Dentistry 3000

Vol 14, No 2 (2026)
ISSN 2167-8677 (online)
DOI 10.5195/d3000/2026.1555

Effect of Storage Time on the Dimensional Stability of 3D Printed Dental Model Resins

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Abstract

The aim of this study was to evaluate the effect of storage-induced aging on the dimensional stability of two 3D printed resins, a plant-based and a conventional dental model resin. Sixteen dental models were fabricated from a maxillary typodont CAD reference file using two resin types (n = 8 each): a conventional resin and a plant-based UV resin, printed on a high-precision LCD 3D printer. Models were stored under standardized dry, dark, room-temperature conditions and digitized at five time points (days 1, 7, 14, 21 and 30). Deviation from the reference CAD file was quantified as the root mean square (RMS) using best-fit surface alignment in Geomagic Control X software. Data were analyzed with two-way ANOVA and Bonferroni post hoc comparisons ($\alpha = 0.05$). Dimensional deviation increased progressively over time for both resins, but the conventional resin exhibited consistently greater deviation, rising from 0.387 mm at day 1 to 0.740 mm at day 30, compared with 0.200 mm to 0.331 mm for the plant-based resin. Significant main effects of resin type and storage time were found ($p < 0.001$), along with a significant resin × time interaction ($p < 0.001$), indicating that the conventional resin deviated sharply through day 14 before plateauing, while the plant-based resin showed a comparatively flat, stable trajectory. Both resins showed progressive dimensional change with storage, but the plant-based resin demonstrated superior long-term dimensional stability.

Open Access
Citation: Sadoon MM et al. (2026) Effect of Storage Time on the Dimensional Stability of 3D Printed Dental Model Resins. Dentistry 3000. 1:a001 doi:10.5195/d3000.2026.1555
Received: August 15, 2026
Accepted: August 26, 2026
Published: September 15, 2026

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Introduction

Dental models are essential across various fields of dental practice, and gypsum casts, regarded as the gold standard, remain widely used as patient replicas for diagnosis, treatment planning and appliance construction, as well as for forensic dentistry. However, their production requires extended manufacturing time and careful handling to prevent fracture or deformation [1,2].

Currently, oral structures can be captured digitally using intraoral scanners, enabling dental treatment planning through computer-aided design (CAD) and the construction of dental models and appliances through computer-aided manufacturing (CAM) technologies [3].

At present, model-free workflows cannot accommodate all prosthetic indications, particularly manually veneered multiple-unit fixed prostheses. Although technological advances have been rapid, and the integration of intraoral scanning (IOS) with laser melting technology shows considerable promise for the fabrication of removable partial denture (RPD) frameworks, a physical dental model is still required to complete RPD fabrication [4,5]. In the same way, fully virtual protocols do not yet replace physically articulated casts in every diagnostic indication [6].

3D printing has developed into a promising technology for dental model production from polymeric materials using stereolithography (STL) files acquired either through laboratory scanners or IOS. Previous studies have demonstrated that 3D printed dental models exhibit clinically acceptable accuracy and reproducibility when compared with conventional gypsum stone casts [7,8]. Furthermore, relative to CAD/CAM milling, 3D printed models have been reported to achieve superior dimensional accuracy [9].

Conventional 3D printing resins used in dentistry are predominantly derived from petrochemical sources and typically incorporate

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methacrylate-based monomers [10]. Although these materials exhibit acceptable mechanical and dimensional properties for dental model applications, growing concerns regarding their environmental impact and the cytotoxicity of residual monomers have prompted increased interest in more sustainable and biologically favorable alternatives.

In response to these concerns, eco-friendly plant-based resins have attracted growing attention as substitutes within polymer science and dental materials research [11]. Plant-based resins are typically synthesized from renewable feedstocks such as soybean oil, linseed oil, castor oil and other vegetable-derived compounds, which can be functionalized with acrylate or methacrylate groups to enable photopolymerization [12].

The dimensional accuracy of 3D printed dental models remains a major challenge, even with the increasing use of additive manufacturing in dentistry, because the fit, marginal adaptation, occlusion and overall clinical success of dental restorations depend on it. Prosthetic adaptation may be jeopardized by any dimensional disparity in the printed model, which could ultimately affect the treatment result. As a result, assessing the durability and accuracy of 3D printed models has grown in importance in contemporary dental research [13,14]. A comparable dependence of clinical precision on the accuracy of the digitally produced device has been reported for computer-aided and guided techniques, in which any deviation of the printed guide is transferred directly to the treatment outcome [15].

