

Original Article

Effect of Printing Orientation and Immersion in Staining Solutions on Surface Roughness and Color Stability of 3D-Printed Removable Complete Dentures

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KEY WORDS

Additive Manufacturing;
Three-Dimensional Printing;
Spectrophotometry;
Surface Roughness;
Discoloration;
Dentures;
Complete;

Received: 6 October 2025;
Revised: 25 November 2025;
Accepted: 2 June 2026;

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ABSTRACT

Background: Additive manufacturing has emerged as a promising technique for fabricating complete dentures, yet the influence of printing parameters- particularly build orientation- on surface quality and color stability remains insufficiently understood.

Purpose: This study aimed to evaluate the effect of three different 3D printing build orientations (0°, 45°, and 90°) on the surface roughness and color stability of removable complete dentures, with the goal of identifying the optimal configuration for clinical application.

Materials and Method: Complete denture bases and artificial teeth were fabricated separately using a 3D printer and subsequently assembled. A total of 90 specimens were fabricated and printed at 0°, 45°, and 90° build orientations (n=10 per subgroup). Surface roughness was measured using a profilometer, and color stability was assessed by spectrophotometric analysis after immersion in commonly encountered staining solutions under simulated oral conditions over time.

Results: Build orientation significantly affected both surface and optical properties of the specimens. The 45° orientation exhibited the highest surface roughness values, whereas the 0° orientation produced the smoothest surfaces. Color evaluation revealed that dentures printed at 90° orientation underwent the greatest discoloration, while those printed at 0° maintained superior color stability throughout the observation period.

Conclusion: Build orientation plays a pivotal role in the long-term esthetic and functional performance of 3D-printed complete dentures. Printing at 0° orientation provides smoother surfaces and improved resistance to discoloration, suggesting it as the most favorable configuration for clinical use. Optimizing printing parameters is essential for enhancing the durability, hygiene, and esthetics of dentures fabricated via additive manufacturing.

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Cite this article as:

Introduction

The fabrication of complete dentures by computer-aided design and computer-aided manufacturing (CAD-CAM) methods has become popular in both clinical and laboratory practices in recent years [1-2]. Two CAD-CAM techniques, a computerized numeric control subtractive milling process and a system of rapid prototyping (RP) that is commonly known as three-dimensional (3D)

printing, an additive manufacturing (AM) process, are available to fabricate CAD-CAM complete dentures [3]. Complete dentures fabricated with either of the CAD-CAM techniques have been evaluated; it is believed that complete dentures that have been elaborated according to digital technology have better mechanical properties, uniform plate thickness in their different sections, and better conformity with the denture field [4-5]. Remova-

ble prostheses fabricated using CAD-CAM technology offer several clinical advantages, such as minimizing the number of required patient visits, enhancing the precision of mucosal fit, and enabling accurate and efficient replication of pre-existing dentures [3, 6-8]. Complete dentures fabricated using the RP technique have also elicited patient satisfaction comparable with that for conventional complete dentures [9-10]. Additionally, 3D printing, as an AM technique, presents notable benefits compared to subtractive manufacturing (SM) methods. The RP approach is cost-effective, as it eliminates tool wear and minimizes material waste, while allowing for the simultaneous production of multiple units [11]. Unlike SM, where fabrication accuracy is constrained by the dimensions and quantity of milling burs, advancements in AM technology have significantly enhanced the consistency and precision of RP-fabricated prostheses [12-14]. Additive technology development and clinical applicability will depend on the gradual improvement of the manufacturing process [15], which implies controlling several variables including the building orientation/direction, the support structure dimension and distribution, and the position of printed parts in the building platform [16]. These variables affect a range of material properties, including dimensional accuracy, flexural strength, compressive strength, flexural modulus, shear bond strength, and surface roughness [17-24]. However, certain characteristics- such as surface roughness [17] and color stability [25-26], remain insufficiently investigated and warrant further research. Printing materials should fulfill the mechanical [27] and biocompatibility requirements needed for the oral service and satisfy patients and clinicians for the esthetic demands. This is why color and optical properties measurement and characterization, and visual color differences evaluation in dentistry are of utter importance [28]. In addition to printing parameters, the exposure of denture base resins to staining media plays a significant role in their long-term color stability, as the interaction between pigments, acidity, and resin polymer matrix may accelerate discoloration and surface degradation. Surface roughness is another critical property, influencing plaque retention, hygiene, and overall esthetics of removable prostheses. Printable acrylic-based materials used in AM exhibit varying degrees of susceptibility to these environmental factors, and their behavior under

prolonged exposure remains insufficiently documented. The present study was designed to evaluate the effect of three different 3D-printing build orientations (0°, 45°, and 90°) on the surface roughness and color stability of 3D-printed denture specimens after immersion in various common staining solutions. The null hypothesis was that printing orientation would have no significant effect on surface roughness or color stability following immersion in different staining media.

