Original Article

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# The effect of surface roughness on the color stability of polyetheretherketone

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The study aimed to evaluate the effects of surface roughness, immersion time, material brand on the color stability of polyetheretherketone (PEEK). Two brands of PEEK (n=48), Smile PEEK and Copra PEEK, were used in this study. Disc-shaped specimens (15 mm in diameter and 3 mm in thickness) were fabricated using milling and sectioned with a high-speed saw. The specimens were then divided into six groups (n = 8 per group) based on the PEEK brand and surface treatment: no polishing, polishing, polishing with glazing. Surface roughness was measured using a 3D laser microscope, and baseline color values were recorded using a spectrophotometer according to the CIELAB system. The specimens were subsequently immersed in distilled water for 60 days. Color changes (ΔE*) were calculated at 15, 30, 45, and 60 days after immersion relative to baseline measurements. Two-way ANOVA revealed that the surface roughness of PEEK was significantly influenced by the polishing protocols. The polishing with glazing group exhibited the lowest surface roughness (Ra), which was significantly lower than that of all other groups ($p<0.05$). Color change data were analyzed using three-way mixed-design ANOVA. Color change (ΔE*) increased significantly with immersion time in distilled water. The polishing with glazing group demonstrated a significantly lower color change ($p<0.05$). No significant differences in ΔE* values were observed between Smile PEEK and Copra PEEK under the same surface treatment conditions ($p>0.05$). Polishing and glazing effectively enhanced the color stability of PEEK materials. Color change increased with immersion time, no significant difference in color stability was found between Smile PEEK and Copra PEEK when subjected to the same surface treatment conditions and immersion durations.

**Keywords:** PEEK, surface roughness, color stability, immersion durations.

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## Introduction

Polyetheretherketone (PEEK) is a semi-crystalline thermoplastic polymer capable of withstanding elevated temperatures and belongs to the family of polyaryletherketones (PAEK) family. Its molecular structure consists of aromatic rings interconnected by ketone and ether functional groups along the polymer backbone [1, 2].

PEEK has a high melting temperature (above 300°C) and excellent thermal stability. It also exhibits high chemical resistance, is chemically inert, and possesses favorable mechanical properties. The elastic modulus of neat (unfilled) PEEK ranges from 3 to 4 GPa. The mechanical properties can be enhanced by modifying its composition, such as in carbon fiber–reinforced PEEK (CFR-PEEK), which exhibits an elastic modulus of approximately 17.4 GPa, comparable to that of cortical bone [3], PEEK demonstrates a flexural strength of 140–170 MPa and relatively high rigidity. Additionally, its radiolucency reduces radiographic imaging artifacts [4].

For dental restorative materials, several properties are critical for long-term clinical

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performance, including color stability, water absorption, dimensional stability, and polishability. Among these, color stability is particularly important for maintaining esthetic outcomes over time. The color stability of dental materials can be affected by exposure to staining agents such as coffee, tea, and red wine. The degree of discoloration is influenced by both the duration of exposure and the surface characteristics of the material [5].

Surface roughness is considered an important factor affecting the color stability of dental materials. Rougher surfaces provide a greater surface area and micro-irregularities that facilitate the adsorption and retention of pigments from staining solutions. These surface irregularities can also increase surface free energy, enhancing the interaction between the material surface and chromogenic substances, which may lead to greater discoloration compared with smoother surfaces. In addition, rough surfaces on dental prostheses increase susceptibility to bacterial adhesion, plaque accumulation, staining, and overall discoloration [6–9].

Another factor influencing color stability is immersion time, which is commonly used in in vitro studies to simulate hydrolytic aging and long-term exposure to the oral environment. Prolonged immersion can increase water absorption and promote the diffusion of staining agents into the material surface or subsurface, potentially resulting in greater color change over time.

The stability of color is an important property of dental materials. Factors affecting color change during clinical use include stain accumulation, material component dissolution, water absorption, surface roughness, exposure to staining agents, and immersion time [10, 11].

Furthermore, variations among commercially available PEEK materials may influence their optical and physical properties. Although most dental PEEK materials are reported by manufacturers to consist primarily of polyetheretherketone, variations in manufacturing processes, additives, or processing conditions may lead to differences in surface characteristics and color stability. Therefore, comparing different commercial PEEK brands is essential to determine whether these materials exhibit comparable performance and material equivalence with respect to color stability.

