

Article

Biomimetic Surface Modification of Dental Zirconia via UV Irradiation for Enhanced Aesthetics and Wettability

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Abstract

Zirconia is a material that mimics human teeth and has been extensively studied and applied. This study investigated the surface modifications of dental zirconia induced by two UV-C wavelengths (222 and 254 nm). A total of 72 zirconia specimens were prepared and divided into groups for irradiation at varying distances (1, 6, 12 cm) and durations (40, 120, 480 and 1440 min), with three specimens retained as untreated controls. Surface changes were assessed by measuring colour difference (ΔE) and water contact angle, and by analyzing surface morphology and elemental composition using SEM and EDX, and XRD was employed to determine the crystalline structure. The results showed that both wavelengths induced clinically perceptible colour changes ($\Delta E > 2.0$), with the most pronounced effect at 6 cm for 222 nm and 1 cm for 254 nm. WCA decreased significantly with irradiation time, showing a linear correlation with $\log(\text{time})$, and 222 nm irradiation yielded lower WCA than 254 nm. While SEM revealed no morphological changes, both UV treatments significantly increased the Zr/O ratio compared to the control. XRD tests confirmed that UV-C irradiation does not damage the zirconium oxide crystal structure. It is concluded that both UV-C wavelengths can alter the colour and enhance the wettability of zirconia; these modifications are particularly relevant for dental restorative applications, specifically in the fabrication of anterior tooth crowns, where achieving a natural tooth-like appearance is desired.

Keywords: zirconia; biomimetic; surface modification; ultraviolet irradiation; colour change; wettability



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1. Introduction

Teeth are not only essential for mastication and speech but also play a crucial role in facial aesthetics and self-confidence [1]. The escalating demand for aesthetic dental restorations has driven the development of biomimetic materials that offer both exceptional durability and a natural appearance [2,3]. Yttrium-stabilized tetragonal zirconia polycrystalline (Y-TZP) has become a material of choice for crowns, bridges, and implants due to its outstanding fracture toughness, biocompatibility, and mechanical properties that closely match natural dentition [4–7]. As a high-performance biomimetic dental ceramic, zirconia's

core advantage lies in its ability to mimic and surpass the ability of natural teeth to resist complex stresses through a “phase transformation toughening” mechanism [8,9]. However, its inherent biomimetic limitations lie in the aesthetic aspect: the off-white appearance and certain opacity of single-layer zirconia make it difficult to completely replicate the translucency and colour gradation of natural tooth tissue [10,11].

To address this aesthetic biomimetic limitation, pre-sintered staining or porcelain veneer techniques are often used clinically [12,13]. While effective, these methods frequently entail technical complexities, the risk of porcelain chipping, and potentially increased restoration thickness [14,15]. Consequently, there is a pressing need for a simpler, more controllable, and potentially in-office method to directly modify the colour of zirconia surfaces without compromising structural integrity or introducing additional bonding interfaces.

Ultraviolet (UV)-induced surface modification technology has emerged as a promising and non-destructive approach for tailoring the physicochemical properties of metal oxide biomaterials without altering bulk mechanical integrity [16–18]. UV irradiation, particularly in the UV-C band (100–280 nm), is known to induce photochemical reactions on metal oxide surfaces and has been widely used in clinical contexts [19,20]. For zirconia, the prevailing theory is that high-energy photons can induce the formation of oxygen vacancies (colour centers) [21,22]. The formation of these defects alters the electronic band structure of the material, reducing the band gap and thus changing the surface’s absorption and reflection properties of visible light, typically manifesting as a visual colour shift from white to yellow or brown [23].

Although the concept of UV modification has been proposed, the specific effects of different UV-C wavelengths on dental zirconia have not been fully explored. Previous studies have largely focused on single wavelengths (e.g., 254 nm) [24,25]. Kurihara et al. investigated the potential mechanism of UV irradiation-induced discolouration of 3 mol% and 5 mol% yttrium oxide-stabilized dental zirconia ceramics, and pointed out that the discolouration may be caused by UV-C-induced electron excitation of the F-center [24]. The emerging 222 nm wavelength, with its higher photon energy, may induce more significant or different surface reactions due to its stronger chemical bond-breaking ability. Bai et al.’s pioneering research demonstrated the feasibility of direct colour printing on 3Y-TZP using 222 nm UV-C light and investigated the effect of ambient temperature on UV-C colour printing performance [26,27]. More importantly, how key parameters such as wavelength, irradiation distance (affecting energy density), and time synergistically regulate the final colour change, surface chemistry, and wettability is crucial for establishing predictable clinical operating procedures [28–31].

Therefore, this study aims to systematically explore and compare the surface modification effects of two specific UV-C wavelengths (222 nm and 254 nm) on dental-grade Y-TZP. Based on the perspective of zirconia as a biomimetic material, this study not only focuses on optimizing its aesthetic properties (colour matching) but also explores the regulation of its surface wettability. By evaluating the induced colour change (ΔE), water contact angle (WCA) changes, and changes in surface elemental composition (Zr/O ratio), as well as the crystal structure, this study aims to verify the following hypothesis: UV irradiation can simultaneously improve the aesthetic biomimetic properties (colour) and wettability of zirconia through a controllable oxygen vacancy generation mechanism, and different wavelength parameters will produce differentiated effects. The results of this study will provide key experimental evidence for the development of a non-invasive, ultraviolet light-based biomimetic colouration for zirconia surfaces, as well as a clinically feasible method to fine-tune the shade of zirconia surfaces—particularly suitable for custom applications, such as front teeth, where colour consistency is critical.

