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Assessing the impact of surface treatment, aging, and post-curing conditions on the water sorption and solubility of 3D-printed denture base resins compared to conventional and milled alternatives

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Abstract

Background High water sorption and solubility in total denture base materials are primary factors contributing to prosthetic failure, as they compromise both mechanical and aesthetic properties. This study investigated how three distinct surface treatments, varying aging protocols, and different curing parameters collectively influence the water sorption (Wsp) and solubility (Wsl) of 3D-printed denture base materials.

Materials and methods This study evaluated the water sorption and solubility of 420 disc-shaped specimens (Ø15 × 2 ± 0,2 mm) fabricated from one conventional heat-cured acrylic resin (Probase; HC), one CAD-CAM Prepolymerized PMMA block (Bilkim; M), and one 3D-printed denture base material (Formlabs; 3DP). All groups underwent three distinct surface treatments (mechanical polishing, Optiglaze, or Vita Akzent Glaze). The 3D-printed specimens were additionally subjected to four curing durations (10, 15, 30, 60 min) and two curing atmospheres (air and glycerin). Water sorption (Wsp) and solubility (Wsl) were assessed after three distinct aging protocols: 7 days of immersion in distilled water (Wsp-DW and Wsl-DW), 6 days of immersion in a denture cleaner (Wsp-DC and Wsl-DC), and 2000 thermocycles (Wsp-TC and Wsl-TC). Statistical analysis was conducted using non-parametric tests, as the Kolmogorov-Smirnov test revealed that the data were not normally distributed ($p < 0.05$). The Mann-Whitney U test was applied for comparisons between two categorical variables, while the Kruskal-Wallis test was used for three or more categories. For related groups, the Friedman test was employed. Pairwise comparisons were performed to identify specific differences among groups. All statistical analyses were conducted with significance levels set at $\alpha = 0.05$ and 0.01.

Results This study demonstrates that both manufacturing technology and surface treatment significantly influence the water sorption and solubility of dental acrylics. Conventional heat-polymerized acrylics exhibited the highest water sorption, whereas 3D-printed materials consistently showed the lowest ($p < 0.01$). Regarding solubility, heat-

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cured materials generally displayed the lowest values. Conversely, 3D-printed materials had the highest Wsl-DW and Wsl-TC, but the lowest Wsl-DC ($p < 0.01$). Glaze application effectively reduced both water sorption and solubility across all groups compared to mechanical polishing. Lastly, while glycerin curing of 3D-printed resins led to higher sorption but lower solubility, curing duration generally had no significant impact, with some 10-minute cured groups occasionally showing higher solubility ($p < 0.01$).

Conclusion All 3D-printed groups, irrespective of surface treatment or curing parameters, demonstrated water sorption (Wsp) and solubility (Wsl) values within the limits defined by ISO 4049 – 2019 (Wsp < 40 µg/mm^3; Wsl < 7.5 µg/mm^3). While glaze application effectively reduces these properties, adequate curing time and the use of a glycerin curing medium can similarly diminish solubility. However, curing duration was not found to have a statistically significant impact on water sorption.

Keywords Glaze, 3D-printing, Post-curing time, Post-curing atmosphere, Water sorption, Solubility

Introduction

3D-printed denture base materials are continually developing, with the potential to essentially replace traditional and milled options [1, 2]. This shift is driven by the significant benefits of additive manufacturing technology, including a substantial reduction in material waste, which helps mitigate environmental pollution through fewer byproducts, lower overall production costs, fewer appointments required, the ability to create complex geometries, and improved fit and accuracy of denture bases [3–8]. These combined advantages make these materials a highly viable and potentially preferred choice for dental practitioners, technicians, and patients alike [9–13]. However, the widespread adoption of 3D-printed denture base materials as a practical alternative to conventional and milled options remains limited by several key issues. Most notably, although 3D base denture resins exhibit clinically acceptable physical properties, they tend to absorb more water and have higher solubility compared to their counterparts [7, 14–17], along with reduced hardness and wear resistance [2, 4, 5]. Water infiltration into a polymer's macrostructure can lead to hydrolytic degradation, which breaks chemical bonds within the resin matrix and consequently impacts the material's solubility [14, 16, 18]. Furthermore, absorbed water acts as a plasticizer, causing softening, decreased mechanical strength, staining, and unfavorable aesthetic effects [9, 16, 18]. In addition, denture cleaner application and oral environmental stressors, characterized by both thermal changes, are recognized for their capacity to augment water sorption and solubility [19–22]. As a result, these stressors can provoke volumetric alterations within the materials, which adversely affect the stability and retention of complete dentures [23–25]. While some studies highlight benefits of glazing 3D-printed denture bases, such as increased hardness, improved wear resistance, and less surface deterioration after thermal cycling, there is still debate about the overall effects of these glaze treatments [26, 27]. Specifically, some researchers report improvements in flexural strength and color stability after glazing [28, 29], while others have found contradictory results [30, 31].

To develop a comprehensive understanding of the clinical impact and performance of glaze materials, it is crucial to carefully evaluate their effect on the water sorption and solubility of denture base materials. These properties are essential and undeniable factors that directly influence the long-term flexural strength and color stability of denture bases, thereby affecting their clinical performance [18, 32–35]. While some studies have investigated the effect of surface treatments on the water sorption and solubility of conventional heat-polymerized denture base materials [36–39], the impact of these glazes on their 3D-printed counterparts remains largely unexplored, to the authors' knowledge [40].

Unlike glaze materials, a method to improve the physical and mechanical properties of 3D-printed denture base materials is the use of an effective and proper post-curing process. Post-curing, an essential step in additive manufacturing, helps further polymerize residual monomer molecules in the polymer that did not fully react during the initial 3D printing process [32]. Following the correct post-curing procedure is vital for ensuring that the properties of the finished dental appliances meet necessary clinical standards [3, 41, 42]. On the other hand, using a poor post-curing process can negatively impact their mechanical strength, reduce dimensional accuracy, and even hinder efforts to reduce cytotoxicity [43–46].

The effectiveness of the post-curing process depends on several factors, including the type of curing unit used [45], the length of the curing cycle [9, 46], the temperature during curing [3, 17, 47, 48], the wavelength of the ultraviolet (UV) light employed [3, 44], and the ambient curing conditions, particularly oxygen levels [49]. Some research indicates that extending the post-curing duration or performing it in an oxygen-free environment —a key step in additive manufacturing —can improve the mechanical and physical properties of 3D-printed denture base materials [49]. However, studies specifically examining how post-curing duration and atmosphere

(with or without oxygen) affect water sorption and solubility in 3D-printed denture bases are limited [46, 50]. Furthermore, no known studies are using various aging protocols to evaluate these properties.

Based on the literature mentioned earlier, the primary objective of this study is to investigate the impact of surface treatment, aging protocols, and post-curing conditions on the water sorption and solubility of 3D-printed denture base materials in comparison to conventional and milled options.

The null hypotheses were as follows:

> H01: Manufacturing technology has no significant impact on the water sorption and water solubility of the tested denture base materials.
> H02: Surface treatment applied to denture base materials does not significantly affect their water sorption and water solubility.
> H03: Different curing times and atmospheres for 3D-printed denture base resins have no significant impact on their water sorption and water solubility.

Materials and methods

The following denture base materials were assessed in this study:

- 3D-printed denture base OP (3DP) (Formlabs, Somerville, MA, USA; Lot number: BF23F26O).
- Heat-polymerized acrylic resin (HC) (Probase Hot, Ivoclar Vivadent AG, Liechtenstein; Polymer Lot number: YB60YF, Monomer Lot number: Z05SGJ).
- CAD-CAM prepolymerized PMMA blocks (M) (Bilkim, Izmir, Turkey, Lot numbers: 2112 – 1024, 2112 – 0424).

Specimen discs with dimensions of Ø15 × 2 ± 0.2 mm were prepared, following previous studies [17, 20]. The sample size was calculated using G*Power software (version 3.1.9.4, Heinrich-Heine University, Dusseldorf, Germany). Based on data from Hanno and Abdul-Monem (2023) [20], an effect size (Cohen's f) of 0.125 was determined. With a 95% confidence level and 95% statistical power, the analysis showed that a total sample of 420 specimens, divided into 30 groups with 14 specimens each, would be sufficient for the study [50].

Preparation of specimens

Fabrication of the traditional heat-cured (HC) specimens was performed using the pressure molding technique, the detailed procedures of which are thoroughly described in an earlier study [26].