Materials and Method

The present research was conducted as an *in vitro* experimental laboratory study using standardized 3D-printed denture specimens. The study protocol was approved by the Ethics Committee of Hamadan University of Medical Sciences (IR.UMSHA.REC.1402.552). A priori power analysis was performed using G*Power (version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) to determine the required sample size. Considering a two-way ANOVA design (3 printing orientations \times 3 immersion solutions), an effect size of $f = 0.25$ (medium), $\alpha = 0.05$ and power $(1-\beta) = 0.80$ (29), the analysis indicated a minimum of 10 specimens per subgroup (total $N = 90$). The selected sample size of 10 specimens per subgroup was determined to provide sufficient statistical power to detect medium-sized effects and their interactions. To evaluate the surface characteristics- namely surface roughness and color stability—of 3D-printed dentures fabricated at varying build angles, first of all a scan was prepared from a maxillary cast model with a missing left first molar. A maxillary cast with a missing left first molar was selected for specimen fabrication, and the molar region was used for surface roughness and color stability measurements. A laboratory scanner (Shining 3D AutoScan DS-EX, Shining 3D Tech Co., Hangzhou, China) was used for digitizing the maxillary cast. The design process was performed using Exocad DentalCAD software (version 3.1; Exocad GmbH, Darmstadt) available in the digital department of The Hamedan Dental Faculty. Next, the teeth and complete denture base for the edentulous region were designed using dental CAD software (Exocad, version 3.1), with a cement gap of 80 μm and a minimum base thickness of 1.5 mm. The specimens were subsequently converted into standard tessellation language (STL) files and imported into dedicated 3D printing software for

fabrication. A digital light processing (DLP) 3D printer (Asiga Freeform PRO2; Asiga, USA) was used to fabricate 90 denture teeth and denture bases as two separate components at 37 °C in three different build orientations (0°, 45°, and 90°). The designated build angles (0°, 45°, and 90°) were set digitally within the printer software relative to the build platform prior to support generation and printing. In total, 90 complete denture specimens were produced and divided into three printing orientation groups (0°, 45°, and 90°). For each build angle (0°, 45°, and 90°), 30 specimens were fabricated (total = 90). Each printing orientation was further divided into three immersion solution subgroups (distilled water, orange juice, and black tea), with 10 specimens allocated to each subgroup (Figure 1), resulting in a 3×3 factorial design (n= 10 per subgroup).

Temporary crown resin material (Detax temp/made in Germany) was used for printing the teeth and pink resin (Free print denture base/made in Germany) for denture bases. Following fabrication, the resin specimens u-



Figure 1: Allocation of 3D-printed specimens into staining solutions

nderwent a two-step cleansing process using 90% isopropyl alcohol for one minute per cycle. Post-curing was performed in a UV polymerization chamber (manufacturer and model details: an institution-supplied standard unit), following the manufacturer's instructions. Residual support structures were eliminated using a low-speed rotary handpiece. Thereafter, both sides of each sample were meticulously finished with water-cooled abrasive papers, progressing to a 1200-grit level. To finalize the surface preparation, all specimens were immersed in an ultrasonic bath for five minutes to eliminate any remaining surface contaminants. Each of the dental and gingival parts was fixed together based on support structures on buccal and palatal walls with light cure pink acrylic resin (Stellar DC Acrylic-Pink) inside the corresponding cavity in the denture base. The denture teeth were bonded into the denture base recesses using a dual-cure gingival acrylic resin (Stellar DC Acrylic Pink; Taubin Dental Products, USA), following the manufacturer's recommendations. Each sample was placed in the UV device under 285nm radiation is placed for 3 minutes post-curing then samples were ground with SiC paper (grit 800) and rinsed with water. To provide a clearer understanding, the printed sample illustration can be observed in Figure 2, offering a visual representation of the concept discussed. Figure 2 illustrates a representative 3D-printed denture base and denture tooth used in the experiment, confirming the morphology of the printed samples and supporting the description of the fabrication process.

The baseline color measurements of the specimens were performed using a spectrophotometer (VITA Easyshade V, digital spectrophotometer). Color measurements were obtained using the CIE Lab* color space, applying the CIE 10-degree standard observer in conjunction with the D65 standard illumination source.

Prior to each measurement session, the device was



Figure 2: The printed sample used for color and hardness testing

calibrated using the manufacturer-supplied white calibration plate. Following baseline color assessment, the specimens within each group were randomly allocated into three subgroups (n=10) and subsequently immersed in one of the following solutions: distilled water, orange juice, or black tea. Tea was prepared by placing 10 g of black tea (ALSAAD Tea, Morocco, North Africa) in 500 mL of boiling water for 15 minutes. Orange juice solution was prepared by dissolving 15 g of powdered drink mix (Tri-C Orange Flavored Artificial Drink Powder, Flavourtech, Turkey) in 250 mL of cold water. All solutions were freshly prepared prior to immersion. The specimens immersed in the staining media were stored in an incubator maintained at 37 °C under dark conditions to prevent light-induced alterations. The staining solutions were renewed on a daily basis, and the aging process was continued for a total duration of 30 days. Color measurements were taken at specific time intervals (1, 7, and 30 days post-immersion), and the color difference (ΔE_{00}) was calculated using the CIEDE1976 formula. According to the study of Guler *et al.* [30], 24 hours of exposure to tea simulates approximately 30 days of regular consumption. Color differences (ΔE) were calculated based on the CIELAB color space, which defines color using a three-axis system. In this model, the L^* axis represents lightness, ranging from 0 (pure black) to 100 (pure white). The a^* coordinate reflects chromaticity along the red-green axis, with positive values indicating redness and negative values indicating greenness. Similarly, the b^* coordinate represents the yellow-blue spectrum, where positive values correspond to yellow and negative values to blue.

$$\Delta E_{76} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$$

Ra was evaluated using a contact profilometer (Test Tech NDT, TR200plus) in accordance with ISO 4287 standards. The device operates within a vertical measuring range of $\pm 80 \mu\text{m}$. Three measurements were recorded from non-overlapping areas of the central palatal region of each specimen, and the mean Ra value was calculated and used for statistical analysis. Each specimen was placed on a stable flat platform, and measurements were performed under standardized conditions according to ISO 4287. A cut-off length of 0.8mm and a tracing length of 4.0mm were used, with the stylus moving at a constant speed of 0.1mm/s. Three readings were obtained from the central palatal region of each speci-

men, ensuring that each measurement was taken in a non-overlapping area. The mean Ra value of these three readings was calculated and used as the representative surface roughness for statistical analysis.