2. Materials and Methods

2.1. Materials and Sample Preparation

For sample preparation, 12 Lava™ Frame zirconia blocks conforming to ISO 6872:2008 (3M ESPE, Seefeld, Germany) were used in this study [32]. Each block was cut into thin slices of approximately 1.2 mm thickness using a low-speed diamond saw (Buehler Isomet, Lake Bluff, IL, USA). To minimize friction and heat accumulation during cutting, a water bath cooling system was employed, and the cutting speed was maintained at a medium setting (approximately 5) to prevent cracking.

All cut samples were batch sintered in a ZYRCOMAT 6000 MS furnace (VITA certified, Bad Säckingen, Germany). The sintering procedure precisely followed the manufacturer's recommended protocol for this specific brand of zirconia, as detailed in the literature [33]. As illustrated in Figure 1, the specific cycle involved heating at rates of 20 °C/min (initial and middle stages) and 10 °C/min (final stage), holding at 1500 °C for 2 h, and then furnace cooling. The entire sintering process lasted approximately 5 h.

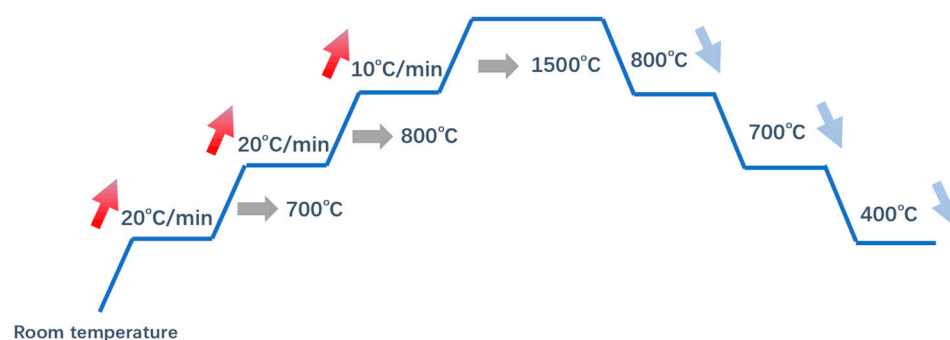


Figure 1. Program of sintering furnace for Lava™ Frame zirconia mill blanks.

2.2. UV-C Irradiation

Before irradiation, 72 specimens were selected from the total sample and thoroughly ultrasonically cleaned in 75% ethanol. The remaining samples were reserved as a control group. The 72 specimens were divided into two main groups according to the irradiation wavelength: Group I (222 nm) and Group II (254 nm). Each group was further subdivided into three subgroups according to the irradiation distance, i (1 cm), ii (6 cm), and iii (12 cm), resulting in six treatment groups (I-i, I-ii, I-iii, II-i, II-ii, II-iii). Within each subgroup, the specimens were further divided into four treatment units according to the irradiation duration: 40 min (i), 120 min (ii), 480 min (iii), and 1440 min (iv). Each treatment unit contained three parallel samples (a, b, c) to reduce error and for data averaging.

UV-C irradiation was performed using two lamps (LiterUV Lighting Technology (Foshan) Co., Ltd., Foshan, China) emitting at 254 nm and 222 nm. During the irradiation, the irradiation intensity was recorded using an ultraviolet radiometer matched to the wavelength (HPL-220 UVC; Hopocolour Co., Ltd., Hangzhou, China). Irradiance at the sample plane was measured at each working distance (1, 6, and 12 cm) using a calibrated UV power meter placed at the same position as the specimens. For the 254 nm lamp, the measured irradiance values were 11.75, 3.19, and 2.33 mW/cm² at 1, 6, and 12 cm, respectively; for the 222 nm lamp, the corresponding values were 1.92, 0.82, and 0.47 mW/cm². Specimens were numbered as Group (uppercase Roman numeral)-Distance (lowercase Roman numeral)-Time (lowercase Roman numeral)-Parallel Sample (letter). For example, a specimen exposed to 222 nm ultraviolet light at a distance of 6 cm for 40 min is numbered I-ii-i-a, and its parallel samples are I-ii-i-b and I-ii-i-c.

2.3. Characterization

2.3.1. Colour Change

After ultraviolet irradiation, the colour and colour change values of zirconia surfaces were tested using a telephoto camera and colour spectrophotometer (NR10QC, 3 nh, Shenzhen, China). To ensure a representative average, measurements were performed at three distinct locations on each sample. The colour change values (ΔE) could be calculated by the following formula [34]:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (1)$$

ΔL^* represents the change in lightness compared to specimens without irradiation. The symbol Δa^* refers to the colour variation from green (−) to red (+), and Δb^* stands for the colour variation from blue (−) to yellow (+).