Preliminary laboratory investigations have focused on evaluating the dimensional accuracy of plant-based 3D printed models [16,17]. However, these studies did not assess the effect of aging on dimensional stability or on the long-term accuracy of the printed models.

This in vitro study aimed to evaluate the effect of storage-induced aging on the dimensional stability of plant-based, eco-friendly 3D printed dental models. The null hypothesis was that storage duration would have no statistically significant effect on the dimensional accuracy of 3D printed models.

Material and Methods

Sixteen dental models were fabricated from two types of 3D printing resin (n = 8 per resin type). The first was a conventional resin (DM12 Dwn6al model resin, Shining 3D Tech, China) and the second was a plant-based resin (Plant-based UV Resin 2.0, Anycubic Technology Co., Shenzhen, China). The STL file of the dental model was generated by digitizing a maxillary Class I MOD 2 typodont dental model (Frasaco GmbH, Germany) with a laboratory scanner (3Shape E2, Copenhagen, Denmark) to obtain the corresponding CAD reference file.

Prior to printing, the resins were homogenized for 5 minutes using an automatic hands-free mixer (Phrozen Resin Mixing Station, Phrozen Tech Co., Taiwan) to ensure uniform viscosity and even distribution of fillers, thereby achieving homogeneous, defect-free prints. The STL files were subsequently exported to a high-precision LCD-based resin 3D printer (AccuFab-L4K, Shining 3D Tech, China) for model fabrication, using a 405 nm UV wavelength, a 75 µm layer thickness and a zero-build orientation [18]. After printing was completed, the models were removed from the build platform and rinsed in 95% isopropyl alcohol (IPA) for 2 minutes in an automated washing unit (FabWash, Shining 3D Tech, China) to remove uncured resin residues, in accordance with the manufacturer's instructions. The models were then air-dried at ambient room temperature to allow complete IPA evaporation. Post-curing was performed for 7 minutes using a 405 nm UV-LED post-polymerization unit at 30 °C (FabCure 2, Shining 3D Tech, China) according to the manufacturer's recommended protocol. Printing support structures were removed manually.

All models were stored at room temperature in dry, dark containers to simulate conventional dental cast storage conditions [19–21].

Dimensional accuracy was evaluated at five-time intervals (1, 7, 14, 21 and 30 days) by comparing the STL file of each 3D printed dental model with the original CAD STL file from which it had been fabricated. Eight printed dental models per resin were digitized to generate the corresponding STL files using a laboratory scanner (3Shape E2, Copenhagen, Denmark) that was calibrated prior to the scanning procedure. All scanning was performed under ambient room conditions.

Accuracy was defined as the deviation between the printed models and the dimensions of the reference CAD object. The analyses were carried out using Geomagic Control X software (Hexagon AB, Stockholm, Sweden), applying a tolerance band of 0.01 mm [22]. The STL file of the maxillary typodont model served as the reference CAD file in Geomagic Control X. Each scanned STL file was first aligned to the reference CAD file by automatic detection of anatomical landmarks (cusp tips and incisal edges), followed by a best-fit alignment based on the iterative closest point algorithm, which minimizes the distance between point clouds across the model surface. A three-dimensional comparison was then performed for each group, during which the software calculated the point-to-surface distance across the entire model. Root mean square (RMS) values, representing the overall deviation between each scanned model and the reference CAD file, were obtained.

The Shapiro–Wilk test was used to assess the distribution of the specimens, and descriptive statistics (mean and standard deviation) were calculated. A two-way ANOVA with Bonferroni pairwise comparisons was performed to evaluate inter-group differences. Data were collected and processed in Microsoft Excel 2021, and SPSS Statistics (v27, IBM Corp., USA) was used to perform the statistical analyses. Statistical significance was set at $p \leq 0.05$.

Results

Table 1 shows that the mean dimensional deviation of the conventional resin increased progressively across the storage period (all values in mm), from 0.387 ± 0.215 at day 1 to 0.576 ± 0.179 at day 7, 0.68 ± 0.174 at day 14, 0.721 ± 0.165 at day 21 and 0.74 ± 0.173 at day 30. A similar upward trend was observed for the eco-friendly resin, with mean values increasing from 0.2 ± 0.016 at day 1 to 0.218 ± 0.024 at day 7, 0.251 ± 0.038 at day 14, 0.267 ± 0.035 at day 21 and 0.331 ± 0.064 at day 30.

Across all five storage intervals, the conventional model resin consistently exhibited a higher mean RMS than the eco-friendly resin, and the magnitude of this difference became more pronounced over time. By day 30 the conventional model resin exhibited a mean deviation more than twice that of its eco-friendly counterpart.