The purpose of this study was to evaluate the effects of surface roughness, immersion time, material brand on the color stability of PEEK material. The first null hypothesis was that immersion time would not significantly affect the color change ($\Delta E^*$) of PEEK. The second null hypothesis was that PEEK brand would not significantly affect the color change ($\Delta E^*$) under identical surface treatment and immersion conditions.

## Material and methods

**Materials**: Two brands of PEEK and one brand of resin glaze material were used in this study (Table 1).

Table 1 Materials were used in this study.

| Material | Product | Composition | Manufacturer |
|---|---|---|---|
| PEEK | Smile PEEK | Polyetheretherketone (PEEK) 100% | Pressing dental, Scavino Onesto, San Marino. |
| | Copra PEEK | Polyetheretherketone (PEEK) 100% | Bio Classic, White PEAKS dental solution, Germany. |
| Resin glaze | SHOFU | Methyl Methacrylate, Multifunctional monomer | SHOFU, Ratingen, Germany. |

## Methods

### Specimen preparation

Two brands of PEEK blocks (15 mm diameter, 20 mm height) were prepared using a milling technique. Then the blocks were cut into discs (15 mm diameter, 3 mm height) using a high-speed saw, Struers Accutom-100 (Struers LLC, Cleveland, USA). The surfaces of all specimens were polished under water cooling using silicon carbide waterproof abrasive papers no.600, 800, 1000, 1500 and 2000 grit (TOA, Samut Prakan, Thailand) with a polishing machine (Struers Model RotoForce-4, USA) for 1 min. Subsequently, the specimens were cleaned in an ultrasonic cleaner and rinsed with distilled water for 5 min.

Specimens (Smile PEEK, Copra PEEK) were divided into six groups (n=8) as shown in Table 2. Group A2, A3, B2, and B3 were polished under water cooling using silicon carbide (SIC) (grit sizes: 600, 800, 1000, 1500, and 2000) (TOA, Samut Prakan, Thailand) with a polishing machine (Struers Model RotoForce-4, USA) at a speed of 150 rpm for 1 min The final thickness of specimens was measured with a digital caliper (accuracy: 0.01 mm). After polishing, specimens in Group A3 and B3 were glazed with resin glaze (SHOFU, Ratingen, Germany). The procedure involved application of a primer, which was allowed to air-dry for approximately 10 seconds, followed by the application of a thin, uniform layer of the resin glaze to the surface. Then the applied glaze was then light-cured for 180 seconds using an LED light (wavelength: 400–410 nm).

After polishing and glazing, the specimens in each group were ultrasonically cleaned, rinsed with distilled water, and air-dried. All specimens were evaluated for baseline surface roughness and color prior to immersion. Baseline color measurements were obtained using the UltraScan® VIS color measurement spectrophotometer (Hunterlab 11491 Sunset Hills Road, Reston, Virginia, USA.). Baseline surface roughness was measured using a 3D laser scanning microscope (LEXT OLS5100, Evident:Olympus, Tokyo, Japan.).

sample size was determined using a power analysis to ensure adequate statistical power for detecting significant differences among the experimental groups. The calculation was performed using G*Power software (version 3.1).

### Immersion in distilled water at different time intervals

Specimens of each group were immersed in individual baths according to the protocols described below and illustrated in Figure 1. for a total duration of 60 days. The specimens were immersed in 600 mL of distilled water at 37°C for 3 days.

Table 2 Specimens will be divided into 6 groups (Code A1-B3).

| Material / Surface treatment | Group (Code) | |
|---|---|---|
| | Smile PEEK | Copra PEEK |
| No polishing | 1 (A1) | 4 (B1) |
| Polishing | 2 (A2) | 5 (B2) |
| Polishing with glazing | 3 (A3) | 6 (B3) |

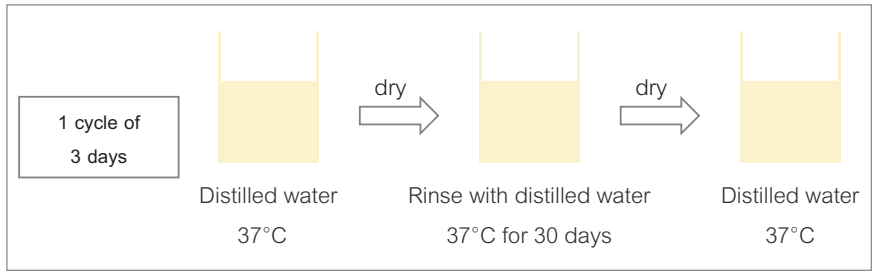



Figure 1 Immersion protocol.