2.3.2. Scanning Electron Microscopy and Energy-Dispersive X-Ray Spectrometry

The morphology and elemental distribution of the samples were characterized using scanning electron microscopy (SEM; Hitachi, Tokyo, Japan) equipped with energy-dispersive X-ray spectroscopy (EDX). The samples were gold sputtered for 45 s before observation; the magnification was at 3000 $\times$. The atomic ratio of Zr to O was calculated from the EDX analysis.

2.3.3. X-Ray Diffraction Analysis

Crystal structure identification was performed on a SmartLab high-resolution X-ray diffractometer (Rigaku Co., Ltd., Tokyo, Japan) with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). Diffraction patterns were recorded over a 2θ range of 20–80° at a scanning rate of 10°/min and a step size of 0.02°.

2.3.4. Water Contact Angle

The surface wettability of the zirconia samples was evaluated by measuring the static water contact angle (WCA) using the sessile drop method. Specifically, the syringe needle was placed 5 mm above the zirconia surface, and a drop of test solution (1 μL) was added. The image was taken 20 s after the droplet impacted the zirconia surface and reached equilibrium. Contact angle values were calculated from droplet images using ImageJ software Version 1.54p (NIH, Bethesda, MD, USA) with its contact angle plug-in.

2.4. Statistic

The Statistical Package for Social Science (SPSS, Version 28.0, IBM, Armonk, NY, USA) was used for statistical analysis; the significance level was pre-set as $\alpha = 0.05$ for all tests. The Shapiro–Wilk test was used for the normality test; the normally distributed samples with homogeneous variance were tested by using one-way analysis of variance (ANOVA) and Turkey's multiple comparison. Otherwise, independent-sample Kruskal–Wallis test and Bonferroni test were performed. SigmaPlot (V16, Grafiti LLC, Palo Alto, CA, USA) was applied for the linear fitting.

3. Results

3.1. Surface Colour and Macroscopic Morphology Analysis

As shown in Figure 2a, after UV-C irradiation (1440 min, 12 cm), both of the zirconia specimens irradiated by 222 and 254 nm UV-C in the experimental groups exhibited visually perceptible colour changes. The corresponding total colour difference (ΔE) values are presented in Figure 2b. All ΔE values were significantly higher than the clinically acceptable threshold ($\Delta E \approx 2.0$), indicating that the colour change was clinically significant.

Data analysis revealed that the colour was dependent on wavelength, distance, and time. Significantly different colour change patterns were induced by the varying UV wavelengths: 254 nm UV light induced the largest colour difference at the closest distance (1 cm) with ΔE values ranging from 7.85 to 8.35, and the change was gradual with prolonged irradiation time. Conversely, the 222 nm UV light elicited the most pronounced colour change at a medium distance (6 cm), yielding ΔE values of 6.70–8.81, where the colour difference increased significantly and continuously with irradiation time.

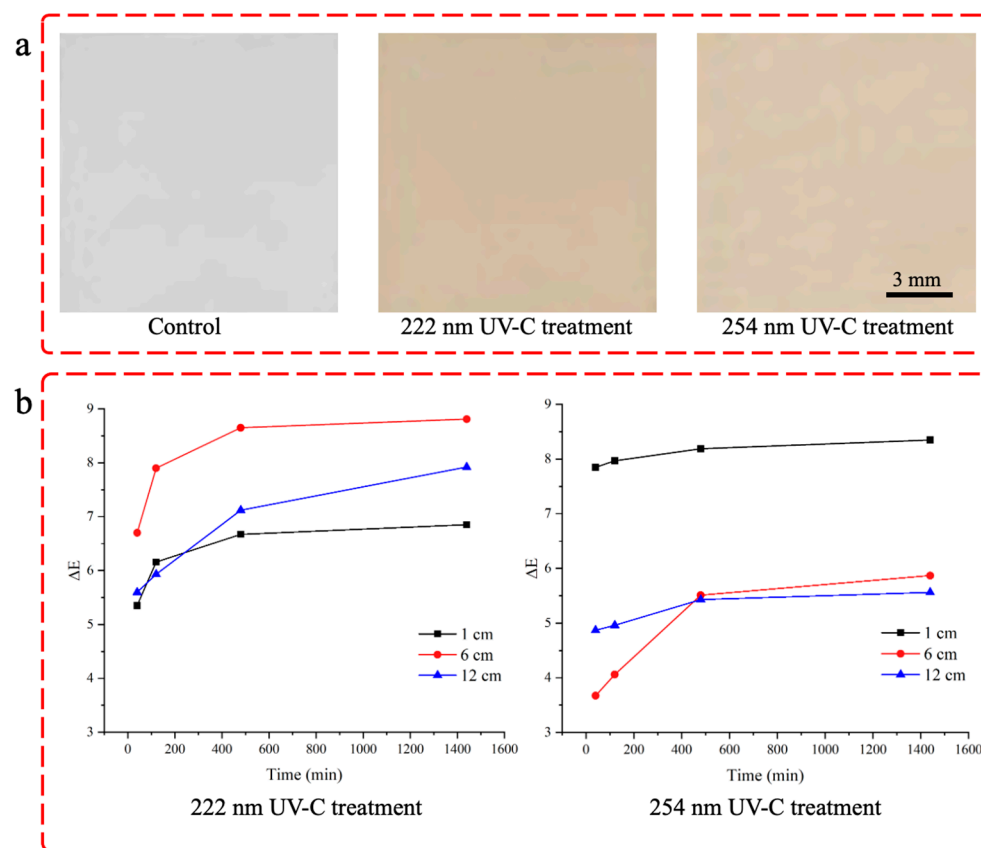


Figure 2. Optical images before and after irradiation (a) and colour change analysis (b).