The distribution of the RMS dimensional deviation values for both resin types across the five storage intervals was assessed with the Shapiro–Wilk test (Table 2). The test confirmed a normal distribution for all groups at all time points ($p > 0.05$).

A two-way analysis of variance (ANOVA) was conducted with resin type as the between-subject factor and storage time as the within-subject factor (Table 3). A statistically significant effect of resin type was found ($p < 0.001$, partial $\eta^2 = 0.725$), confirming that overall dimensional deviation differed significantly between the two resins, with the conventional resin exhibiting substantially greater deviation than the plant-based resin.

A significant main effect of time was also observed ($p < 0.001$, partial $\eta^2 = 0.725$), indicating that dimensional deviation increased significantly across the storage period irrespective of resin type.

Most notably, a significant resin × time interaction was identified ($p < 0.001$, partial $\eta^2 = 0.487$), indicating that the trajectory of dimensional change over the storage period differed significantly between the two resins. This interaction (Figure 1) shows the conventional resin rising steeply between days 1 and 14 before plateauing, while the plant-based resin

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followed a comparatively flat and stable trajectory throughout.

Bonferroni pairwise comparisons (Table 4) confirmed that dimensional deviation increased significantly between most consecutive and non-consecutive time points (all $p \leq 0.017$), with the exception of the day 14–day 21 ($p = 0.087$) and day 21–day 30 ($p = 0.064$) intervals, which did not reach statistical significance, suggesting that dimensional change plateaued in the later storage period.

The estimated marginal means of RMS for the resin × time interaction (Table 5) showed that the dimensional deviation of the conventional resin rose from 0.387 mm (day 1) to 0.740 mm (day 30), while that of the plant-based resin rose from 0.200 mm to 0.331 mm over the same interval, corroborating the significant interaction and indicating superior dimensional stability of the plant-based resin throughout the 30-day storage period.

Discussion

This study evaluated the dimensional stability of dental models printed from conventional and plant-based (eco-friendly) resins over a 30-day storage period. The results demonstrated that both resins underwent a progressive increase in dimensional deviation from the reference CAD file over time; however, the conventional resin exhibited greater and more rapidly accumulating deviation than the plant-based resin at every time point. By day 30, the mean RMS of the conventional resin (0.74 ± 0.17 mm) was more than double that of the plant-based resin (0.33 ± 0.06 mm), and the significant resin × time interaction confirmed that the two resins followed fundamentally different trajectories of dimensional change rather than merely differing in magnitude. This indicates that resin chemistry, rather than storage duration alone, is the dominant determinant of long-term dimensional stability in printed dental models.

The finding that storage time significantly affects the dimensional accuracy of 3D printed dental models is consistent with a growing body of literature. Joda et al. [23] reported that 3D printed dental models are no longer suitable after three weeks of aging. Similarly, Lin et al. [24] found that storage significantly affects the full-arch trueness of printed models for up to six weeks after printing. The present results extend this literature by showing that the magnitude and trajectory of this time-dependent deviation are not fixed properties of 3D printed models in general, but depend strongly on the specific resin formulation used, with the conventional resin deviating far more severely than its plant-based counterpart over an identical 30-day observation period.

After post-curing, the resin retains a fraction of unreacted monomer and pendant functional groups within the polymer network. Alharbi et al. [25] demonstrated that residual monomer elution from 3D printed resins is directly related to the degree of post-printing polymerization, with incomplete conversion resulting in greater monomer release. Continued dark polymerization, secondary cross-linking and stress relaxation within an incompletely converted network can proceed for days after the initial UV cure, producing measurable post-printing shrinkage and warping even under dry storage conditions. In addition, methacrylate networks are known to be hygroscopic; even the low ambient humidity inside a closed storage container can be sufficient to drive slow water sorption into the polymer matrix, causing local swelling that is superimposed on the shrinkage arising from residual cure [26]. The combination of these two opposing but co-occurring mechanisms — continued cross-linking shrinkage and moisture-driven expansion — likely explains both the magnitude and the biphasic (steep-then-plateau) shape of the deviation curve seen for the conventional resin in this study.

In contrast, the plant-based resin displayed a flat and stable trajectory across the full 30-day period. Bio-based resins are typically formulated with renewable building blocks such as plant-oil-derived acrylates or bio-based polyester acrylates, which can produce comparable or even superior network conversion and thermomechanical stability, depending on the formulation [27].