All specimens were maintained in 600 mL of solution and incubated at 37 °C throughout the 60-day experimental period. The solutions were renewed every 3 days. At 15, 30, 45, 60 days, the specimens were removed, rinsed with distilled water for 5 minutes, and gently blotted dry with tissue paper. Color measurements based on the CIELAB system using a spectrophotometer was performed by one investigator.

## Surface roughness measurement

Surface roughness (Ra) was measured using a 3D measuring laser microscope (Evident, Olympus, Japan). Each specimen was measured in three separate readings using a cut off length of 0.25 mm and a tracing length of 3 mm (Figure2). The tracing speed was set at 0.5 μm/s. Ra values were recorded in micrometers (μm), and the mean Ra value for each specimen was used for statistical analysis. A two-way ANOVA was performed to evaluate the effect of polishing protocols on the surface roughness of PEEK.

## Color stability measurement

Color parameters were obtained using a portable spectrophotometer (The UltraScan® VIS color measurement spectrophotometer, the hunterlab, Reston, Virginia, USA). The color of each specimen was evaluated using the CIELAB color system. In this system, L* represents lightness, with values ranging from 0 (black) and 100 (white). a* coordinate represents the red-green axis, where positive values indicate red and negative values indicate green. b*coordinate represents the yellow-blue axis [12].

Color changes (ΔE*) were evaluated at 15, 30, 45, and 60 days of immersion relative to the baseline values recorded on day 0 prior to the start of immersion. ΔE* values were calculated by comparing the L*, a* and b* values obtained at

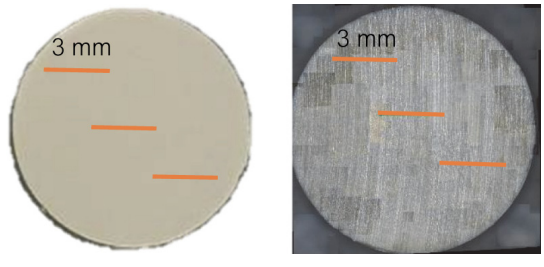



Figure 2 Surface roughness measurement: (A measurement length of 3 mm was used.).

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$

Figure 3 Total color difference (ΔE *) [13].

each time point with the corresponding baseline measurements. This approach enabled the assessment of progressive color changes in each specimen over the 60-day experimental period.

The normality of the data distribution was assessed using the Shapiro-Wilk test and homogeneity of variances was evaluated using Levene's test Subsequently, the data were analyzed using a three-way mixed-design ANOVA followed by Bonferroni post hoc tests. Statistical analyses were performed using in SPSS version 30.0 (IBM Corp, Armonk, NY, USA)

## Result

The surface roughness (Ra) values of PEEK specimens after different surface treatments are presented in Table 3 and Figure 4. Two-way ANOVA revealed that the surface roughness was significantly affected by the polishing protocols ($p<0.05$). Unpolished specimens exhibited the highest Ra values (0.654 and 0.646 μm). Specimens polished using silicon carbide abrasive papers (600-2000 grit) showed reduced Ra values (0.222 and 0.220 μm). The lowest Ra values (0.083 μm for both groups). No statistically significant difference in surface roughness was found between the two PEEK brands when the same surface treatment was applied ($p>0.05$). Representative surface morphology images at different magnifications (5X, 10X, 20X) using Surface Roughness Tester (LEXT OLS5100) are shown in Figure 5-10.

Table 4 and Figure 11 present the mean ± standard deviation (SD) of color change values (ΔE*) of PEEK materials after immersion in distilled water at different time intervals (15, 30, 45, and 60 days). Two types of PEEK materials (Smile PEEK and Copra PEEK), each subjected to three surface treatments (no polishing, polishing, and polishing with glazing), were evaluated.