The collected numerical data were entered into SPSS software (version 26.0; IBM Corp., Armonk, NY, USA) for statistical analysis. Prior to inferential testing, data distribution was examined using the Shapiro–Wilk test to confirm normality, and homogeneity of variances was assessed using Levene’s test. Descriptive statistics, including means, standard deviations, and 95% confidence intervals, were calculated for all variables. To evaluate the influence of printing orientation and immersion solution on surface roughness and color difference, a two-way analysis of variance (ANOVA) was performed to test both main effects and interaction effects between the two factors. When statistically significant differences were detected, pairwise post-hoc comparisons were conducted using Tukey’s HSD test to identify specific group differences. Furthermore, repeated-measures ANOVA was applied to analyze the effect of immersion time on changes in surface roughness and color values across measurement intervals. Mauchly’s test of sphericity was carried out, and when the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. All statistical tests were performed using a significance level of $\alpha = 0.05$.

Results

Color stability

Table 1 presents the mean ΔE_{00} values for all printing angles, immersion solutions, and time intervals. Tea and orange juice produced greater discoloration than distilled water across all printing orientations. ΔE_{00} values incr-

Table 1: Color stability of 3D-printed dentures at different build angles, immersion solutions, and time intervals (Mean±STD), analyzed using One-Way Repeated Measures ANOVA

Staining Solution	Print angle	Day 1	Day 7	Day 30
		Mean+STD	Mean+STD	Mean+STD
Orange Juice	0°	4.21+0.98	3.87+1.02	5.25+0.76
	45°	3.00+0.53	3.27+1.29	4.70+0.66
	90°	4.24+1.04	4.58+0.40	8.77+0.98
Tea	0°	3.87+0.74	4.00+1.07	17.80+3.26
	45°	3.34+0.99	4.30+0.91	21.89+3.96
	90°	3.64+0.53	5.16+0.25	22.79+1.45
Distilled water	0°	3.63+0.14	3.78+0.55	4.32+0.58
	45°	2.73+0.23	3.87+0.62	4.46+0.30
	90°	2.75+1.08	3.02+0.40	3.50+0.59

STD: standard deviation; ANOVA: analysis of variance

Table 2: Statistical tests and *p* values corresponding to color stability results

Analysis level / Comparison	Statistical test	<i>p</i> Value
Effect of print angle with-in Orange juice	One-Way Repeated Measures ANOVA	<0.001
Effect of print angle with-in Tea	One-Way Repeated Measures ANOVA	0.002
Effect of print angle with-in Distilled water	One-Way Repeated Measures ANOVA	<0.001
Effect of immersion solution at print angle 0°	One-Way Repeated Measures ANOVA	<0.001
Effect of immersion solution at print angle 45°	One-Way Repeated Measures ANOVA	<0.001
Effect of immersion solution at print angle 90°	One-Way Repeated Measures ANOVA	<0.001
Main effect of immersion solution	Two-Way Repeated Measures ANOVA	<0.001
Main effect of print angle	Two-Way Repeated Measures ANOVA	<0.001
Interaction: solution×print angle	Two-Way Repeated Measures ANOVA	<0.001
Pairwise comparisons of print angles	Post Hoc Test (Tukey)	<0.001
Pairwise comparisons of staining solutions	Post Hoc Test (Tukey)	<0.001

eased from day 1 to day 30 in all groups, and specimens printed at 90° showed the highest discoloration within each solution, particularly in the tea.

The statistical results for color stability are summarized in Table 2. Printing angle and immersion solution had statistically significant effects on ΔE00 (*p* < 0.001), and a significant interaction was observed between the two factors (*p* < 0.001). Within orange juice and distilled water, printing angle significantly affected ΔE00 (*p* < 0.001). In tea, the most pronounced difference was between 0° and 90° (*p* = 0.002). Within each printing angle (0°, 45°, and 90°), immersion solution significantly influenced color change (*p* < 0.001). Tukey post hoc comparisons confirmed multiple significant pairwise differences among printing angles and staining solutions as reported in Table 2.

Figure 3 shows the interaction between printing angle, immersion solution, and immersion time. ΔE00 values increased from day 1 to day 7 and from day 7 to day 30 for all conditions. Tea produced the highest discoloration at all time points, followed by orange juice and distilled water. Samples printed at 90° generally exhibited higher ΔE00 values than those printed at 0° and 45°.