The effect of irradiation distance is closely related to wavelength. For 222 nm UV light, the colour difference exhibited a non-monotonic relationship of “6 cm > 12 cm > 1 cm”. For 254 nm ultraviolet light, a clear trend of “1 cm > 12 cm > 6 cm” was observed.

Under all experimental conditions, the ΔE value monotonically increased with increasing irradiation time, confirming that the cumulative irradiation dose is the key factor driving colour change. Specifically, under the conditions of 222 nm and 6 cm, the colour difference increased most significantly from 40 to 1440 min (from 6.70 to 8.81, a relative increase of approximately 31.5%), indicating that the photochemical reaction did not reach saturation within 1440 min.

3.2. Surface Micromorphology and Elemental Composition Analysis

SEM was used to characterize the zirconia samples to observe the differences in surface morphology between the irradiated and untreated samples. As shown in Figure 3, compared with the SEM image of the control group, there is no significant difference in surface morphology between the samples before and after UV-C irradiation.

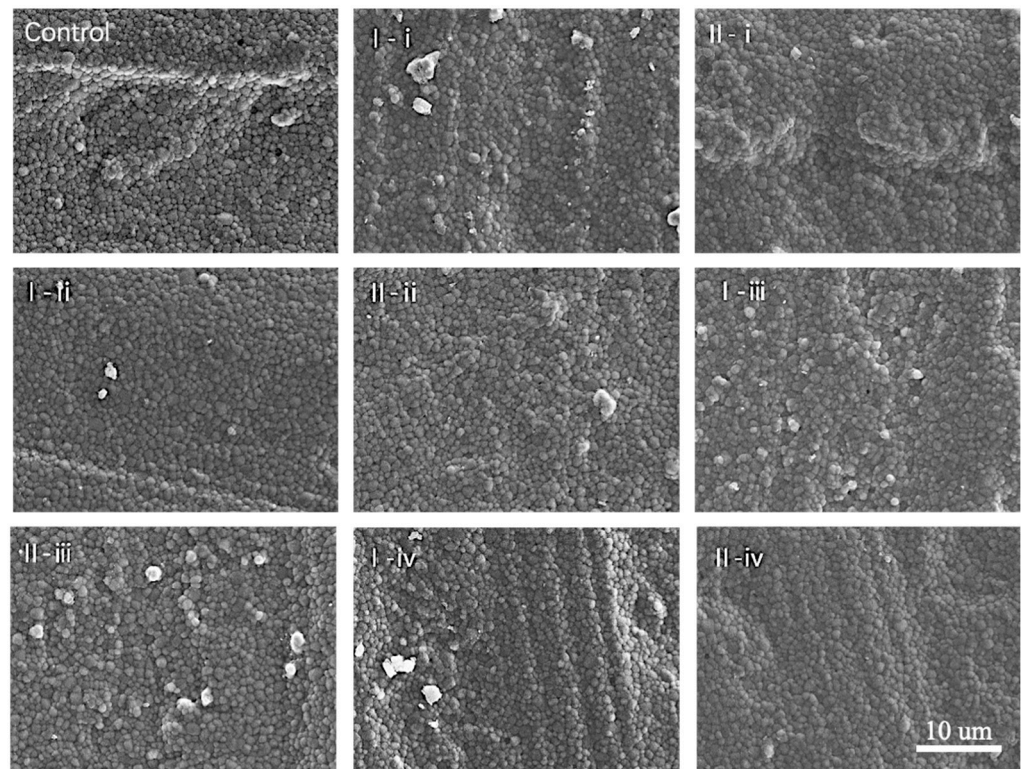


Figure 3. SEM images of zirconia samples before and after irradiation (control: before irradiation; I-i, ii, iii, iv: 222 nm UV-C irradiation after 40, 120, 480 and 1440 min at 6 cm; II-i, ii, iii, iv: 254 nm UV-C irradiation after 40, 120, 480 and 1440 min at 6 cm).

Figure 4 and Table 1 show the results of statistical analysis of the Zr/O ratio after EDX test by using SPSS software. A similar trend occurred in samples treated with UV irradiation at two different wavelengths. At a constant irradiation distance, no significant differences were observed across varying irradiation times. Nevertheless, these changes were consistently and significantly different from the control group. Similarly, when irradiation time was held constant, no significant differences in sample colour changes were found at different irradiation distances; however, these changes also proved to be significantly different from the control.

Table 1. Zr/O ratio analysis after different UV-C irradiation procedures.