For the no-polishing group, ΔE* values increased significantly overtime ($p<0.05$). However, no statistically significant difference was observed between day 15 ($\Delta E_{15}$ = 0.351 and 0.339 and day 30 $\Delta E_{30}$ = 0.458 and 0.450) ($p>0.05$). At all-time points, the no-polishing groups exhibited significantly higher color change than the polishing and polishing-with-glazing groups ($p<0.05$).

In contrast, the polishing and polishing-with-glazing groups showed no statistically significant changes in ΔE* values across all immersion time points ($p>0.05$). Furthermore, no statistically significant difference in ΔE* values were found between Smile PEEK and Copra PEEK under the same surface treatment conditions ($p>0.05$).

Table 3 Surface roughness (Ra) values of of groups A1-B3 after different surface treatments.

| Material | Surface treatment (N=8 per each group) | Ra (μm) Mean±SD |
|---|---|---|
| Smile PEEK | No polishing | 0.654±0.025[a] |
| | Polishing | 0.222±0.082[b] |
| | Polishing with glazing | 0.083±0.010[c] |
| Copra PEEK | No polishing | 0.646±0.022[a] |
| | Polishing | 0.220±0.012[b] |
| | Polishing with glazing | 0.083±0.013[c] |

*Different lowercase letters within the same column indicate statistically significant differences ($p<0.05$).

**Table 4** Mean ± standard deviation (SD) of color change (ΔE*) of PEEK after immersion in distilled water at different immersion time intervals.

| Material | Surface treatment | Color change(ΔE±SD) | | | |
|---|---|---|---|---|---|
| | | Immersion time (days) | | | |
| | | 15 | 30 | 45 | 60 |
| Smile PEEK | No polishing | $0.351±0.035^{A,a}$ | $0.458±0.020^{C,a}$ | $0.599±0.016^{E,b}$ | $0.811±0.014^{G,c}$ |
| | Polishing | $0.187±0.009^{B,d}$ | $0.197±0.001^{D,d}$ | $0.218±0.007^{F,d}$ | $0.237±0.007^{H,d}$ |
| | Polishing with glazing | $0.140±0.005^{B,e}$ | $0.156±0.005^{D,e}$ | $0.184±0.008^{F,e}$ | $0.206±0.012^{H,e}$ |
| Copra PEEK | No polishing | $0.339±0.072^{A,a}$ | $0.450±0.045^{C,a}$ | $0.585±0.058^{E,b}$ | $0.774±0.070^{G,c}$ |
| | Polishing | $0.190±0.016^{B,d}$ | $0.208±0.023^{D,d}$ | $0.221±0.021^{F,d}$ | $0.214±0.039^{H,d}$ |
| | Polishing with glazing | $0.139±0.024^{B,e}$ | $0.158±0.024^{D,e}$ | $0.180±0.028^{F,e}$ | $0.201±0.027^{H,e}$ |

* Different uppercase letters within the same column and lowercase letters within the same row indicate statistically significant differences ($p<0.05$).