For the design of both milled and 3D-printed experimental specimens, a software program (Tinker CAD, Autodesk Inc., USA) was used to create the specimen, which was then saved as a file in the standard tessellation language (STL) format.

For the milled group, the specimen's STL file design was imported into MILLBOX CAM software (MILLBOX, CIM SYSTEM, Milan, Italy) to generate an optimized milling strategy. Subsequently, the CAM file was sent to a 5-axis CAM unit (M20; Camcube, Montreal, Canada) to fabricate the CAD-CAM milled specimens from prepolymerized PMMA-based polymer blocks (Bilkim, Izmir, Turkey).

For the 3D-printed group, the identical digital design file was transmitted to PreForm 3.40 slicer software (Formlabs Inc., Somerville, MA, USA) and subsequently to a Form 3 printer (Formlabs) to fabricate the 336 specimens using Denture Base OP resin (Formlabs). During the printing process, specimens were oriented at a 45° oblique angle relative to the build platform, with a uniform layer thickness of 50 µm maintained across all groups, in accordance with the manufacturer's instructions.

Establishing post-curing conditions for 3D specimens

Unlike the conventional and milling specimens, the 3D printed group (Formlabs/3DP) underwent a washing process in a Form Wash unit (Formlabs, Somerville, MA, USA) using 99.9% isopropyl alcohol (IPA) for 10 min. Post-curing was then performed in a Form Cure device (Formlabs, Somerville, MA, USA) at a steady temperature of 80 °C for all specimens. It is important to note that two different curing environments—glycerin and air—were used across four curing times: 10, 15, 30, and 60 min. Specifically, specimens cured for 60 min received a separate 30-minute curing cycle on each surface.

The application of surface treatments

After post-curing, the specimens were divided into three groups based on surface treatment: mechanically polished (P), glazed with Optiglaze (O), or glazed with Vita Akzent Glaze (V). Figure 1.

All specimens designated for glaze application were roughened on a single surface using a diamond tool certified to ISO 13485:2016 [51], from NPOOO "SYSTEM" (Minsk, Belarus), and then thoroughly cleaned with oil-free air. The specimens were randomly divided into two groups. According to the manufacturers' instructions, a thin layer of Vita Akzent® LC GLAZE (VITA Zahnfabrik, Germany, LOT:201540) was applied to the roughened surface of one group with a soft brush in a single direction. The other group received a similar application of Optiglaze (GC America Inc, Alsip, IL, LOT:2402141). After a 20-second application period [31], all specimens were light-polymerized for 3 min using a Solidilite V unit (SHOFU Dental Corp, Japan).

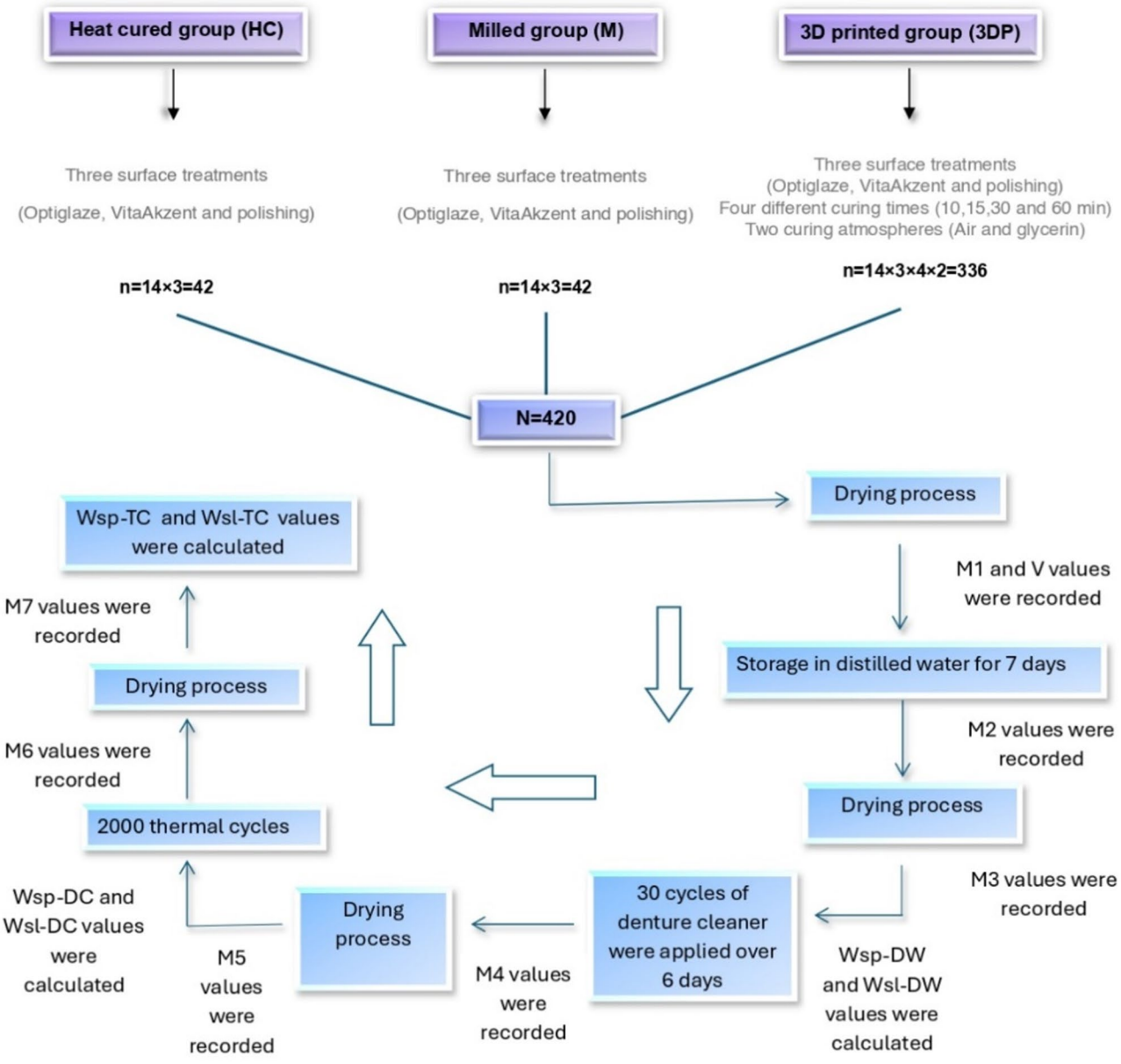


Fig. 1 Flowchart illustrating the preparation of experimental groups and corresponding sample sizes, along with a detailed explanation of the research stages

For the mechanically polished group, specimens were initially processed on one surface with 600- to 1200-grit silicon carbide abrasive papers (Deerfos, Incheon, Korea) under water irrigation for 10 s [26, 33]. This was followed by a standard polishing procedure on a polishing lathe (Dentaurum GmbH & Co. KG, Germany) at 1500 rpm. A pumice slurry (BLAUpum, Efes Dental, Bursa, Turkey) and a soft bristle brush were used for the first 90 s, after which a polishing paste (Universal Polishing Paste, Ivoclar Vivadent AG, Schaan, Liechtenstein, LOT: Z03T49) and a flannel buffing wheel were employed until achieve a high-gloss surface [26, 33]. To maintain uniformity, all grinding and polishing procedures were exclusively performed by a single researcher (E.I.). Water sorption and solubility assessments were conducted in accordance with the ISO 4049 – 2019 standard [41]. Following the experimental procedures, the specimens were meticulously arranged on a two-tier rack and subsequently placed within two desiccators (Isotherm Lab., Turkey) containing freshly dried silica gel. These desiccators were then transferred to a BD115 model oven (Binder Inc., Tuttlingen, Germany) and maintained at a temperature of 37 °C for a duration of 22 ± 1 h to ensure effective drying.

Following the designated period, the desiccators were extracted from the oven, and the specimens, remaining on their rack, were promptly removed. Concurrently, the used silica gel was substituted with fresh silica gel. The specimens were then immediately returned, still on their rack, to the desiccators containing freshly dried silica gel and maintained at a controlled temperature of 23 ± 1 °C for an additional two hours. Upon completion of the conditioning phase, the specimens were weighed with an accuracy of 0.1 mg utilizing an AND GR-200 analytical balance (A&D Company, Tokyo, Japan). The entire procedure of drying, re-desiccating, and weighing was meticulously repeated until a stable mass, designated as m1, was achieved. The consistency of the mass was defined as a mass loss not exceeding 0.1 mg for each specimen over any consecutive 24-hour interval.