Wavelength /nm	Time/min		40	120	480	1440
	Distance/cm					
222	1		0.98 ± 0.15 ^{aA}	0.93 ± 0.10 ^{aA}	1.04 ± 0.11 ^{aA}	1.02 ± 0.04 ^{aA}
	6		0.96 ± 0.11 ^{aA}	1.08 ± 0.07 ^{aA}	0.98 ± 0.09 ^{aA}	0.98 ± 0.07 ^{aA}
	12		1.04 ± 0.08 ^{aA}	1.06 ± 0.10 ^{aA}	1.11 ± 0.05 ^{aA}	1.09 ± 0.03 ^{aA}
254	1		1.07 ± 0.10 ^{aA}	1.03 ± 0.07 ^{aA}	1.03 ± 0.08 ^{aA}	1.19 ± 0.09 ^{aA}
	6		1.02 ± 0.14 ^{aA}	0.97 ± 0.07 ^{aA}	1.05 ± 0.09 ^{aA}	0.95 ± 0.11 ^{aA}
	12		1.00 ± 0.06 ^{aA}	1.04 ± 0.05 ^{aA}	0.97 ± 0.02 ^{aA}	1.10 ± 0.11 ^{aA}

Lowercase letters indicate significant differences at different times within the same distance, and the uppercase letters indicate significant differences at different distances within the same time.

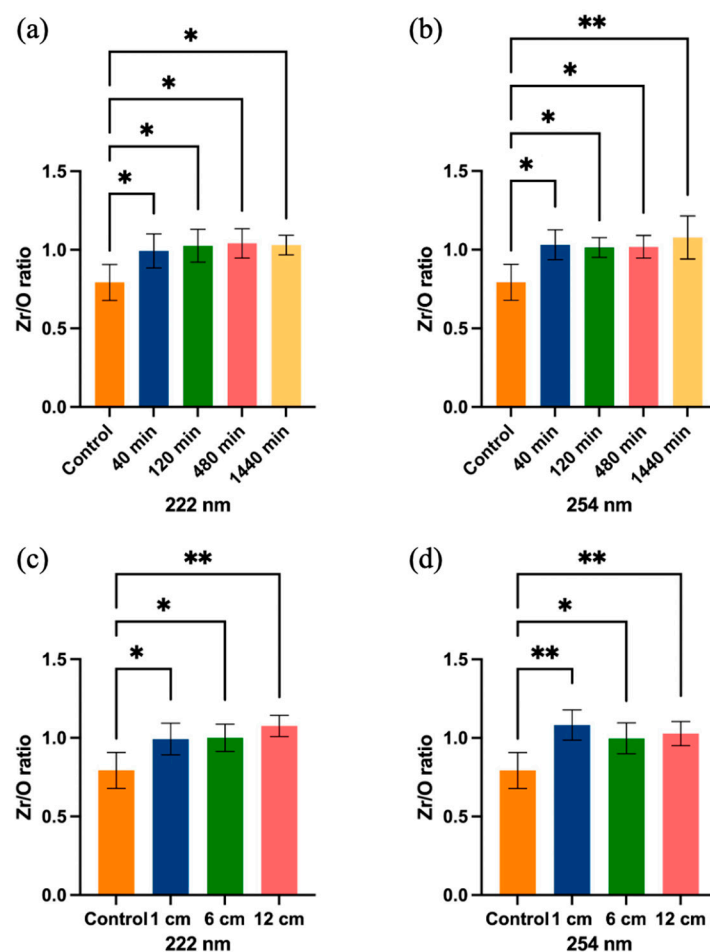


Figure 4. Zr/O ratio after different UV-C irradiation procedures: different irradiation time of (a) 222 nm and (b) 254 nm; and different irradiation distance of (c) 222 nm and (d) 254 nm. (*: $p < 0.05$ and **: $p < 0.01$).

3.3. Surface Wettability Analysis

Figure 5 and Table 2 illustrate the changes in sample contact angle following treatment, as determined by the contact angle test. For the 222 nm wavelength, after UV-C radiation treatment, the contact angles of samples at different radiation times and the same radiation distance showed significant differences and were also significantly different from the control group. At the same radiation time, there were varying degrees of significant differences in the contact angles of samples at different radiation distances, but all were significantly different from the control group.

Table 2. Water contact angles after different UV-C irradiation procedures.

Wavelength /nm	Time/min		40	120	480	1440
	Distance/cm					
222	1		67.97 ± 1.85 ^{aA}	53.10 ± 0.82 ^{bA}	51.00 ± 0.62 ^{cA}	44.57 ± 0.71 ^{dA}
	6		58.90 ± 0.53 ^{aA}	53.47 ± 0.47 ^{bA}	46.33 ± 0.96 ^{cB}	46.13 ± 0.85 ^{cA}
	12		56.50 ± 0.95 ^{aB}	53.73 ± 2.20 ^{aA}	52.33 ± 0.65 ^{aB}	43.67 ± 0.42 ^{bB}
254	1		64.77 ± 0.55 ^{aA}	63.40 ± 0.30 ^{bA}	59.80 ± 0.66 ^{cA}	50.10 ± 0.70 ^{dA}
	6		76.40 ± 1.04 ^{aB}	66.40 ± 0.17 ^{bB}	57.20 ± 0.36 ^{cA}	50.63 ± 0.38 ^{dA}
	12		66.40 ± 1.08 ^{aA}	61.03 ± 0.51 ^{bA}	60.77 ± 1.27 ^{bA}	57.47 ± 0.55 ^{cA}

Lowercase letters indicate significant differences at different times within the same distance, and the uppercase letters indicate significant differences at different distances within the same time.