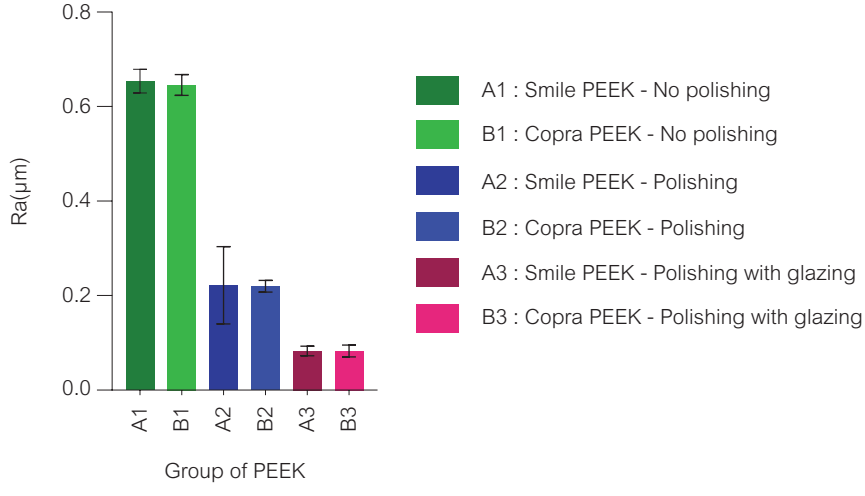



**Figure 4** Surface roughness (Ra) values of PEEK specimens after different surface treatments.

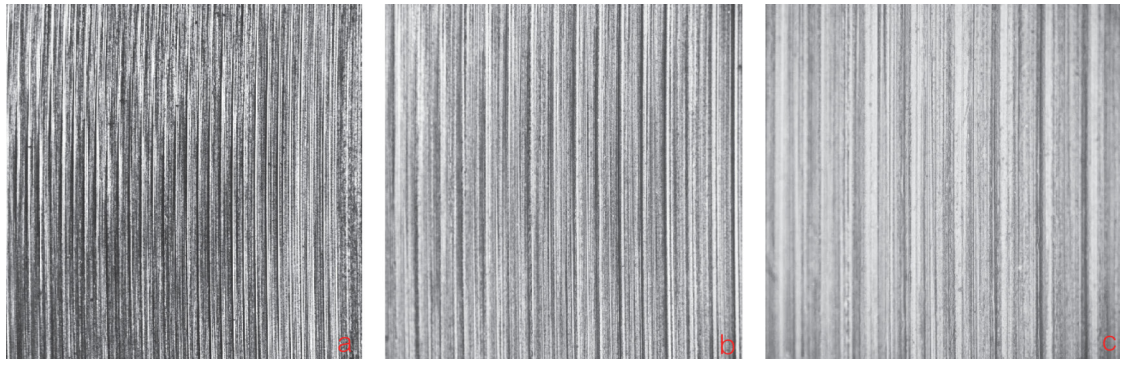



**Figure 5** Surface morphology of Smile PEEK with no polishing: (a) 5X, (b) 10X and (c) 20X magnification.




**Figure 6** Surface morphology of Smile PEEK after polishing: (a) 5X, (b) 10X and (c) 20X magnification.




**Figure 7** Surface morphology of Smile PEEK after polishing with glazing: (a) 5X, (b) 10X and (c) 20X magnification.

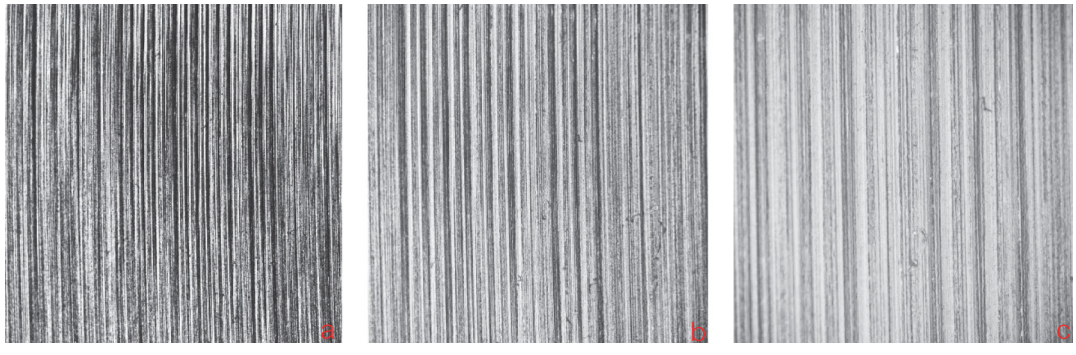



**Figure 8** Surface morphology of Copra PEEK with no polishing: (a) 5X, (b) 10X and (c) 20X magnification.




**Figure 9** Surface morphology of Copra PEEK, after polishing: (a) 5X, (b) 10X and (c) 20X magnification.




Figure 10 Surface morphology of Copra PEEK after polishing with glazing: (a) 5X, (b) 10X and (c) 20X magnification.