Following the recording of m1, the specimen's diameter was meticulously measured at three distinct points, with each measurement performed perpendicular to the previous one. This procedure guaranteed comprehensive assessment of the specimen's circularity. All diameter measurements were conducted using a digital caliper (Dasqua®, Italy), with an accuracy of 0.01 mm. The average diameter was subsequently determined from these three readings to minimize measurement error.

To determine the specimen's thickness, measurements were taken at its center and at four evenly spaced points around its circumference. Consistency was maintained by using the same digital caliper for all thickness measurements, again ensuring an accuracy of 0.01 mm. The average thickness was then calculated from these five data points. Finally, the volume (V) of the specimen, measured in cubic millimeters (mm^3), was calculated using the formula $V = \pi r^2 h$, where r is the mean radius (calculated from the mean diameter) and h represents the mean thickness.

In accordance with the ISO 4049 standard, a sufficient number of test tube racks were used to maintain a minimum distance of 3 mm between specimens, hold them in a vertical position, and prevent contact with each other. The specimens, coded with a heat- and water-resistant pen, were randomly placed vertically, with one specimen per hole, into the 15 mm diameter holes of the rack, which were equal to the specimens' diameter. Each rack was then immersed in the same amount of water, ensuring all specimens were fully submerged. The specimens were immersed in distilled water for 7 days, with the temperature carefully maintained at 37 ± 2 °C inside an oven. Following this immersion period, the racks were gently removed from the water, and the specimens were then taken out of the racks using clean gloves and polymer-coated tweezers to prevent contamination or damage. Each specimen was subsequently rinsed with deionized water to remove any surface contaminants. Any excess surface moisture was carefully blotted until no water was visible. To ensure consistent drying, each specimen was briefly waved in the air for 15 s. Finally, the mass of each specimen was precisely recorded as m2. To evaluate the water solubility of the specimens, the same drying protocol employed for the initial m1 mass measurement was meticulously repeated. Following this drying process, the mass of each specimen was recorded as m3. This consistent methodology ensures precise calculation of the soluble mass loss of the specimens subsequent to immersion. The water sorption value (Wsp-DW), expressed in micrograms per cubic millimeter (μg/mm^3), was determined in accordance with ISO 4049 [41] using the following formula:

$$Wsp_DW = \frac{m2 - m3}{V} \quad (1)$$

Similarly, the solubility value (Wsl-DW) of the specimens was calculated using the formula:

$$Wsl_DW = \frac{m1 - m3}{V} \quad (2)$$

Here, m3 signifies the ultimate dry mass of the specimen subsequent to the re-drying procedure, following immersion in distilled water.

Procedure for denture cleanser tablet immersion

After the m3 values were recorded, the coded specimens, which now had a mass of m3, were again randomly placed back into the test racks. The first denture cleaner application was then performed. The denture cleaner solution was prepared using Corega™ tablets (GlaxoSmithKline Healthcare, Istanbul, Turkey), maintaining a ratio of one Corega tablet per 250 ml of water, as per the manufacturer's instructions. Through the racks, the specimens from the heat-cured, milled, and 3D-printed groups were then immersed in this solution for the manufacturer's recommended 3 min. After this time, the specimens were removed from the cleaning solution and thoroughly rinsed under running water. This 3-minute submersion was repeated for 30 cycles over 6 days (5 cycles per day), simulating 180 days of continuous immersion of a prosthesis in a denture cleaner. Between cycles, the specimens were stored in distilled water at 37 °C [20, 25]. Following this 6-day cleaning regimen, the specimens subjected to denture cleaner aging were immediately reweighed, applying the same weighing protocol used to record m2 using the same precision balance, and their mass was recorded as m4. Then, applying the previously used drying protocol for obtain m1 and m3, the specimens underwent a re-drying process until their mass stabilized (defined as a mass loss not exceeding 0.1 mg for

each specimen over any consecutive 24-hour interval). At this point, their mass was recorded as m5. The water sorption (Wsp-DC) and solubility (Wsl-DC) caused by applying the denture cleaner were calculated using the following formulas:

$$Wsp_DC = \frac{m4 - m5}{V} \quad (3)$$

$$Wsl_DC = \frac{m3 - m5}{V} \quad (4)$$

Thermal cycling

The specimens with a mass of m5 were subjected to an intensive process comprising 2000 thermal cycles (TCs) (DTS B1, Dentester, Salubris Technica, Istanbul, Turkey). Each cycle consisted of a 30-second immersion in distilled water at 5 °C, followed by a 10-second transfer to distilled water at 55 °C, with an equivalent 30-second dwell time. This 2000 TC protocol is designed to simulate a two-year period within the oral cavity [25, 29]. The distilled water was replaced with fresh water every twelve hours. Immediately after thermocycling aging, the specimens were reweighed using the same weighing protocol and precision balance as for m2 and m4, and their mass was meticulously recorded as m6. Subsequently, they underwent a re-drying process, using the previously described drying protocol for obtain m3 and m5, until a stable mass was achieved, designated as m7. The water sorption (Wsp-TC) and solubility (Wsl-TC) resulting from thermocycling were then measured using the respective formulas.

$$Wsp_TC = \frac{m6 - m7}{V} \quad (5)$$

$$Wsl_TC = \frac{m5 - m7}{V} \quad (6)$$

Data analysis was conducted using IBM SPSS Statistics 26.0. The Kolmogorov-Smirnov test results showed that all variables significantly deviated from a normal distribution ($p < 0.05$). As a result, all subsequent analyses in this study used non-parametric tests. Specifically, the Mann-Whitney U test was employed for comparisons between two categorical variables, while the Kruskal-Wallis test was used for comparisons involving three or more categorical variables. For related groups, the Friedman test was applied. To determine which specific categories showed significant differences in analyses with three or more categories, pairwise comparisons were performed. All statistical analyses were completed, with significance levels set at $\alpha = 0.05$ and 0.01.

Results

Material-specific water sorption and solubility following various aging protocols

The results of the Kruskal-Wallis test indicated that conventional heat-polymerized acrylic (Probase; HC) consistently demonstrated the highest water sorption at all measured time points, irrespective of surface treatment or aging protocol ($p < 0.01$). Conversely, the Formlabs 3D-printed group exhibited the lowest water sorption ($p < 0.01$). Furthermore, no statistically significant difference in Wsp-DC was observed between the heat-polymerized acrylic and Bilkim milled groups ($p > 0.01$). (Fig. 2A) Regarding water solubility (Wsl) values, the heat-cured group (Probase; HC) consistently showed the lowest Wsl-DW, regardless of surface treatment ($p < 0.01$). In contrast, the 3D-printed group (Formlabs; 3DP) exhibited the highest Wsl-DW and Wsl-TC levels, regardless of the curing parameters ($p < 0.01$). However, the 3D-printed (Formlabs; 3DP) group showed the lowest Wsl-DC values ($p < 0.01$), although there was no statistically significant difference in Wsl-TC between the milled (Bilkim; M) and heat-cured (Probase; HC) groups ($p > 0.01$). (Table 1) (Fig. 2B).

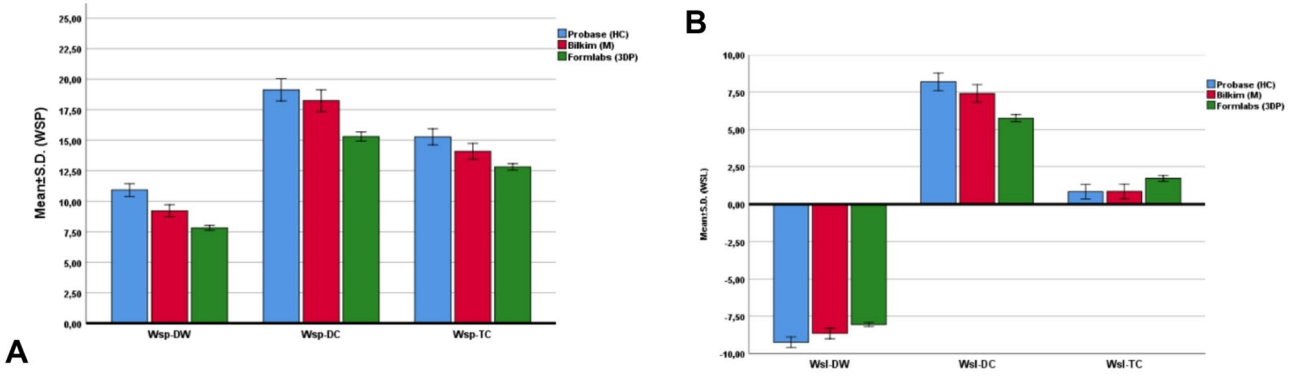


Fig. 2 Comparison of **A** Water Sorption (Wsp) and **B** Water Solubility (Wsl) values across different materials and time points