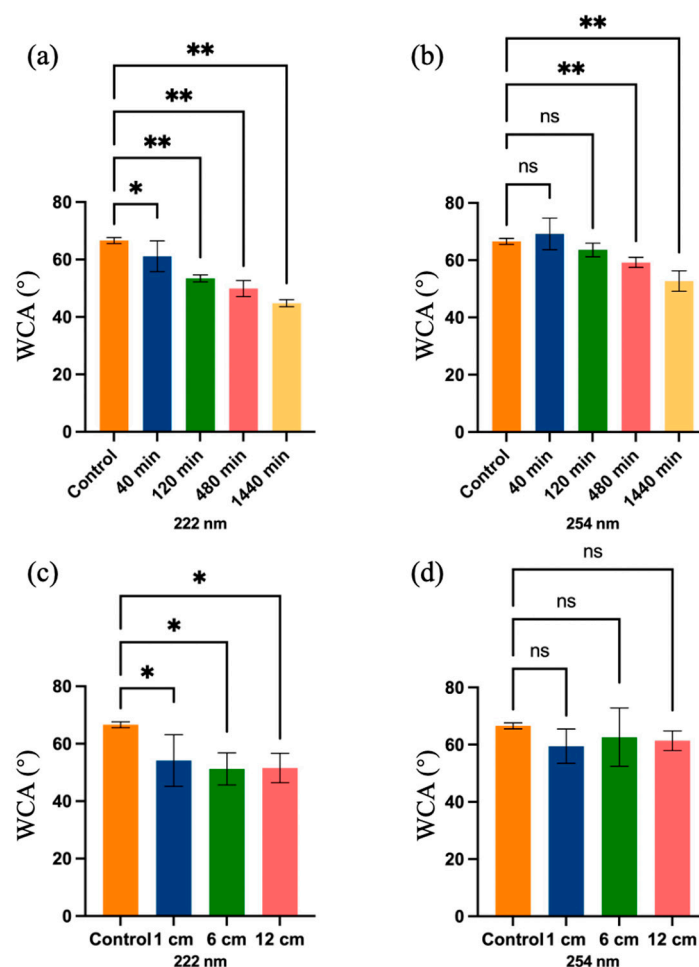


Figure 5. Water contact angles after different UV-C irradiation procedures: different irradiation time of (a) 222 nm and (b) 254 nm; and different irradiation distance of (c) 222 nm and (d) 254 nm. (*: $p < 0.05$ and **: $p < 0.01$).

When the wavelength was 254 nm, after UV-C irradiation treatment, the contact angles of the samples at different irradiation times showed significant differences at the same irradiation distance. Furthermore, the contact angles of the samples at irradiation times of 480 min and 1440 min were significantly different from those of the control group. However, at the same irradiation time, the contact angles of the samples at different irradiation distances showed almost no significant differences, and also no significant differences compared to the control group.

In addition to the statistical analysis of SPSS, a normal-log plot (Figure 6) was generated using SigmaPlot 15.1 to illustrate the relationship between irradiation times and water contact angles. This plot was designed to achieve a good linear fit. By making the independent variable (irradiation time) in log scale and adding colour marks, it was easier to separate the parameters for different wavelengths and identify the tendency of regression clearly. Furthermore, we were able to determine which UVC light with a certain wavelength should be used to irradiate the sample surface to get favourable water contact angles according to the SigmaPlot graph. Therefore, the goal to control the hydrophilic or hydrophobic properties of zirconia samples could be achieved. A higher coefficient of determination (r^2), approaching 1.0, indicates a stronger correlation between water contact angles and irradiation time. With the range from 0.748 to 0.773, a good correlation between WCA and irradiation time was evident.

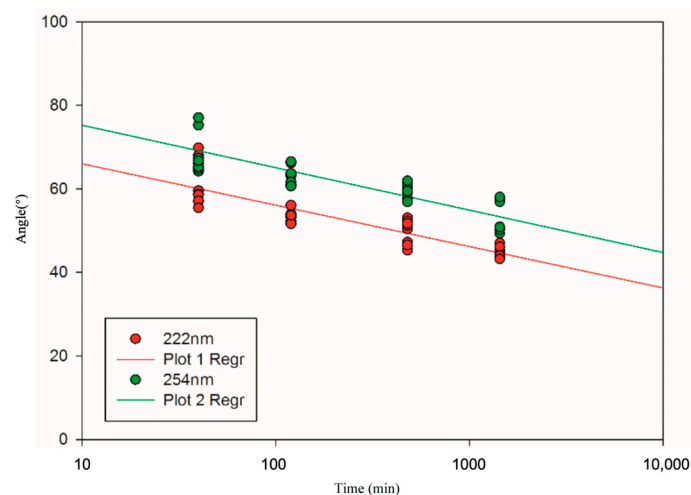


Figure 6. Water contact angle–time (in log scale) plot regression.