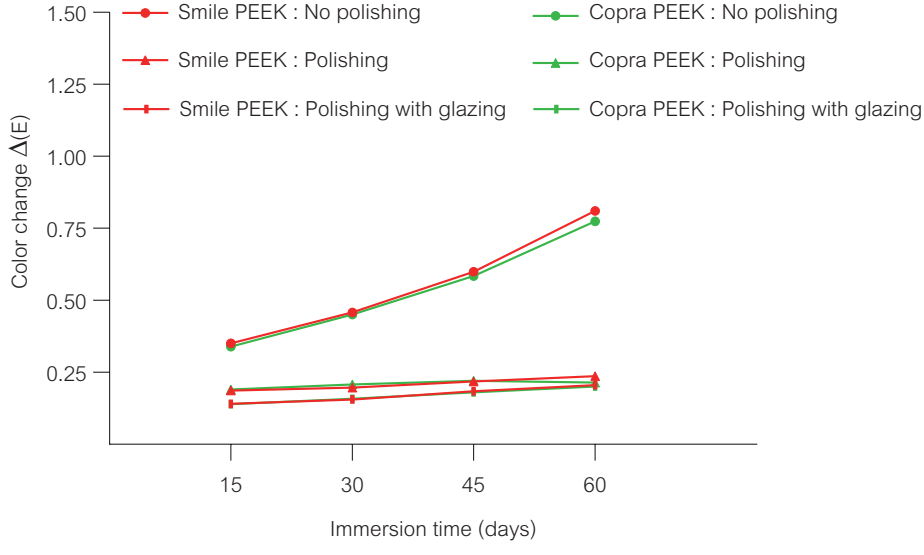



Figure 11 Mean color change (ΔE*) of PEEK after immersion in distilled water at different time intervals.

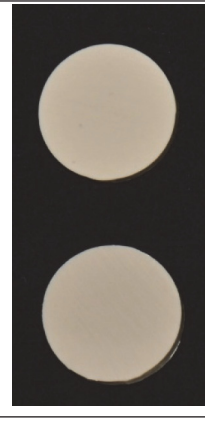
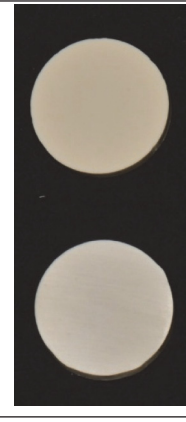
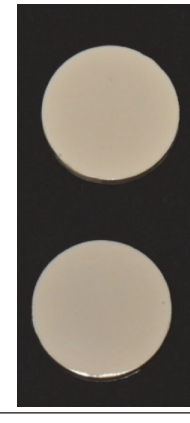
| | No polishing | Polishing | Polishing with glazing |
|---|---|---|---|
| Smile PEEK |  |  |  |
| Copra PEEK | | | |

Figure 12 Representative images of Smile PEEK and Copra PEEK after different surface treatments (no polishing, polishing, polishing with glazing).

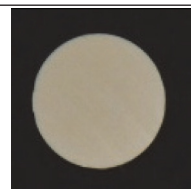
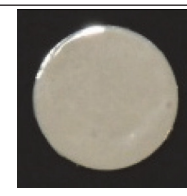
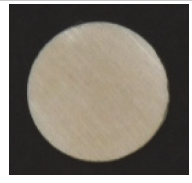
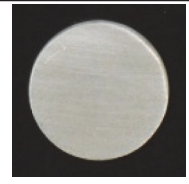
| | No polishing | Polishing | Polishing with glazing |
|---|---|---|---|
| Smile PEEK |  |  |  |
| Copra PEEK |  |  |  |

Figure 13 Representative images of Smile PEEK and Copra PEEK after immersion in distilled water for 60 days.

## Discussion

### Color stability

Color stability is a critical physical property of polyetheretherketone (PEEK), defined as the ability of a material to maintain its original shade over time. In this study, the color change (ΔE*) of Smile PEEK and Copra PEEK was evaluated after immersion in distilled water for 15, 30, 45, and 60 days. Statistical analysis revealed significant differences in ΔE* values across immersion times and surface treatments. Therefore, the first null hypothesis—stating that no statistical difference exists in color change after immersion—was rejected.

However, no significant difference in ΔE* values was observed between the two PEEK brands. Consequently, the second null hypothesis—stating that no difference exists between the two materials—was accepted.

### Surface roughness measurement

Surface characteristics are critical for the long-term performance of dental restorations, influencing color stability, water absorption, dimensional stability, and polishing ability. Increased surface roughness has been associated with greater bacterial adhesion, plaque accumulation, staining, and discoloration [5-8].

Clinically, dental restorations should be polished to achieve a surface roughness below approximately 0.2 μm, a threshold reported to minimize bacterial plaque adhesion [14]. Furthermore, Jones *et al.* suggested that surface roughness should not exceed 0.5 μm to remain undetectable to patients [15]. Surface roughness is commonly quantified using the Ra parameter, and in this study, measurements were obtained using a laser microscope [16].