Surface roughness

Table 3 presents the mean surface roughness (Ra) values for denture teeth and denture bases across printing angl-

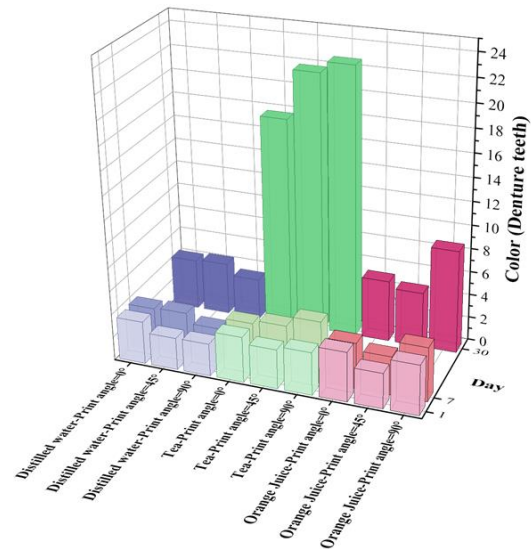


Figure 3: Investigation of the effects of immersion solutions, print angles, and time intervals on color changes

es, immersion solutions, and time points. Specimens printed at 45° frequently exhibited higher Ra values compared with those printed at 0° and 90°. Roughness values progressively increased from day 1 to day 30 in all groups. Orange juice and tea produced greater increases in Ra compared with distilled water.

Table 4 summarizes the statistical analysis for surface roughness. Staining solution (*p* < 0.001), sample type (*p* = 0.01), and printing angle (*p* < 0.001) showed statistically significant main effects. A significant interaction was found between sample type and printing angle (*p* = 0.02), while all other interactions were not statistically

Table 3: Surface roughness of 3D-printed dentures at different build angles, immersion solutions, and time intervals (Mean±SD), analyzed using One-Way Repeated Measures ANOVA

Staining solutions	Sample	Print angle	Day 1 Mean±STD	Day 7 Mean±STD	Day 30 Mean±STD
Orange Juice	Denture teeth	0°	0.04+0.04	0.08+0.05	0.14+0.05
		45°	0.06+0.01	0.17+0.02	0.29+0.03
		90°	0.09+0.06	0.12+0.04	0.21+0.05
Tea	Denture Base	0°	0.03+0.03	0.06+0.03	0.18+0.08
		45°	0.09+0.06	0.16+0.07	0.31+0.07
		90°	0.05+0.03	0.10+0.06	0.20+0.04
Distilled water	Denture teeth	0°	0.02+0.02	0.06+0.04	0.11+0.04
		45°	0.07+0.02	0.14+0.02	0.29+0.05
		90°	0.05+0.04	0.14+0.04	0.22+0.05
Orange Juice	Denture Base	0°	0.03+0.03	0.02+0.06	0.10+0.06
		45°	0.06+0.07	0.14+0.03	0.25+0.05
		90°	0.03+0.04	0.07+0.05	0.15+0.08
Tea	Denture teeth	0°	0.01+0.01	0.05+0.04	0.11+0.03
		45°	0.05+0.02	0.14+0.02	0.26+0.02
		90°	0.04+0.06	0.11+0.07	0.22+0.06
Distilled water	Denture Base	0°	0.02+0.04	0.03+0.04	0.09+0.05
		45°	0.05+0.05	0.16+0.03	0.24+0.03
		90°	0.07+0.11	0.07+0.10	0.13+0.09

STD: standard deviation; ANOVA: analysis of variance

Table 4: Statistical tests and *p* Values corresponding to surface roughness results

Analysis level / Comparison	Statistical test	<i>p</i> Value
Main effect of staining solution	Three-way Repeated Measures ANOVA	< 0.001
Main effect of sample type (teeth vs base)	Three-way Repeated Measures ANOVA	0.01
Main effect of print angle	Three-way Repeated Measures ANOVA	< 0.001
Interaction: Staining solution × Sample type	Three-way Repeated Measures ANOVA	0.141
Interaction: Staining solution × Print angle	Three-way Repeated Measures ANOVA	0.919
Interaction: Sample type × Print angle	Three-way Repeated Measures ANOVA	0.02
3-way interaction: Solution×Sample×Print angle	Three-way Repeated Measures ANOVA	0.996
0° vs 45° (print angle)	Post Hoc Test (Tukey)	< 0.001
0° vs 90° (print angle)	Post Hoc Test (Tukey)	< 0.001
45° vs 90° (print angle)	Post Hoc Test (Tukey)	< 0.001
Orange juice vs Tea (solution)	Post Hoc Test (Tukey)	0.003
Orange juice vs Distilled water	Post Hoc Test (Tukey)	< 0.001
Tea vs Distilled water	Post Hoc Test (Tukey)	0.642

significant. Tukey post hoc comparisons demonstrated significant pairwise differences among all printing angles (0°-45°, 0°-90°, and 45°-90°; *p*< 0.001). For immersion solutions, orange juice differed significantly from tea (*p*= 0.003) and distilled water (*p*< 0.001), while tea and distilled water did not differ significantly (*p*=0.642).