3.4. Crystal Structure Analysis

X-ray diffraction (XRD) patterns for zirconia samples irradiated with 222 nm and 254 nm UV-C light (at a distance of 1 cm, for 40, 120, 480, and 1440 min) are presented in Figure 7. As shown in Figure 7a, the presence of zirconium yttrium oxide in samples irradiated by 222 nm UVC light was mainly at 2-theta of 30.179°, 35.126°, 50.211°, 50.523° and 59.985°. The strong diffraction peaks at 30.179°, 50.211° and 59.985° corresponded respectively to (101), (112) and (211) crystal planes of the zirconium yttrium oxide, and these interplanar spacings were 2.9589 nm, 1.8155 nm and 1.5409 nm. This indicated a well-defined crystalline structure for the zirconium yttrium oxide. Similar observations were made for samples irradiated by 254 nm UV-C light (Figure 7b). At 2-theta of 30.167°, 50.157° and 60.018°, the diffraction peaks corresponded to certain crystal planes, including (101), (112), and (211) based on Figure 7b.

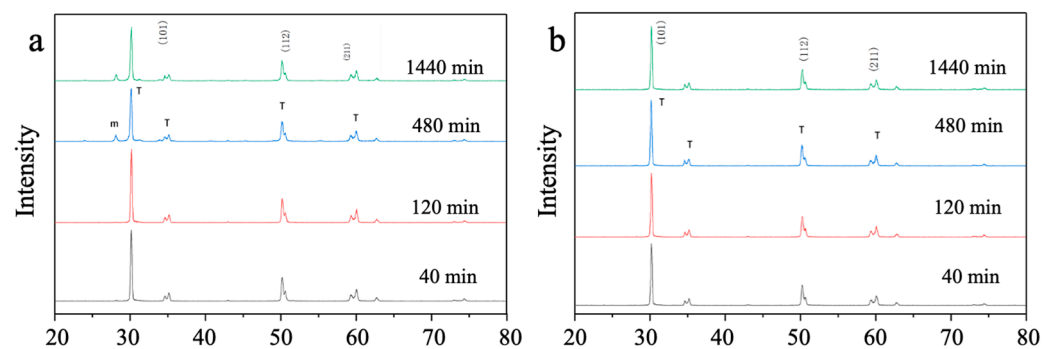


Figure 7. XRD patterns of samples irradiated by 222 nm (a) and 254 nm (b) UV-C lights respectively at 1 cm distance for different irradiation times.

4. Discussion

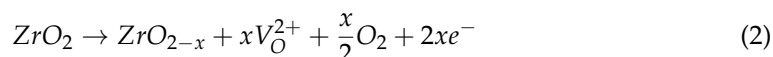
This study systematically investigated the effects of UV-C irradiation under different wavelengths (222 nm and 254 nm), distances (1, 6, and 12 cm), and durations (40 to 1440 min) on the surface properties of dental zirconia. The results demonstrate that UV-C irradiation significantly alters the surface colour, wettability, and surface chemistry without affecting the crystalline structure and surface topography of zirconia.

4.1. Surface Colour Change and Its Mechanism

The observed colour changes ($\Delta E > 2.0$) in all irradiated groups indicate that UV-C irradiation induces clinically perceptible colour shifts in zirconia. This dependence of

ΔE on wavelength, distance, and time suggests a photochemical process influenced by photon energy, accumulated dose, and irradiation geometry. Factors such as scattering and absorption may further modulate the effective surface exposure.

The mechanism underlying this colouration remains to be fully elucidated. A widely cited hypothesis in the literature attributes UV-induced yellowing in yttria-stabilized zirconia to the formation of oxygen vacancies, specifically F-type colour centers. Under high-energy photon irradiation, lattice oxygen may be released, generating doubly ionized oxygen vacancies that trap electrons. These trapped electrons can undergo photoexcitation, reducing the effective band gap and causing increased absorption in the blue/violet region (~430–480 nm), which manifests as a yellow-to-brown hue. This process is often represented schematically as



Several observations in the present study are consistent with this hypothesis, although they do not constitute direct proof. First, the monotonic increase in ΔE with irradiation time supports a cumulative, dose-dependent process—a characteristic feature of defect generation. Second, colouration is uniform across the entire irradiated surface and occurs in the absence of any liquid, solvent, or applied coating. This makes transient surface contamination or adsorbed chromophores unlikely primary causes, as such species would not produce the homogeneous, time-dependent colouration observed. Third, the fact that colouration was not saturated within 24 h suggests continued defect accumulation rather than a self-limiting surface phenomenon.

However, alternative explanations cannot be definitively excluded. Possible mechanisms include UV-induced photolysis of residual surface hydrocarbons (though this typically increases wettability without producing a stable yellow chromophore), subtle changes in local zirconia coordination chemistry, or measurement artefacts related to surface roughening—although profilometry confirmed no significant topographic changes after irradiation (see Section 3.2), mitigating the latter concern.