Table 1 Results of the statistical analysis (Mean ± SD (Median)) of water sorption (Wsp) and solubility (Wsl) values according to material and time point

Material	Probase (HC)	Bilkim (M)	Formlabs (3DP)	Difference	p^2
Wsp-DW	10,92 ± 2,09 (11,1)	9,24 ± 1,96 (9,6)	7,82 ± 1,87 (8,28)	HC > M > 3DP	0,01**
Wsp-DC	19,12 ± 2,93 (11,6)	18,24 ± 4,01 (17,2)	15,29 ± 3,39 (14,8)	HC, M > 3DP	0,01**
Wsp-TC	15,27 ± 2,56 (15,1)	14,09 ± 1,47 (14,4)	12,8 ± 2,61 (13,1)	HC > M > 3DP	0,01**
Difference	2 > 3 > 1	2 > 3 > 1	2 > 3 > 1		
p^1	0,01**	0,01**	0,01**		
Wsl-DW	−9,24 ± 2,36 (−8,84)	−8,66 ± 1,31 (−8,34)	−8,05 ± 1,08 (−7,93)	HC < M < 3DP	0,01**
Wsl-DC	8,19 ± 2,61 (8,13)	7,41 ± 1,70 (6,92)	5,75 ± 2,19 (5,67)	HC > M > 3DP	0,01**
Wsl-TC	0,83 ± 1,93 (0,66)	0,82 ± 1,34 (0,99)	1,71 ± 1,85 (1,66)	HC, M < 3DP	0,01**
Difference	2 > 3 > 1	2 > 3 > 1	2 > 3 > 1		
p^1	0,01**	0,01**	0,01**		

† p^1: Friedman Test, p^2: Kruskal Wallis Test, $^{**}p < 0{,}01$, Difference: pairwise comparisons

‡ *Wsp-DW, Wsl-DW* Water sorption and solubility values, respectively, after 7 days of immersion in distilled water, *Wsp-DC, Wsl-DC,* Water sorption and solubility values, respectively, following denture cleaner aging, *Wsp-TC, Wsl-TC* Water sorption and solubility values, respectively, after thermocycling aging

‡‡ *Wsp* and Wsl values for materials represent the mean of all surface treatments and aging protocols values. For detailed data, see Table 2

Influence of surface treatment

For the heat-cured group (Probase; HC), surface treatment did not significantly affect water solubility for either Wsl-DW ($p = 0.212$) or Wsl-TC ($p = 0.910$). However, mechanical polishing resulted in significantly higher Wsl-DC values compared to both glazed groups ($p = 0.033 < 0{,}05$). No statistically significant difference in Wsl-DC was observed between the Vita Akzent Glaze and Optiglaze groups ($p > 0{,}01$).

Regarding water sorption, the mechanically polished groups consistently showed higher water sorption values (Wsp-DW, Wsp-DC, and Wsp-TC) across all time points for the heat-cured group ($p < 0.01$). This was noted despite no statistically significant difference between the two glazing materials themselves. (Table 2) (Fig. 3) For the milled group (Bilkim; M), surface treatment showed no statistically significant effect on Wsp-DW ($p = 0.722$) or Wsp-DC ($p = 0.133$). However, the mechanically polished group exhibited a higher Wsp-TC value ($p < 0{,}05$). No statistically significant difference in Wsp-TC was observed between the two glazing materials. Regarding water solubility, while surface treatment did not affect Wsl-DW ($p = 0.842$) and Wsl-TC ($p = 0.798$), mechanically polished groups showed significantly higher Wsl-DC values compared to both glazed materials ($p < 0.01$). (Table 2)(Fig. 3) Considering the 3D-printed group (Formlabs; 3DP), surface treatment had no statistically significant effect on Wsp-DW ($p = 0.540$). However, Vita Akzent Glaze significantly reduced Wsp-DC and Wsp-TC values ($p < 0.01$). No statistically significant difference was observed between Optiglaze and mechanical polishing

Table 2 Results of the statistical analysis (Mean ± SD (Median)) of water sorption (Wsp) and solubility (Wsl) values within each material based on surface treatment and time point

Material	Surface treatment	Wsp-DW	Wsp-DC	Wsp-TC	p^2	Wsl-DW	Wsl-DC	Wsl-TC	p^2
Probase(HC)	O	10,49 ± 1,78(10,4)	18,19 ± 2,16(17,9)	14,55 ± 1,91(14,4)	**	−9,84 ± 3,76(−9,8)	7,64 ± 1,85(7,6)	0,72 ± 1,69(0,7)	**
	V	10,23 ± 2,01(10,3)	18,94 ± 3,41(17,8)	13,74 ± 2,34(13,8)	**	−9,25 ± 1,11(−9,2)	7,68 ± 1,64(7,6)	0,65 ± 1,79(0,6)	**
	P	12,04 ± 2,11(12,5)	20,24 ± 2,86(20,6)	17,51 ± 1,72(17,1)	**	−8,64 ± 1,14(−8,6)	9,24 ± 3,66(9,2)	1,12 ± 2,31(1,1)	**
	Difference	P > O,V	P > O	P > O,V			P > V,O		
	p^1	0,003**	0,003**	0,01**		0,212	0,033*	0,91	
Bilkim(M)	O	9,27 ± 1,34(9,3)	19,17 ± 5,98(16,9)	13,66 ± 1,36(13,6)	**	−8,67 ± 1,13(−8,6)	7,06 ± 1,46(7,1)	0,82 ± 1,53(0,8)	**
	V	9,45 ± 1,77(10,1)	17,25 ± 3,32(16,5)	13,91 ± 1,26(13,9)	**	−8,45 ± 0,58(−8,4)	6,62 ± 0,96(6,6)	0,88 ± 1,32(0,9)	**
	P	8,99 ± 2,63(9,5)	18,29 ± 1,13(18,2)	14,69 ± 1,64(15,2)	**	−8,85 ± 1,92(−8,8)	8,54 ± 1,95(8,5)	0,74 ± 1,21(0,7)	**
	Difference			P > O			P > V,O		
	p^1	0,722	0,133	0,031*		0,842	0,01**	0,798	
Formlabs(3DP)	O	7,8 ± 1,91(8,2)	15,24 ± 3,13(14,8)	12,93 ± 1,31(13,1)	**	−8,25 ± 1,21(−8,2)	5,36 ± 1,5(5,4)	1,62 ± 1,5(1,6)	**
	V	7,72 ± 1,81(8,2)	14,82 ± 3,71(14,2)	12,19 ± 3,93(12,7)	**	−8,17 ± 0,96(−8,1)	5,13 ± 1,87(5,1)	1,99 ± 1,89(1,9)	**
	P	7,94 ± 1,9(8,4)	15,82 ± 3,26(15,2)	13,3 ± 1,67(13,5)	**	−7,74 ± 0,99(−7,7)	6,75 ± 2,69(6,7)	1,53 ± 2,08(1,5)	**
	Difference		P, O > V	P, O > V		P > O,V	P > O,V		
	p^1	0,54	0,01**	0,01**		0,01**	0,01**	0,279	

† p^1: Kruskal Wallis Test, p^2: Friedman Test,, $^*p < 0{,}05$, $^{**}p < 0{,}01$, Difference: pairwise comparisons

‡ *Wsp-DW, Wsl-DW* Water sorption and solubility values, respectively, after 7 days of immersion in distilled water; *Wsp-DC, Wsl-DC* Water sorption and solubility values, respectively, following denture cleaner aging, *Wsp-TC, Wsl-TC* Water sorption and solubility values, respectively, after thermocycling aging, *P* polishing, *O* Optiglaze, *V* VitaAkzent