Figures 4-5 depict the roughness progression for denture teeth and denture bases. In all conditions, Ra values increased across the three time intervals, with high

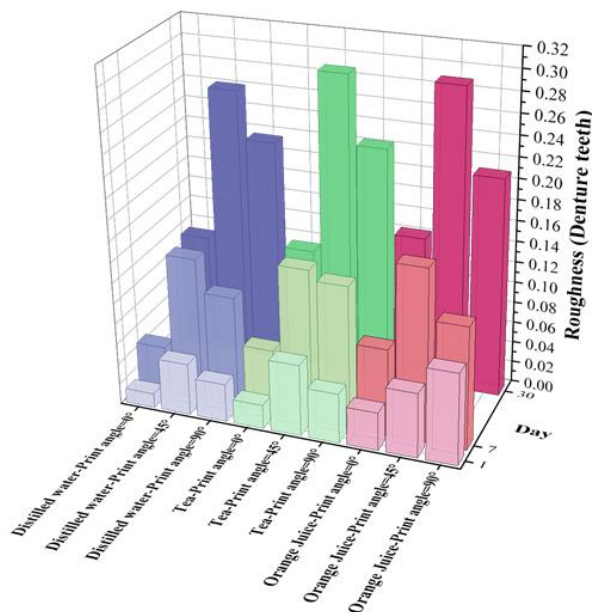


Figure 4: Surface roughness measurements of denture teeth at different printing angles, immersion solutions, and time intervals

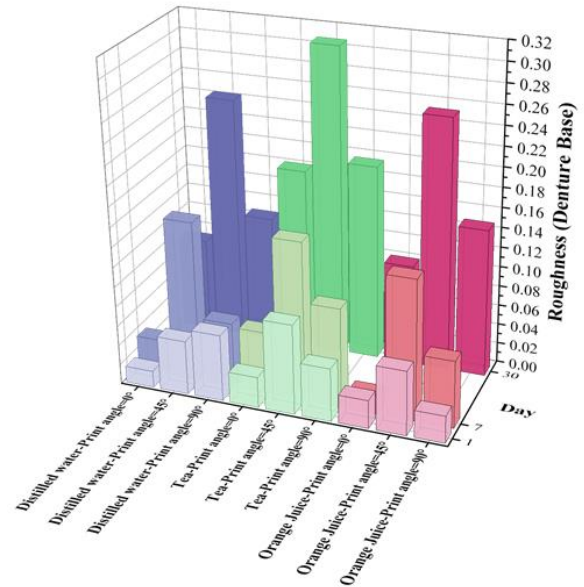


Figure 5: Surface roughness measurements of denture base at different printing angles, immersion solutions, and time intervals

er roughness values observed in immersion in tea and orange juice compared with distilled water.

Discussion

The purpose of this study was to evaluate the effect of printing orientation on the surface characteristics, and the color stability and stainability of 3D-printed denture resin specimens fabricated with the DLP printer. Based on the statistical results, significant differences were detected across printing orientations; therefore, the null hypothesis- stating that printing angle would have no effect on color stability or surface roughness- was rejected.

In relation to the prolonged clinical use of complete dentures, factors such as plaque accumulation, cleaning efficacy, and surface discoloration are strongly influenced by the surface properties of the denture base material [31-32]. The influence of printing angle is evident, with specimens printed at 90° consistently exhibiting the highest ΔE00 values across all media and time intervals. This could be attributed to surface texture or layer orientation at this build angle, which may promote greater absorption of staining agents. On the other hand, dentures printed at 45° demonstrated relatively lower ΔE00 values, suggesting better resistance to discoloration in comparison to 0° and 90° angles. These findings highlight the strong staining potential of tea, likely due to its chromogens and tannins. Orange juice also caused

noticeable color changes, particularly at the 90° orientation, likely due to its acidic nature. In contrast, distilled water resulted in the least color change across all angles and time points, indicating its minimal impact as a neutral medium. *In vitro* incubation of specimens in staining solutions for 24 hours has been shown to mimic the effects of 30 days of food exposure [33]. Moreover, an immersion duration of 30 days in a coffee solution has been estimated to simulate roughly 2.5 years of regular coffee intake under clinical conditions [34]. The specimens were maintained in an incubator at 37°C to simulate oral temperature. To eliminate the influence of ambient light on color changes, the specimens immersed in staining solutions were kept in a dark environment.

Color changes increased progressively across all groups, with the greatest differences occurring between day 1 and day 30. This trend highlights the cumulative effect of prolonged exposure to staining solutions. Tea, in particular, exhibited a more marked and progressive discoloration effect, emphasizing the importance of long-term evaluations in assessing materials. The observed color stability results are consistent with the expected physical and chemical interactions between 3D-printed resin surfaces and staining solutions. The significant influence of print angle on color stability in orange juice and distilled water can be attributed to the exposure of layer lines and surface irregularities, which vary with orientation and facilitate differential absorption of staining agents. For tea, differences between printing angles were less pronounced, likely due to its uniformly high chromogenic potential, which can overshadow structural variations. Similarly, the significant effects of immersion solutions across fixed angles underscore the critical role of solution chemistry, with acidic environments (like orange juice) promoting polymer breakdown and enhanced discoloration, while neutral solutions like distilled water exert minimal but still measurable effects.