The results demonstrated that unpolished specimens (A1: Smile PEEK and B1: Copra PEEK) exhibited the highest Ra values (~0.64–0.65 μm), indicating a relatively rough surface. This observation is consistent with previous studies reporting that untreated PEEK surfaces are inherently coarse due to their semi-crystalline structure and manufacturing processes [17]. Such increased roughness may contribute to greater color change by creating micro-irregularities that facilitate pigment retention and penetration, resulting in higher ΔE* values.

Following mechanical polishing (A2 and B2), a significant reduction in surface roughness was observed, with Ra values decreasing to approximately 0.22–0.23 μm. This confirms that

polishing effectively smoothens the PEEK surface, which may enhance clinical performance by reducing plaque accumulation and improving esthetics [14].

Notably, the combination of polishing and glazing (A3 and B3) produced the lowest Ra values (<0.1 μm), demonstrating a synergistic effect of the two finishing techniques. These findings are consistent with those of Porojan *et al.,* who reported that glazing significantly improves the surface smoothness of PEEK, with mean Ra values below 0.13 μm regardless of aging or staining conditions [13]. Glazing likely fills residual micro-irregularities after polishing, forming a smoother and more homogeneous surface layer [18]. This effect is particularly advantageous in prosthodontic applications, where both esthetics and hygiene are essential [19]. Additionally, glazing may act as a sealing layer, reducing surface porosity and water penetration, thereby limiting pigment infiltration and enhancing color stability.

Importantly, no statistically significant differences in surface roughness were observed between Smile PEEK and Copra PEEK across all treatment groups. This finding is expected, as both materials are composed of the same base polymer, polyetheretherketone, resulting in similar microstructural and physical properties. Previous studies have likewise demonstrated comparable surface behavior among different commercial PEEK materials when subjected to identical finishing protocols [20].

## Effect of Surface Treatment on Color Stability of PEEK

Surface treatment plays a critical role in the color stability of PEEK materials. Previous studies have demonstrated that the discoloration of restorative materials is strongly influenced by surface roughness [21-23]. In principle, materials with higher surface roughness and greater surface free energy are more susceptible to discoloration due to increased pigment adsorption and penetration. This concept is supported by evidence indicating that the color stability of PEEK is significantly affected by these surface characteristics, particularly under conditions of artificial aging and staining [12,13].

In the present study, unpolished specimens exhibited the highest color change (ΔE*) values among all groups. This finding can be attributed to the increased surface roughness of untreated PEEK, which provides greater surface area and micro-irregularities that facilitate pigment retention and penetration [13]. In contrast, specimens subjected to polishing demonstrated improved color stability, while those treated with polishing followed by glazing exhibited the lowest ΔE* values under all immersion conditions.

The superior performance of the polishing-with-glazing group may be explained by the formation of a smoother and more homogeneous surface layer. Glazing likely reduces surface porosity and acts as a sealing layer, thereby limiting pigment infiltration and enhancing resistance to discoloration. Consequently, glazing was more effective in improving color stability than mechanical polishing alone [24]. These findings are consistent with previous reports indicating that smoother surfaces are less prone to staining and discoloration [13, 25-27].

Beyond color stability, surface roughness has important clinical implications. A surface roughness (Ra) below approximately 0.2 μm is considered a critical threshold for minimizing bacterial adhesion and plaque accumulation. In this study, specimens treated with polishing followed by glazing achieved Ra values below this threshold (~0.083 μm), suggesting improved surface smoothness and favorable clinical performance.

Previous investigations have commonly assessed color stability using chromogenic solutions such as coffee, red wine, or tea, which contain pigments capable of penetrating restorative materials and causing significant discoloration. These studies consistently demonstrate that materials with higher surface roughness exhibit greater ΔE* values due to increased pigment adsorption. Accordingly, surface finishing procedures that reduce roughness—such as polishing and glazing—have been shown to enhance staining resistance [28].

In contrast, distilled water was used as the immersion medium in the present study to provide a controlled baseline environment that simulates the aqueous conditions of the oral cavity without introducing external staining agents. This approach enables the evaluation of intrinsic color stability and the isolated effect of surface treatment. Distilled water is widely used as a standard storage medium in in vitro studies investigating the aging behavior and optical stability of dental materials.