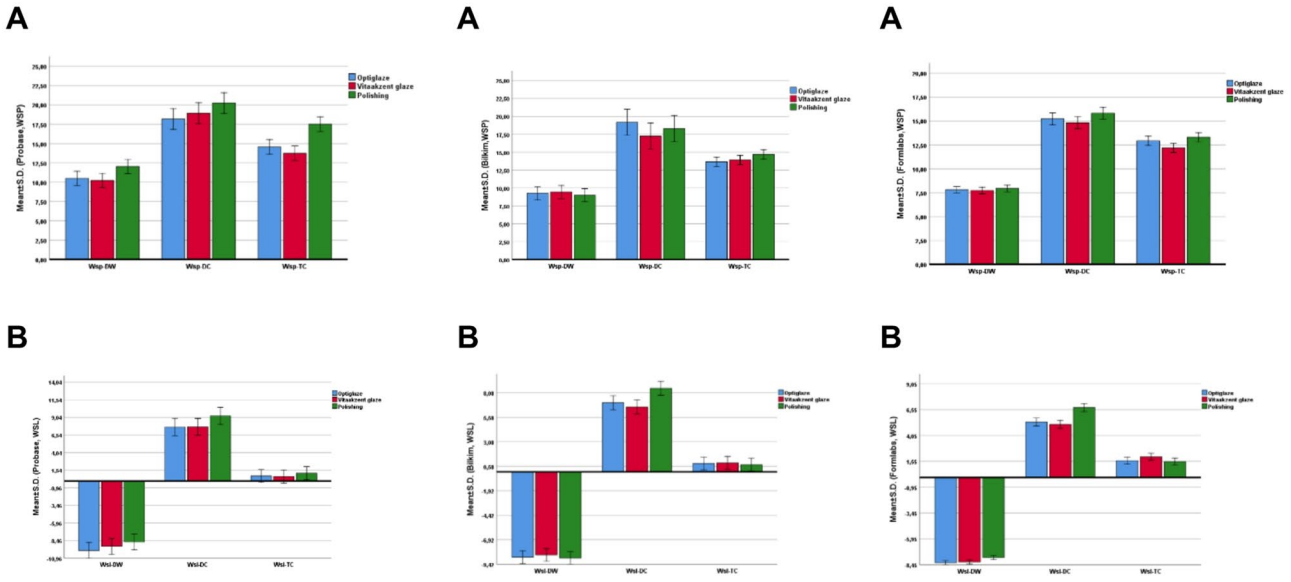


Fig. 3 Presents a comparison of **A** Water Sorption (Wsp) and **B** Water Solubility (Wsl) values across different Surface Treatments and time points

Table 3 The results of the statistical analysis (Mean ± SD (Median)) of Wsp and Wsl values for formlabs material by curing atmosphere and time point

Time point	Atmosphere		p^2
	Air	Glycerin	
Wsp-DW	7,53 ± 1,74(8,08)	8,12 ± 1,95(8,58)	0,01**
Wsp-DC	14,69 ± 2,15(14,58)	15,9 ± 4,21(14,97)	0,003**
Wsp-TC	12,64 ± 3,34(13,01)	12,97 ± 1,58(13,18)	0,204
Difference	2 > 3 > 1	2 > 3 > 1	
p^1	0,01**	0,01**	
Wsl-DW	−7,95 ± 1,03(−7,89)	−8,16 ± 1,13(−8,02)	0,063
Wsl-DC	6,07 ± 2,56(5,85)	5,43 ± 1,71(5,38)	0,01**
Wsl-TC	1,99 ± 1,80(1,89)	1,44 ± 1,85(1,50)	0,01**
Difference	2 > 3 > 1	2 > 3 > 1	
p^1	0,01**	0,01**	

† p^1 Friedman, Test, p^2 Mann Whitney U-Test

**$p < 0,01$, Difference: pairwise comparisons

‡ Wsp-DW, Wsl-DW: Water sorption and solubility values, respectively, after 7 days of immersion in distilled water, *Wsp-DC, Wsl-DC* Water sorption and solubility values, respectively, following denture cleaner aging, *Wsp-TC, Wsl-TC* Water sorption and solubility values, respectively, after thermocycling aging

regarding Wsp-DC and Wsp-TC. For the 3D-printed group (Formlabs; 3DP), surface treatment showed no statistically significant effect on Wsl-TC ($p = 0.279$). Conversely, both Vita Akzent Glaze and Optiglaze significantly lowered Wsl-DW and Wsl-DC values compared to mechanical polishing. (Table 2) (Fig. 3).

Effect of post-curing parameters on 3D-printed resins

The Mann-Whitney U-Test demonstrated that, although the post-curing atmosphere did not have a statistically significant impact on Wsp-TC ($p = 0.204$), it did exert influence on Wsp-DW and Wsp-DC values. Specifically, the group cured in a glycerin environment exhibited significantly higher Wsp-DW and Wsp-DC values ($p < 0.01$). Concerning water solubility, the post-curing atmosphere did not notably affect Wsl-DW values. Nonetheless, specimens subjected to post-curing in glycerin displayed statistically lower Wsl-DC and Wsl-TC values. (Table 3)(Fig. 4).

Regardless of whether the curing atmosphere was air or glycerin, the curing duration had no statistically significant effect on Wsp-DW ($p = 0.500$), Wsp-DC ($p = 0.729$), or Wsp-TC ($p = 0.053$) values.

Although 3D-printed denture base materials subjected to different curing durations in an air environment exhibited no statistically significant differences in Wsl-DW ($p = 0.434$), Wsl-DC ($p = 0.748$), or Wsl-TC ($p = 0.316$), the groups cured for varying durations in a glycerin environment generally yielded comparable results. Nevertheless, specific differences were noted: the group cured for 10 min in glycerin demonstrated higher Wsl-DW and Wsl-DC values relative to other groups, whereas the group cured for 30 min in glycerin exhibited higher Wsl-TC values compared to the others. (Table 4)(Fig. 5).

Discussion

This study investigated the influence of surface treatment, aging, and post-curing conditions on the water sorption and solubility characteristics of a specific 3D-printed denture base resin, in comparison with conventional and milled alternatives.

Sorption, a physical and chemical process, involves the retention of a gas or vapor (sorbate) by a condensed substance (solid or liquid), known as the sorbent. This process is comparable to a sponge absorbing water. Sorption encompasses two primary subprocesses: absorption,

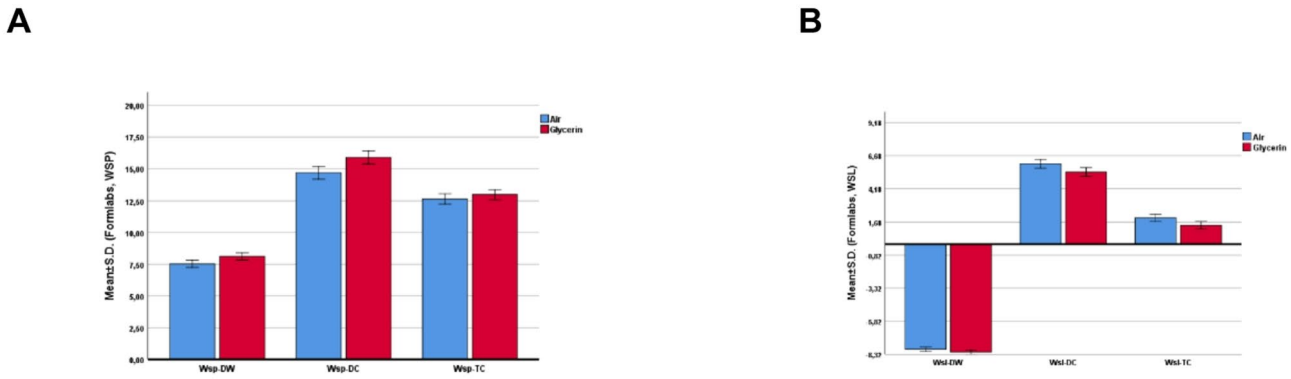


Fig. 4 Comparison of **A** Water Sorption (Wsp) and **B** Water Solubility (Wsl) values across various curing atmospheres and time points

Table 4 Results of the statistical analysis (Mean ± SD (Median)) of Wsp and Wsl values for formlabs material compared by curing atmosphere and curing time at three different time points

