color differences observed in studies underscore the importance of considering cementation- and substrate-related effects when translating intrinsic color data into clinical decision-making in esthetically demanding situations (25-28). The limitations of this study include the absence of aging protocols and thermocycling procedures. The use of disc-shaped specimens represents a limitation for direct clinical extrapolation, as anatomical restorations may exhibit different optical behavior; moreover, as an in vitro investigation, the present study does not fully replicate clinical conditions. Incorporating these variables in future studies would enhance the clinical relevance and predictive validity of the findings.

## CONCLUSION

Resin-based restorative materials labeled as A2 showed significant differences in CIE  $L^*$ ,  $a^*$ ,  $b^*$ , and  $\Delta E_{00}$  values, indicating that the A2 shade designation does not ensure an accurate color match with the VitaPan Classical A2 shade tab reference. Only Filtek Z250 demonstrated an acceptable color difference ( $\Delta E_{00} < 1.8$ ), while all other tested materials exceeded the acceptability threshold. These findings highlight that color matching is highly material-dependent, and clinicians should consider intrinsic optical properties rather than relying solely on manufacturer-assigned shade labels, particularly in esthetically demanding clinical situations.

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