### Effect of Immersion Time

The duration of immersion significantly influenced the color change of the specimens. Under all experimental conditions, ΔE* values increased progressively over time, indicating a time-dependent effect. This trend suggests cumulative water uptake and potential surface or microstructural alterations resulting from prolonged exposure to the solution. For example, unpolished Smile PEEK demonstrated an increase in ΔE* from 0.351 at 15 days (T15) to 0.811 at 60 days (T60), although these values remained below the clinically acceptable threshold (ΔE*>3.3) [29]. According to the National Bureau of Standards (NBS) classification, this level of discoloration corresponds to a slight color change [13]. These findings suggest that surface treatments providing smoother and more sealed surfaces may effectively delay discoloration over time.

The observed time-dependent increase in ΔE* highlights the importance of considering exposure duration when evaluating the esthetic longevity of PEEK restorations, particularly in patients with frequent consumption of pigmented beverages [30].

Although PEEK is characterized by high chemical stability and low water absorption, prolonged immersion in distilled water can still result in measurable optical changes. Water molecules may diffuse into the amorphous regions of the polymer, leading to subtle microstructural alterations that affect light scattering and optical properties. In addition, long-term exposure to water and dissolved oxygen may induce minor surface oxidation or polymer chain rearrangement, potentially generating chromophoric groups that contribute to discoloration. Furthermore, the leaching of residual processing additives or impurities present in commercial PEEK materials may also influence color stability. These mechanisms suggest that even highly stable polymers such as PEEK are not entirely resistant to optical changes during extended water aging [31-33].

### Effect of PEEK Brand

No statistically significant differences in color change were observed between Smile PEEK and Copra PEEK when subjected to identical surface treatments and immersion conditions. For example, after 60 days of immersion in distilled water, specimens treated with polishing followed by glazing exhibited ΔE* values of 0.206 for Smile PEEK and 0.201 for Copra PEEK.

Both materials are commercially available and widely used in dentistry for the fabrication of prosthetic frameworks, implant-supported restorations, and removable prostheses, owing to

their favorable mechanical properties, high biocompatibility, and chemical stability. With the increasing adoption of CAD/CAM technology in prosthodontics, PEEK has gained considerable attention as a metal-free alternative for various clinical applications.

According to manufacturers' specifications, both Smile PEEK and Copra PEEK consist of unfilled polyetheretherketone (PEEK) with similar manufacturing processes. Therefore, the comparable color stability observed in this study is expected. The materials were selected due to their common use as CAD/CAM milling blanks in dental laboratory workflows.

The absence of statistically significant differences between the two materials is consistent with previous studies. Schwitalla and Müller described PEEK as a semi-crystalline thermoplastic polymer with high chemical resistance and low water absorption, contributing to its stability in the oral environment [17]. Similarly, Stawarczyk *et al.* reported minimal variation among commercially available PEEK materials when identical fabrication and surface treatment protocols are applied [20].

Compared with modified or filler-reinforced PEEK composites, unfilled PEEK generally exhibits greater chemical stability and lower water absorption, which may enhance resistance to color change. This may explain the minimal differences observed between Smile PEEK and Copra PEEK in the present study.

From a clinical perspective, these findings suggest that both materials demonstrate comparable color stability and may be considered interchangeable under similar surface treatment and clinical conditions

## Conclusion

This study demonstrated the following findings:

- Polishing combined with glazing significantly improved the color stability of PEEK.
- Increasing immersion time in distilled water significantly increased the color change ($\Delta E^*$) of PEEK.
- No statistically significant difference in color stability was observed between Smile PEEK and Copra PEEK when subjected to identical conditions, indicating comparable material performance.

Limitations

1. This was an in vitro study; therefore, the results may not fully replicate intraoral conditions, such as saliva dynamics, temperature fluctuations, and mechanical abrasion.
2. Only a single immersion medium (distilled water) was evaluated; common staining agents such as coffee, tea, wine, juices, and denture cleansers were not included.
3. Only two commercially available PEEK materials were tested; results may vary with other brands or modified PEEK formulations.

## Recommendations

1. A combination of polishing and glazing is recommended to enhance the color stability of PEEK restorations, particularly in patients with high exposure to staining agents.
2. Future studies should incorporate simulated oral aging conditions, including toothbrushing and thermocycling, to better reflect clinical performance.
3. Further investigations comparing additional PEEK brands and compositions are warranted to broaden material selection for clinical applications.

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