Atmosphere	Time	Wsp-DW	Wsp-DC	Wsp-TC	p^2	Wsl-DW	Wsl-DC	Wsl-TC	p^2
Air(A)	10 min	7,75 ± 1,78(8,28)	14,9 ± 1,69(14,72)	13,05 ± 1,21(13,2)	**	−7,72 ± 0,82(−7,7)	6,04 ± 1,61(6,1)	1,96 ± 1,7(1,9)	**
	15 min	7,53 ± 1,44(7,87)	14,55 ± 2,16(14,58)	12,1 ± 6,34(13,1)	**	−8,04 ± 0,98(−7,9)	5,86 ± 1,99(5,9)	2,32 ± 2,46(2,2)	**
	30 min	7,52 ± 1,88(8,00)	14,43 ± 1,73(14,50)	13,03 ± 1,16(13,1)	**	−7,87 ± 0,88(−7,9)	5,77 ± 1,77(5,8)	2,01 ± 1,58(1,9)	**
	60 min	7,31 ± 1,87(8,08)	14,87 ± 2,85(14,43)	12,37 ± 1,33(12,5)	**	−8,16 ± 1,34(−7,9)	6,61 ± 4,06(5,8)	1,68 ± 1,25(1,7)	**
	p^1	0,5	0,729	0,053		0,434	0,748	0,316	
Glycerin(G)	10 min	8,01 ± 1,99(8,45)	16,2 ± 4,24(15,14)	12,81 ± 2,2(13,4)	**	−7,84 ± 1,38(−7,6)	6,06 ± 1,48(6,1)	1,07 ± 2,17(1,5)	**
	15 min	8,05 ± 2,35(8,58)	16,85 ± 5,82(15,25)	12,93 ± 1,46(13,2)	**	−8,41 ± 0,88(−8,2)	5,49 ± 2,18(5,6)	1,55 ± 2,19(1,6)	**
	30 min	7,83 ± 1,75(8,07)	15,58 ± 4,02(14,70)	13,1 ± 1,36(13)	**	−8,19 ± 1,18(−7,8)	4,87 ± 1,4(5)	2,00 ± 1,5(1,8)	**
	60 min	8,58 ± 1,61(8,91)	14,94 ± 1,51(14,96)	13,05 ± 1,15(13,1)	**	−8,20 ± 0,95(−8,1)	5,30 ± 1,48(5,2)	1,14 ± 1,3(0,1)	**
	p^1	0,135	0,262	0,969		0,01**	0,013*	0,035*	
	Difference					10 min.>15 min	10 min.>30 min	30 min.>10 min	
Total	*p*	0,01**	0,049*	0,228		0,002**	0,01**	0,002*	
	Difference	G60 > A60,30,15	G15 > A15,A30			A10 > G15	A60 > G15,30,60	A15 > G10,60	

† p^1: Kruskal Wallis Test

p^2: Friedman Test

*:$p < 0,05$,

**$p < 0,01$, Difference pairwise comparisons

‡ *Wsp-DW, Wsl-DW* Water sorption and solubility values, respectively, after 7 days of immersion in distilled water, *Wsp-DC, Wsl-DC* Water sorption and solubility values, respectively, following denture cleaner aging, *Wsp-TC, Wsl-TC* Water sorption and solubility values, respectively, after thermocycling aging, *A* air, *G* Glycerin

whereby the sorbate penetrates the internal structure of the sorbent directly, and adsorption, in which the sorbate adheres solely to the surface of the sorbent. Furthermore, water solubility refers to the maximum amount of a chemical substance that can dissolve in water at a specified temperature [16, 38].

The intrinsic polar characteristics of these 3D-printed materials, primarily attributed to ester groups, facilitate hydrogen bonding with water molecules [13]. This interaction promotes water absorption, leading to the diffusion of water molecules into the polymer network, which can induce hydrolytic degradation, cleaving chemical bonds within the resin matrix, and thereby influencing its solubility [16, 38]. The solubility is further exacerbated by the leaching of unreacted monomers, plasticizers, and initiators [18]. The absorbed water can act as a plasticizer, resulting in softening and a reduction in mechanical properties [9, 25, 45]. Furthermore, this fluid uptake negatively impacts color stability [33] and can permeate the interpolymeric spaces, causing resin swelling and potentially compromising the cohesion and integrity of the printed layers [14]. Environmental stressors such as thermal fluctuations and fluid exposure, which are critical in the oral environment, are known to increase water sorption and solubility, potentially compromising the aesthetic and functional longevity of denture base materials [12, 21]. These stressors can lead to the release of residual unreacted monomers, which may irritate the oral mucosa [12]. They can also cause volumetric alterations, which negatively affect the stability and retention of dentures [16, 23, 24]. The degradation of mechanical properties is also a result of cyclic exposure to wet and dry conditions, which cause polymer chains to expand and contract, leading to the formation of micro-cracks that can propagate and cause catastrophic fractures [16]. To simulate this, specimens in this study underwent 2000

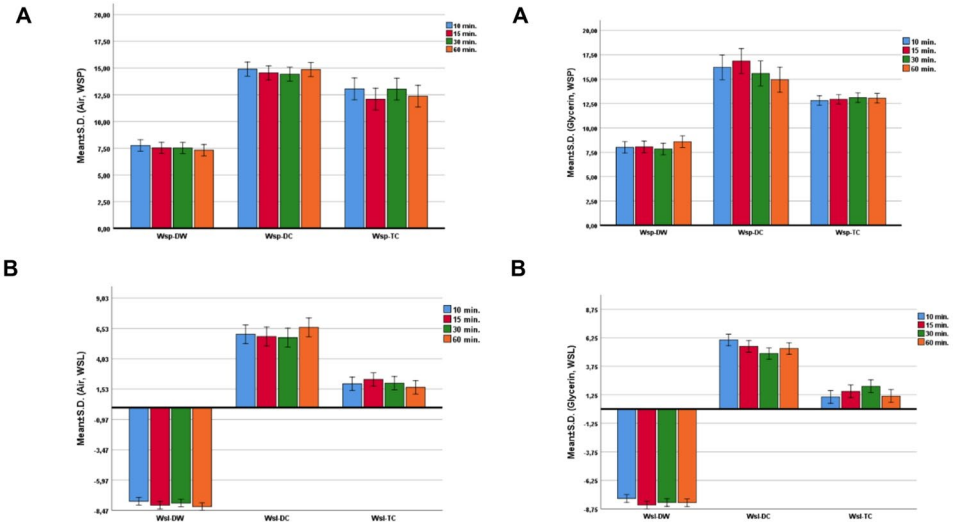


Fig. 5 Comparison of **A** water sorption (Wsp) and **B** water solubility (Wsl) values for Formlabs material across different curing atmospheres and curing times at three separate time points

thermal cycles, a procedure that approximates two years of clinical use [16, 25, 29]. Thermal cycling not only facilitates water absorption but also hydrolytically degrades polymer chains and can weaken the bond between the resin matrix and reinforcing fillers [5–7, 19]. The water sorption of polymeric denture base materials is not solely caused by exposure to oral fluids and thermal changes in the mouth. Denture cleaning agents, which are crucial for maintaining prosthesis hygiene and the health of the underlying mucosa, also play an essential role. For example, Corega, an alkaline peroxide-based denture cleaner, is widely used for its effectiveness in removing moderate stains and debris from denture base materials. As a primarily perborate-based cleansing agent, Corega functions as an oxidizing agent. It disintegrates and releases oxygen, which effectively removes stains and kills bacteria through an effervescent action [22]. These cleansing agents often contain enzymes and compounds that release oxides, leading to widened intermolecular spaces and allowing chemicals and water to infiltrate the polymer matrix [20]. To examine the effects of these denture cleansers on water sorption and solubility, 30 submersion cycles, each lasting 3 min, were performed over 6 days to simulate 180 days of prosthesis immersion [20, 25].

Material-based water sorption and solubility

The first null hypothesis of this study, which states that manufacturing technology exerts no significant influence on the water sorption and water solubility of the examined denture base materials, was ultimately rejected.

Our research demonstrates that the 3D-printed group exhibited significantly lower water sorption (Wsp) values in comparison to both milled and heat-cured denture base materials. This observation notably contrasts with multiple studies that typically report higher water sorption for 3D-printed materials, irrespective of the aging protocol employed. For instance, Hanno et al. observed no statistically significant difference in water sorption between the 3D-printed and milled groups following aging in denture cleaning agents. However, before this aging process, a notable difference was observed, with the 3D-printed group demonstrating greater water sorption [20]. In a similar vein, Lawson et al., in their assessment of one milled, one heat-cured, and four 3D-printed groups, reported that only one of the 3D-printed materials exhibited increased water absorption relative to the reference materials; the remaining three 3D-printed denture base materials exhibited comparable or lower water sorption, with no statistically significant difference compared to the heat-cured and milled groups [1]. Conversely, another investigation by Gad et al. identified a significant elevation in water sorption among 3D-printed resins in comparison to a heat-cured group, both with and without thermal cycling [14]. Consistent with the findings of our study, research conducted by Dimitrova et al. examined two heat-cured, one milled, and one 3D-printed denture base material, indicating that the milled group exhibited greater water absorption than the 3D-printed material [16]. Nonetheless, their results also demonstrated that the 3D-printed group showed higher water sorption compared to the heat-cured groups. A study by Öztürk et al. compared a 3D-printed denture base with a heat-polymerized one. Consistent with our findings, the heat-polymerized conventional base material exhibited higher water sorption. Additionally, the 3D-printed denture base group demonstrated a higher rate of water solubility [8]. Consistent with our findings, Mudhaffer et al. reported that their milled control

group exhibited higher water sorption compared to the 3D-printed group, attributing this difference to variations in chemical composition [35].