These interactions likely result from variations in surface topography across print angles, which influence solution penetration and staining. Acidic and chromogenic solutions, such as orange juice and tea, interact differently with the microstructural variations introduced by print angles, amplifying discoloration in specific combinations [35]. The contact angle of a liquid on the resin surface serves as an indicator of the total sur-

face energy and wettability, which in turn influences the color stability and susceptibility to staining of 3D-printed resins immersed in staining solutions. A smaller contact angle suggests better wettability, thereby increasing the likelihood of discoloration due to staining [35]. Eun-Hyuk Lee *et al.* (26) reported that the ΔE_{00} values for the 0-degree orientation group were significantly lower than those of the 45-degree and 90-degree orientation groups with the same layer thickness, when immersed in staining solutions at the same time interval. In contrast, Castro *et al.* [36] found no effect from the printing angle on color change. Tuğba Temizci *et al.* [37] demonstrated the highest color change in samples produced at 90. Espinar *et al.* [25] also reported significant differences between 0° and 90° orientations. Similarly, our findings show that higher print angles intensify the staining effects due to increased surface exposure. These findings highlight the complex interplay between material structure, printing parameters, and environmental exposure in determining long-term performance. Since no universally accepted optimal build orientation has been established in the existing literature, the present study directly compared the three most commonly used printing orientations (0°, 45°, and 90°). The findings suggest that printing orientation plays a critical role in determining both surface roughness and color stability, with lower build angles generally demonstrating more favorable surface characteristics. These observations may assist clinicians and dental technicians in selecting appropriate printing parameters for improved long-term prosthetic performance. They also show that both printing angle and immersion medium act synergistically in influencing staining behavior.

Surface characteristics play a critical role in microbial adhesion to denture base surface [38-39]. A rough and hydrophobic surface is conducive to plaque adhesion [31, 40]. The smaller the Ra values, the smoother the surface becomes. A previous study [41] examined the effect of surface roughness on hydrophobicity, revealing that an increase in surface roughness corresponds to enhanced hydrophobic properties. Our results suggest that orange juice, with its acidic and potentially erosive properties, has a more pronounced impact on surface roughness compared to the other solutions. The absence of a significant difference between tea and distilled water further emphasizes the role of solution pH

and composition in determining surface alterations. From a prosthodontic perspective, these findings provide a basis for advising patients on the potential effects of dietary habits on the surface quality of 3D-printed dentures. For example, limiting exposure to highly acidic solutions may help reduce surface degradation. For denture teeth, orange juice caused slightly higher roughness, whereas for denture bases, tea produced the most pronounced increase. Conversely, for the denture base, tea was associated with the most pronounced increase in roughness. These differences underscore the unique interactions between the material surfaces and the chemical properties of the solutions. Most notably, the printing angle had a significant effect on surface roughness. Across both denture teeth and denture base samples, the 45° build angle consistently resulted in the highest roughness values, followed by the 90° angle, with the 0° angle exhibiting the lowest roughness. This uniform trend suggests that the 45° orientation may create inherent microstructural vulnerabilities or surface irregularities that exacerbate roughness under environmental exposure. Similarly, Ping Li *et al.* [42], study showed that surface roughness (Sa value) was significantly affected by the build angle rather than by the AM method and the build angle of 45° showed the inferior surface characteristics for both stereolithography apparatus (SLA) and digital light processing (DLP) denture bases. In contrast, de Castro *et al.* [36] indicated that build orientation did not influence any of the variables evaluated (Sa and $\Delta E00$). However Shan Yan *et al.* [43] demonstrated that specimens fabricated at a 0-degree build angle exhibited the most advantageous surface qualities, characterized by smoother topography and enhanced hydrophilic behavior. Moreover, the highest roughness was observed in the group printed at a 45-degree orientation in Ji Suk Shim *et al.* [44] study; in specimens printed at a 45-degree orientation, the layers were deposited in a staggered manner, resulting in step-wise interfaces. These interlayer step formations contributed to deviations in dimensional precision and increased surface roughness. By minimizing the height of step edges through reduction in layer thickness, the errors in both thickness and surface roughness of specimens printed at a 45-degree orientation may be improved. Cheng *et al.* [45] further reported that incorporating a mild inclination angle (15°) along with a de-

creased layer thickness (25 μm) resulted in noticeably smoother surfaces, effectively minimizing the staircase artifact typically observed in AM. In Christin Arnold *et al.* [46] studied between 0° and 15° print angle, the samples with a support structure (15° inclination) showed their highest Ra values in the X direction, particularly at the printing resolution of 100 μm .

From a prosthodontic perspective, these findings carry significant clinical implications, as increased roughness can negatively affect aesthetics, hygiene, and the longevity of 3D-printed prostheses. Increased roughness can negatively impact the aesthetics, hygiene, and longevity of 3D-printed prostheses. The pronounced effect of the 45° build angle suggests that clinicians and technicians should exercise caution when selecting printing parameters, particularly for patients requiring prostheses exposed to challenging oral environments. Additionally, the variable influence of immersion solutions highlights the need for patient-specific recommendations regarding dietary habits and oral hygiene practices may help reduce surface degradation over time. Results underscore the complex interplay between printing parameters, environmental factors, and material properties in determining the long-term performance of 3D-printed dental prostheses. Future research should focus on optimizing printing strategies and material formulations to enhance surface stability and reduce susceptibility to roughness under real-world conditions. One limitation of this study was the lack of investigation into the mechanisms by which layer thickness and printing orientation (15°, 25°, 75°) influence discoloration and surface roughness. The current study investigates a single 3D printing method and resin material. Future research should expand to assess the performance of build angles across different manufacturing processes and materials. This study was conducted *in vitro*, whereas the oral environment is far more complex, involving factors such as the presence of saliva, oral flora adhesion, and temperature fluctuations, which cannot be fully replicated under the present experimental conditions. Moreover, various factors in 3D printing, such as layer thickness and post-curing temperature, may influence the results and should be considered in future studies.