From a clinical perspective, the perceptibility of $\Delta E > 2.0$ requires careful contextualization. In conventional prosthetic workflows where colour stability is paramount, a ΔE exceeding 2.0 would indeed be considered undesirable. Crucially, however, the colour shift reported in this study is not intended as an uncontrolled side effect, but rather as a deliberately tunable response for specific aesthetic indications. By controlling exposure parameters (e.g., 15 min at 222 nm produces $\Delta E \sim 2\text{--}3$), the clinician can select a target colour shift appropriate to the clinical need—ranging from a subtle warm correction for excessively high-value monolithic zirconia to more pronounced chromaticity when indicated. While this treatment is contraindicated for clinical scenarios requiring pure whiteness, it offers a simple, chairside-compatible alternative to traditional staining techniques in cases where natural, tooth-like warmth is desired.

4.2. Surface Chemistry and Wettability Modifications

Despite the noticeable colour change, SEM images revealed no significant alterations in surface morphology after UV-C irradiation. This indicates that the photochemical reactions primarily occur at the atomic/subatomic level without causing macroscopic topological changes. However, EDX analysis showed a consistent increase in the Zr/O ratio in all irradiated samples compared to the control group, suggesting a relative loss of surface oxygen, likely through the formation of oxygen vacancies as previously discussed. The absence of significant differences among different irradiation times and distances indicates that even short-duration or low-intensity UV exposure can induce measurable surface chemical changes.

The water contact angle (WCA) measurements further confirmed the surface activation by UV-C. For 222 nm irradiation, WCA decreased significantly with increasing time and varied with distance, indicating enhanced hydrophilicity. In contrast, 254 nm irradiation showed a less pronounced distance-dependent effect, with significant WCA reduction mainly observed after longer exposures (480 min and 1440 min). The log-linear relationship between WCA and irradiation time ($r^2 \approx 0.748\text{--}0.773$) supports a time-dependent surface activation process, likely due to the increase in surface hydroxyl groups (Zr–OH) formed via the reaction of oxygen vacancies with atmospheric moisture.

Improved wettability offers clinical advantages, as hydrophilic surfaces promote better adhesive bonding and biological integration. For example, in dental zirconia restorations or implant abutments, improved wettability is particularly important for areas with mucosal penetration. It helps with soft tissue closure (epithelial attachment), reduces bacterial microleakage, and improves the integrity of adhesive margins. However, the differential responses to 222 nm and 254 nm irradiation suggest that wavelength selection should be tailored according to the desired surface property.

4.3. Crystalline Structure Stability

XRD patterns confirmed that neither 222 nm nor 254 nm UV-C irradiation induced phase transformation in the yttria-stabilized zirconia. All characteristic peaks of the tetragonal phase were retained, and no monoclinic phase was detected. This structural stability is crucial for the mechanical integrity of zirconia restorations, as phase transformations (particularly $t \rightarrow m$) are associated with strength degradation and microcracking. The results confirm that UV-induced surface modifications are limited to electronic and chemical changes without compromising the crystalline framework, and previous research has also confirmed that UV irradiation does not reduce the mechanical properties of ZrO₂ [26,35], which is reassuring for the clinical use of UV-treated zirconia.

4.4. Limitations

While this study provides insights into the biomimetic surface modification of dental zirconia via UV-C irradiation, several limitations should be acknowledged. First, the *in vitro* nature of this investigation does not fully replicate the complex oral environment, where factors such as humidity, temperature fluctuations, salivary flow, and masticatory forces may influence the stability and durability of UV-induced surface modifications. Second, wettability assessment was limited to water contact angle measurements; surface free energy (SFE), which provides a more comprehensive characterization of surface thermodynamic properties, was not calculated, and the bioactivity or clinical significance of changes in wettability also requires further investigation. Third, the study focused on a single zirconia brand and composition; thus, the generalisability of the findings to other zirconia formulations (e.g., different yttria content, multilayered or highly translucent grades) requires further validation. Lastly, the biological relevance of the improved wettability—such as its effect on protein adsorption, cell adhesion, or biofilm formation—was not assessed. Future studies should address these limitations through accelerated ageing tests, *in vivo* or simulated oral environment models, surface-sensitive chemical characterization, and biological assays to better establish the clinical translatability of this photon-based functionalization strategy.

5. Conclusions

This study demonstrates that UV-C irradiation is an effective biomimetic surface functionalization strategy capable of synchronously enhancing the aesthetic and interfacial properties of zirconia as a dental biomimetic material. By controlling key parameters

including wavelength, irradiation distance, and duration, UV-C treatment can induce oxygen vacancy formation and bandgap reduction without compromising the material's microstructure and physical properties. Concurrently, the modified surface chemistry (increased Zr/O ratio) significantly improves wettability, thereby enhancing its bio-interfacial activity. While this study still has limitations, such as the lack of intraoral environment simulation testing and the limited variety of zirconia, this study drives a biomimetic optical shift, producing colour changes toward more natural tooth-like shades. Consequently, this photon-based surface modification offers a non-invasive and tunable clinical approach to advance the colour biomimetic integration and potential adhesive performance of zirconia-based restorations.

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