Researchers attribute the higher water sorption observed in 3D-printed denture base materials compared to alternative options to several interconnected factors. These encompass lower degrees of polymerization, resulting in more unreacted monomers, a reduction in cross-link density, variations in resin chemical composition, and the presence of micro-voids within the printed components. The polar nature of the material also plays a contributory role. Water molecules from absorbed moisture can readily infiltrate and diffuse into these internal voids and through polar sites, thereby increasing sorption levels. Furthermore, the quantity of filler content is recognized as a factor influencing the quality of polymerization, which may indirectly affect water sorption [1, 12, 15–17, 25]. The lower water sorption observed in our 3D-printed groups, which contrasts with certain preceding studies, may be attributable to their markedly higher water solubility (Wsl) following both 7 days of water immersion and thermocycling. As Wsl signifies material dissolution or leakage, substantial loss of soluble constituents might obscure the actual water sorption value (Wsp), even if the specimen initially absorbs a substantial amount of water [10]. A secondary contributing factor is that the specific heat-cured and milled denture base materials utilized in our investigation differed from those employed in other studies, thereby resulting in elevated water sorption values. Furthermore, the water sorption and solubility of heat-cured denture base materials are significantly influenced by parameters such as mixing ratios and polymerization protocols [38]. Variations in these parameters across different studies may account for discrepancies observed in our results. To ensure accuracy, heat-cured specimens in our study were fabricated strictly in accordance with the manufacturer's recommended polymer-to-monomer ratio (22.5 g:10 mL), measured with an analytical balance, consistent with our previous work. The mixture was subsequently packed into a mold, the flask was sealed, and then it was immersed in cold water. Following the manufacturer's protocol, the water was heated to 100 °C (212 °F) and maintained at a rolling boil for 45 min [26], emphasizing the rigorous adherence to standardized procedures. The increased sorption observed in the milled group may diminish the apparent advantages of its production technology, particularly considering that prepolymerized PMMA discs are manufactured under high-temperature and high-pressure conditions [15]. Corroborating this, research conducted by Vukšić et al. examining the residual unreacted monomer content—a crucial factor affecting both water sorption and solubility—revealed significant disparities among different brands of prepolymerized PMMA discs. This suggests that the technology employed in denture base production is not the sole determinant of residual monomer levels; rather, variations in material composition and likely diverse industrial manufacturing processes for prepolymerized discs also substantially impact the outcomes [4].

The 3D-printed group exhibited a higher water solubility rate following both 7 days of water storage and subsequent thermocycling, a finding corroborated by multiple other studies. Nevertheless, Hanno et al.'s research demonstrated no significant difference in solubility between the 3D-printed and milled groups [20]. This solubility observed in 3D-printed resins may be attributed to the leaching of unreacted monomers and other soluble substances. Furthermore, the presence of water could induce hydrolytic decomposition of chemical bonds within the polymer matrix, thereby diminishing the mechanical properties of these materials [14, 18]. Consistent with these findings, previous studies have also documented instances of negative solubility results, whereby the measured mass after drying exceeds the initial mass. This phenomenon is frequently attributed to the chemical binding of water molecules by the material itself or its constituents, which effectively impedes the complete release of absorbed water [13, 18, 49]. Although research by Gad et al., Altarazi et al., Dimitrova et al., and Luo et al. consistently demonstrates that 3D-printed denture base materials frequently exhibit higher water sorption and solubility compared to their milled and heat-cured counterparts, these materials still conform to the clinically acceptable values outlined in ISO 20,795 or ISO 4049 standards. This observation aligns with our own results, which show that regardless of surface treatment or post-curing conditions, water sorption values consistently remained below 40 μg/mm^3 and water solubility below 7.5 μg/mm^3, thereby complying with ISO 4049:2019 guidelines [12, 14, 16, 41, 49, 52]. Consequently, the discrepancies in the results of various studies underscore the necessity for further research into water sorption and solubility, with a focus on factors beyond just production technology, such as post-curing conditions and chemical composition.

Effects of surface treatments on water sorption and solubility

Based on the results, the second null hypothesis—that surface treatment applied to denture base materials has no significant effect on their water sorption and water solubility—was partially rejected. According to a study by Morel et al., our findings also indicate that the application of a glaze can reduce the water sorption and solubility values of these materials, potentially enhancing their clinical performance [40]. Specifically, Vita Akzent glaze notably reduced water sorption caused by

denture cleaner and thermocycling aging. Furthermore, both Optiglaze and Vita Akzent significantly decreased water solubility induced by seven days of water storage and denture cleaner aging. Conventional understanding suggests that a decrease in contact angle enhances a surface's hydrophilicity, potentially leading to increased water uptake. Although Carneiro-Pereira et al. [31] and Morel et al. [40] reported that glaze applications reduce the contact angle, thereby creating a more hydrophilic surface and increasing surface free energy, our findings demonstrate that glaze applications diminish both water sorption and solubility. This discrepancy highlights the necessity of investigating additional factors, such as surface polarity, that influence water sorption and solubility to achieve a comprehensive understanding of these material behaviors. Furthermore, it underscores the need to include a wider range of different glaze materials in future research. Although this study did not examine the impact of mechanical polishing on reducing water sorption and solubility, existing scholarly literature suggests that mechanical polishing has the potential to diminish these properties in denture base materials. This phenomenon is primarily due to several factors. Firstly, the heat generated during conventional polishing often exceeds the glass transition temperature (Tg) of the acrylic, which may result in surface smearing of the resin. Such surface smearing consequently reduces the polarity of the acrylic by decreasing the number of polar sites available for hydrogen bonding with water molecules [37]. Furthermore, the irregular surface of unpolished specimens provides a greater surface area compared to polished specimens, thereby creating an expanded interface for water molecule interaction, which may result in improved water absorption. This phenomenon can also be explained by contact angle hysteresis, where water droplets tend to form lower contact angles on rougher surfaces. Surfaces with lower contact angles are more hydrophilic, thus increasing the material's affinity for water [37, 38].

The benefits of glaze applications in minimizing water sorption and solubility can be ascribed to various mechanisms. The glaze potentially acts as a barrier, encapsulating residual monomers and preventing their leaching, thus reducing both water absorption and dissolution [36, 38]. Alternatively, these glaze materials might fill surface defects and microvoids, thereby impeding water penetration [28]. According to the manufacturer's documentation, Optiglaze consists of 5–15% silica filler, whereas Vita Akzent glaze contains 8–11% silica filler as inorganic constituents. This presence of inorganic filler may have contributed to the decrease in water sorption and potentially altered the surface polarity of these materials [34]. Another potential explanation for the decreased water solubility observed in the glazed 3D-printed groups is the supplementary polymerization triggered by the application of the glaze. This secondary polymerization may have led to an increased degree of conversion (DC) within these 3D-printed groups [44].

A study conducted by Barnard et al. also found that both mechanical polishing and glaze application reduced water sorption and solubility, and consistent with our research, glazed groups had lower water sorption values [39]. However, their finding that mechanically polished groups exhibited lower water solubility values compared with glazed groups conflicts with our results, highlighting the need for further investigation. The finding that Vita Akzent glaze can reduce the water sorption of Formlabs 3D-printed denture base materials aligns with our previous study where this glaze similarly maintained the material's color stability, a critical factor influenced by water sorption [26].

Effects of post-curing conditions on water sorption and solubility

In this study, a single Form Cure (FO) unit was employed to eliminate potential variations from different post-curing units. This device, equipped with 13 LEDs (3 W, 405 nm), ensured uniform light intensity across all samples. The literature consistently demonstrates that increasing the post-curing temperature enhances the mechanical properties and degree of conversion (DC) of 3D-printed parts. This is because higher temperatures decrease resin monomer viscosity, boost free radical movement, and encourage unpaired electrons to participate in chemical reactions, leading to more cross-links [17, 47]. In this study, a single curing temperature of 80 °C was uniformly applied to all 3D-printed specimens to minimize the influence of varying curing temperatures and to ensure consistency. It is important to acknowledge that although higher temperatures may enhance the physical properties of 3D-printed components, the associated polymerization shrinkage could adversely affect the accuracy of the prosthesis. This underscores the necessity of utilizing an optimal curing temperature [43].