Overall, these results underscore the importance of selecting optimal build angles to minimize surface ir-

regularities, highlighting that printing orientation is a key factor influencing prosthetic outcomes. Clinically, these findings highlight that the choice of build angle during the printing process is not merely a technical consideration but a key factor influencing prosthetic outcomes.

Conclusion

The findings of this study demonstrate that printing orientation significantly influenced both color stability and surface roughness of 3D-printed dentures. Specimens printed at a 90° orientation exhibited the greatest discoloration over time, indicating higher susceptibility to staining. Regarding surface characteristics, the highest surface roughness was observed in specimens printed at a 45° orientation, followed by 90°, while the 0° orientation produced the smoothest surfaces. These results highlight the importance of optimal build-angle selection to improve the aesthetic and functional performance of 3D-printed dental prostheses.

Funding information

The authors declare that no funding was received for this study.

Data availability statement

The original data is available upon request.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

- [1] Baba NZ, AlRumaih HS, Goodacre BJ, Goodacre CJ. Current techniques in CAD/CAM denture fabrication. *Gen Dent*. 2016; 64: 23-28.
- [2] Torabi K, Farjood E, Hamedani S. Rapid prototyping technologies and their applications in prosthodontics: a review of literature. *J Dent (Shiraz)*. 2015; 16: 1-9.
- [3] Kattadiyil MT, Al-Helal A. An update on computer-engineered complete dentures: a systematic review on clinical outcomes. *J Prosthet Dent*. 2017; 117: 478-485.
- [4] Hirayama H. Digital removable complete denture (DRCDD). In: Miyazaki T, Hotta Y, Baba K, editors. *Digital Restorative Dentistry: A Guide to Materials, Equipment, and Clinical Procedures*. 1st ed. Quintessence Pub: Tokyo; 2019. p. 115-136.
- [5] Steinmassl O, Dumfahrt H, Grunert I, Steinmassl PA. CAD/CAM produces dentures with improved fit. *Clin Oral Investig*. 2018; 22: 2829-2835.
- [6] Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. *J Prosthet Dent*. 2013; 109: 361-366.
- [7] Kattadiyil MT, Jekki R, Goodacre CJ, Baba NZ. Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting. *J Prosthet Dent*. 2015; 114: 818-825.
- [8] Bidra AS, Farrell K, Burnham D, Dhingra A, Taylor TD, Kuo CL. Prospective cohort pilot study of 2-visit CAD/CAM monolithic complete dentures and implant-retained overdentures: clinical and patient-centered outcomes. *J Prosthet Dent*. 2016; 115: 578-586.
- [9] Ucar Y, Akova T, Aysan I. Mechanical properties of polyamide versus different PMMA denture base materials. *J Prosthodont*. 2012; 21: 173-176.
- [10] Inaya Pereyra NM, Marano J, Subramanian G, Quek S, Leff D. Comparison of patient satisfaction in the fabrication of conventional dentures vs. DENTCA (CAD/CAM) dentures: a case report. *J N J Dent Assoc*. 2015; 86: 26-33.
- [11] Alikhasi M, Jafarian Z. Additional manufactured interim restorations: a review on the literature. *J Dent (Shiraz)*. 2022; 23: 424-431.
- [12] Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. *Int J Dent*. 2014; 2014: 1-9.
- [13] Berman B. 3-D printing: the new industrial revolution. *Bus Horiz*. 2012; 55: 155-162.
- [14] Bosch G, Ender A, Mehl A. A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes. *J Prosthet Dent*. 2014; 112: 1425-1431.
- [15] Bafandeh MA, Alihemmati M, Jamali Ghomi A, Jahangiri M, Sherafatmand Y, Shayegh SS. *In vitro* accuracy of dental 3D printers for the fabrication of laminate veneers with different preparation designs. *J Dent (Shiraz)*. 2025; 23: 123-130.
- [16] Alharbi N, Wismeijer D, Osman RB. Additive manufacturing techniques in prosthodontics: where do we currently stand? A critical review. *Int J Prosthodont*. 2017; 30: 432-444.
- [17] Khanlar LN, Revilla-León M, Barmak AB, Ikeda M, Alsandi Q, Tagami J, et al. Surface roughness and shear bond strength to composite resin of additively manufac-