The influence of oxygen shielding during post-polymerization is well-documented. Atmospheric oxygen diffusion can impede polymerization by reacting with free radicals, which creates an oxygen inhibition layer (OIL) that consists of unreacted monomers and non-activated photo-initiators. This OIL reduces cross-link density and, due to its heightened hydrophilicity, may lead to increased water sorption [48]. To mitigate this, various oxygen-reducing environments, such as nitrogen gas, water, vacuum, and glycerin, have been used, with glycerin being considered a highly effective method for eliminating oxygen and enhancing DC [18, 25, 48]. Research consistently indicates that oxygen-shielding conditions improve the DC of 3D-printed components [48].

Based on our study's results, the third null hypothesis—that different curing times and atmospheres for 3D-printed denture base resins have no significant effect on their water sorption and water solubility—was partially rejected. In contrast to a study by Luo et al., which found no statistically significant differences in water sorption or solubility among groups cured in air, water, and glycerin [49], our glycerin-cured groups demonstrated increased water sorption after seven days of water storage and denture cleaner aging, but reduced water solubility following denture cleaner and thermocycling aging. The higher water sorption and lower water solubility observed in the glycerin-cured group can be linked to its increased degree of conversion (DC), which is a result of effective oxygen shielding. An increased DC leads to a reduction in the concentration of unreacted residual monomers which might block water from penetrating and diffusing into the material. This could consequently increase water sorption while simultaneously reducing water solubility [45]. While some researchers have traditionally suggested a negative relationship between DC and water sorption [12], recent studies have provided evidence supporting a positive relationship between these properties [45]. Similarly, Greil et al. observed that the Nextdent denture base (DEN) group, despite having a high DC, also showed a high-water sorption (Wsp) value [15].

A study by Lee et al. examined the influence of post-polymerization time (PPT) and atmosphere (PPA) on the degree of conversion (DC) in 3D-printed denture base materials [42]. Their investigation encompassed three curing durations (5, 10, and 20 min) and two curing atmospheres (air and nitrogen). The results indicated that DC was significantly affected by the PPA, whereas variations in PPT did not exert a notable effect. Post-hoc analysis revealed that the mean DC value in the nitrogen PPA group was significantly higher than that in the air PPA group. These findings corroborate our own results, particularly the observation that the group cured in a glycerin atmosphere exhibited lower solubility compared to the group cured in air, thereby suggesting a higher degree of conversion [42].

Some researchers have observed that increasing post-curing time improves the degree of conversion, which in turn influences water sorption and solubility values [42, 45]. Further analysis by Lee et al. on four post-curing durations (0, 5, 10, and 20 min) revealed a consistent increase in DC with longer curing times: 66.5% at 0 min, 80.4% at 5 min, and 89.2% at 10 min. No significant difference in DC was found between the 10-minute and 20-minute groups. Regarding water sorption (Wsp), the uncured group exhibited significantly lower values compared to all other groups, which supports a positive correlation between DC and Wsp. Furthermore, no statistically significant differences in Wsp were found among the remaining post-cured groups, which is consistent with our study's findings. Similarly, the uncured group showed a significantly higher water solubility (Wsl) compared to all other groups, while no significant differences in Wsl were observed among the remaining post-cured groups. This also corroborates our results, although our research did not include an uncured group [10]. The findings of our study, which demonstrate a positive correlation between Degree of Curing (DC) and water sorption (Wsp), are in contrast to those documented by Luo et al., whose uncured samples exhibited the highest water sorption [49]. This inconsistency underscores the pressing necessity for additional research to definitively elucidate the relationship between DC and Wsp. Theoretically, a group exhibiting a higher degree of conversion (DC) owing to extended curing duration should demonstrate reduced water solubility. Nevertheless, this well-established principle, corroborated by numerous studies, paradoxically conflicts with our findings at a certain juncture. Notably, an anomaly was detected: the group cured in a glycerin atmosphere for 30 min displayed greater water solubility than the group cured for 10 min subsequent to thermocycling. Aati et al. reported a comparable intriguing outcome, whereby their 10-minute cured cohort exhibited lower water solubility than the 20-minute cured cohort [45]. Similarly, Alharbi et al. demonstrated that the group cured for 60 min possessed higher residual monomer content and water solubility relative to the group cured for 40 min [32]. This inconsistency underscores the necessity for further research to elucidate these phenomena.

A study conducted by Altarazi et al. investigated the influence of orientation angle on water sorption and solubility characteristics of 3D-printed denture base materials, with angles set at 0°, 45°, and 90°. The results indicated that the 0-degree group exhibited the highest water sorption values, whereas no statistically significant difference was observed between the 45- and 90-degree groups. Regarding solubility, no significant differences were identified among any of the three groups [9]. Additionally, Mudhaffer et al. reported a significant effect of orientation angle on the water sorption and solubility of 3D-printed restorative materials [35]. To mitigate the potential influence of varying orientation angles in our study, a uniform angle of 45 degrees was employed for all specimens across all experimental groups, in accordance with the manufacturer's recommendations. To the best of the authors' knowledge, no studies have specifically examined the effect of layer thickness on the water sorption and solubility of 3D-printed denture base materials. Therefore, further research in this area is highly advisable. In our study, to eliminate the potential influence of layer thickness, a single layer thickness of 50 µm, as

recommended by the manufacturer, was used for the fabrication of all specimens.

Limitations and future recommendations

This study provides valuable insights into the water sorption and solubility characteristics of 3D-printed denture base materials. Nevertheless, it is important to acknowledge certain limitations, which subsequently present opportunities for future research.

Initially, our research was confined to examining the effect of glaze applications on water sorption and solubility. Subsequent studies are advised to broaden this scope to encompass the influence of glaze materials on surface polarity and surface free energy. A comprehensive understanding of these properties will elucidate the fundamental mechanisms through which glazes impact water behavior.

Secondly, to ensure consistency, our study utilized a single specific brand of material for each manufacturing technology. Future research would benefit from incorporating a broader spectrum of materials and brands across various manufacturing methodologies to enhance the generalizability of the findings.

Thirdly, the specimens were evaluated using simple geometric shapes, following previously established and standardized testing protocols. While this approach ensures comparability with existing literature, future studies might consider more complex, clinically relevant geometries to better mimic in-mouth conditions.

Furthermore, the study was limited to using only one type of post-processing device and employed solely distilled water as the immersion medium. Future research should examine the effects of different post-processing units and various immersion solutions that mimic the complex oral environment. It is important to consider the impact of oral fluids, saliva pH, and enzymes, as these factors can cause further degradation of resin materials.

Finally, as an in vitro study, it does not fully replicate the dynamic and multifactorial conditions of the oral environment. Future in vivo studies or more advanced in vitro models with continuous exposure to biological fluids would provide a more comprehensive understanding of the long-term performance of these materials.

Conclusions

Within the limitations of this study, the following conclusions can be drawn:

1. Irrespective of the surface treatment and curing parameters, all groups produced via 3D printing demonstrated water sorption (Wsp) and water solubility (Wsl) values that are deemed clinically acceptable in accordance with ISO 4049 – 2019 standards, with Wsp less than 40 μg/mm³ and Wsl less than 7.5 μg/mm³.
2. Applying glaze can enhance the performance of 3D-printed denture base materials by lowering their Wsp and Wsl.
3. An adequate post-curing duration can reduce the water solubility of these materials.
4. A glycerin atmosphere facilitates more effective curing, thereby decreasing the water solubility of 3D-printed denture base materials.

Abbreviations

HC	heat cured group
M	milled group
3DP	3D printed group
DC	Degree of conversion
Wsp	Water sorption
Wsl	Solubility
Wsl-DW	Solubility after 7 days of immersion in distilled water
Wsp-DW	Water sorption after 7 days of immersion in distilled water
Wsl-DC	Solubility following denture cleaner aging
Wsp-DC	Water sorption following denture cleaner aging
Wsl-TC	Solubility after thermocycling aging
Wsp-TC	Water sorption after thermocycling aging
O	Optiglaze glaze material
V	VitaAkzent LC glaze material
P	Mechanical polishing
A	Air
G	Glycerin

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Not applicable.

Authors' contributions

All authors contributed to this study. Eİ and EE made equal contributions to the conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—review & editing, and visualization. EE was responsible for the supervision and project administration. All authors have read and approved the final manuscript.

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Data availability

The datasets produced and examined during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare no competing interests.

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