- tured interim restorative material with different printing orientations. *J Prosthet Dent.* 2023; 129: 788-795.
- [18] Castro EF, Nima G, Rueggeberg FA, Giannini M. Effect of build orientation in accuracy, flexural modulus, flexural strength, and microhardness of 3D-printed resins for provisional restorations. *J Mech Behav Biomed Mater.* 2022; 136: 105479-105490.
- [19] Yu BY, Son K, Lee KB. Evaluation of intaglio surface trueness and margin quality of interim crowns in accordance with the build angle of stereolithography apparatus 3-dimensional printing. *J Prosthet Dent.* 2021; 126: 231-237.
- [20] Keßler A, Hickel R, Ilie N. *In vitro* investigation of the influence of printing direction on the flexural strength, flexural modulus and fractographic analysis of 3D-printed temporary materials. *Dent Mater J.* 2021; 40: 641-649.
- [21] Derban P, Negrea R, Rominu M, Marsavina L. Influence of the printing angle and load direction on flexure strength in 3D printed materials for provisional dental restorations. *Materials (Basel).* 2021; 14: 3376-3388.
- [22] Ryu JE, Kim YL, Kong HJ, Chang HS, Jung JH. Marginal and internal fit of 3D printed provisional crowns according to build directions. *J Adv Prosthodont.* 2020; 12: 225-231.
- [23] Park GS, Kim SK, Heo SJ, Koak JY, Seo DG. Effects of printing parameters on the fit of implant-supported 3D printing resin prosthetics. *Materials (Basel).* 2019; 12: 2533-2544.
- [24] Osman RB, Alharbi N, Wismeijer D. Build angle: does it influence the accuracy of 3D-printed dental restorations using digital light-processing technology? *Int J Prosthodont.* 2017; 30: 182-188.
- [25] Espinar C, Della Bona A, Pérez MM, Tejada-Casado M, Pulgar R. The influence of printing angle on color and translucency of 3D printed resins for dental restorations. *Dent Mater.* 2023; 39: 410-417.
- [26] Lee EH, Ahn JS, Lim YJ, Kwon HB, Kim MJ. Effect of layer thickness and printing orientation on the color stability and stainability of a 3D-printed resin material. *J Prosthet Dent.* 2022; 128: 1-8.
- [27] Tasaka A, Okano H, Odaka K, Matsunaga S, Goto T, Abe S, et al. Comparison of artificial tooth position in dentures fabricated by heat curing and additive manufacturing. *Aust Dent J.* 2021; 66: 182-187.
- [28] Espinar C, Della Bona A, Pérez MM, Pulgar R. Color and optical properties of 3D printing restorative polymer-based materials: a scoping review. *J Esthet Restor Dent.* 2022; 34: 853-864.
- [29] Cohen J. *Statistical power analysis for the behavioral sciences.* Routledge; 2013 May 13.
- [30] Guler AU, Yilmaz F, Kulunk T, Guler E, Kurt S. Effects of different drinks on stainability of resin composite provisional restorative materials. *J Prosthet Dent.* 2005; 94: 118-124.
- [31] Gendreau L, Loewy ZG. Epidemiology and etiology of denture stomatitis. *J Prosthodont.* 2011; 20: 251-260.
- [32] Al-Dwairi ZN, Al-Quran FA, Al-Omari OY. The effect of antifungal agents on surface properties of poly(methyl methacrylate) and its relation to adherence of *Candida albicans*. *J Prosthodont Res.* 2012; 56: 272-280.
- [33] Ertas E, Guler AU, Yucel AC, Koprulu H, Guler E. Color stability of resin composites after immersion in different drinks. *Dent Mater J.* 2006; 25: 371-376.
- [34] Shin JW, Kim JE, Choi YJ, Shin SH, Nam NE, Shim JS, et al. Evaluation of the color stability of 3D-printed crown and bridge materials against various sources of discoloration: an *in vitro* study. *Materials (Basel).* 2020; 13: 5359-5370.
- [35] Gould RF. *Contact Angle, Wettability, and Adhesion.* American Chem Soc; Washington (DC): 1964. p.1-51.
- [36] de Castro EF, Nima G, Rueggeberg FA, Araújo-Neto VG, Faraoni JJ, Palma-Dibb RG, et al. Effect of build orientation in gloss, roughness and color of 3D-printed resins for provisional indirect restorations. *Dent Mater.* 2023; 39: e1-e11.
- [37] Temizci T, Kölüş T. Effects of printing angle and post-curing time on the color and translucency of 3D-printed temporary restoration. *Biomimetics (Basel).* 2024; 9: 420-431.
- [38] Schubert A, Wassmann T, Holtappels M, Kurbad O, Krohn S, Bürgers R. Predictability of microbial adhesion to dental materials by roughness parameters. *Coatings.* 2019; 9: 456-467.
- [39] Ferreira M, Barboza A, Fernandez M, Ribeiro de Andrade J, Pappen F, Hwang G, et al. Antifungal agents incorporated in denture base materials: a scoping review of the current evidence and technology prospecting. *Aust Dent J.* 2024; 69: 1-9.
- [40] Kraemer Fernandez P, Unkovskiy A, Benkendorff V, Klink A, Spintzyk S, et al. Surface characteristics of milled and 3D printed denture base materials following polishing and coating: an *in vitro* study. *Materials (Basel).*

- 2020; 13: 3305-3320.
- [41] De Foggi CC, Machado AL, Zamperini CA, Fernandes D, Wady AF, Vergani CE. Effect of surface roughness on the hydrophobicity of a denture-base acrylic resin and *Candida albicans* colonization. *J Investig Clin Dent*. 2016; 7: 141-148.
- [42] Li P, Fernandez PK, Spintzyk S, Schmidt F, Beuer F, Unkovskiy A. Effect of additive manufacturing method and build angle on surface characteristics and *Candida albicans* adhesion to 3D printed denture base polymers. *J Dent*. 2022; 116: 889-902.
- [43] Yan S, Zhou JL, Zhang RJ, Tan FB. Evaluation of the influence of different build angles on the surface-characteristics, accuracy, and dimensional stability of the complete denture base printed by digital light processing. *Heliyon*. 2024; 10: e1-e9.
- [44] Shim JS, Kim JE, Jeong SH, Choi YJ, Ryu JJ. Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. *J Prosthet Dent*. 2020; 124: 468-475.
- [45] Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. *J Dent*. 2021; 109: 103630-103642.
- [46] Arnold C, Monsees D, Hey J, Schweyen R. Surface quality of 3D-printed models as a function of various printing parameters. *J Mater*. 2019; 12: 1970-1985.