From a clinical perspective, these findings carry direct implications for the digital dental workflow. Printed models are frequently retained for delayed procedures such as indirect restoration fabrication, orthodontic appliance manufacture or medico-legal record keeping, during which the model may remain in storage for days to weeks before use. Etemad-Shahidi et al. [28] reported that clinically acceptable error thresholds for 3D printed dental models range from 100 µm for high-accuracy prosthodontic applications up to 500 µm for orthodontic applications. Within this framework, the plant-based resin remained closer to a clinically tolerable range for a longer portion of the storage period, whereas the conventional resin exceeded the stricter prosthodontic thresholds relatively early, particularly after day 7. Beyond restorative indications, printed models and templates are also central to three-dimensional treatment planning workflows, where any storage-related distortion of the model propagates directly into the planned outcome [29].

Several limitations should be considered when interpreting these findings. All models were fabricated from a single reference typodont using one printer, one layer thickness and one post-processing protocol, and only one commercially available plant-based resin was tested. The observation period was limited to 30 days; although a plateau in dimensional change was observed toward the later storage intervals, longer-term behavior beyond this window remains unknown. Finally, this was an in vitro investigation conducted under controlled laboratory conditions, and the findings should be confirmed clinically.

Conclusion

Both the conventional and the plant-based 3D printed dental model resins exhibited a progressive increase in dimensional deviation over the 30-day storage period.

The conventional model resin showed greater deviation than the plant-based resin by day 30. The plant-based resin had superior long-term dimensional stability, which may offer a meaningful advantage over conventional resin when models must be stored prior to use.

Funding Statement

None.

Conflict of Interest

The authors declare no conflict of interest.

Availability of Data and Materials

All data generated or analyzed during this study are included in this published article.

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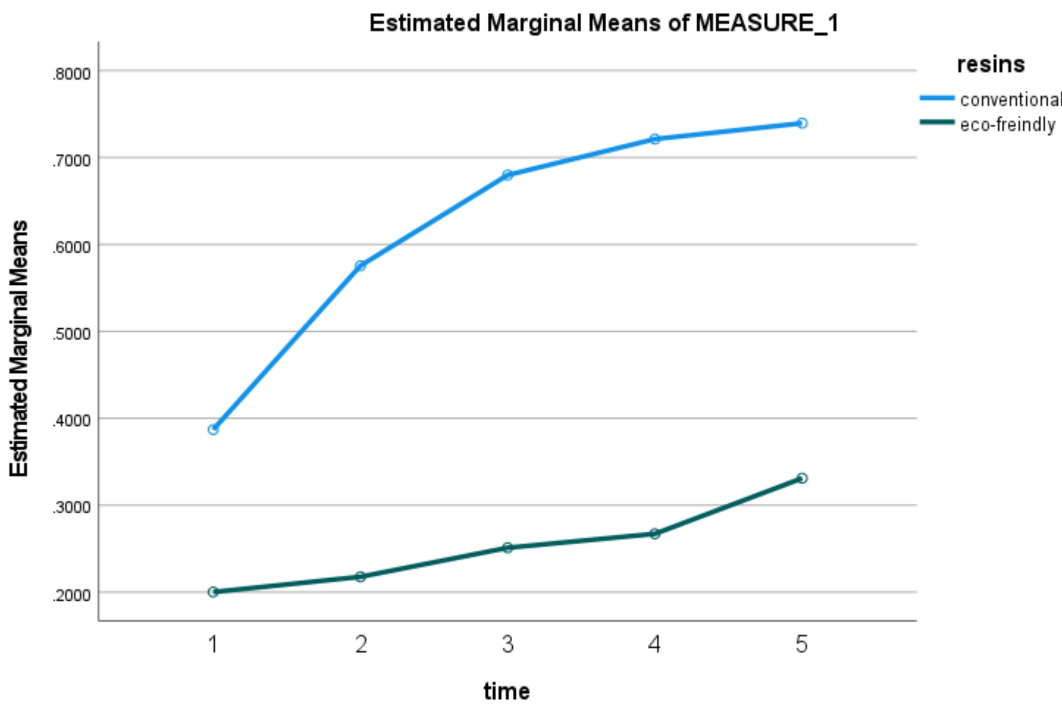

Figure 1. Profile plot of the resin × time interaction for dimensional deviation.

Table 1. Mean and standard deviation of RMS (mm) for the two 3D printed model resins.

	Material	Mean RMS (mm)	SD	n
Day 1	Conventional	0.387	0.215	8
	Eco-friendly	0.2	0.016	8
	Total	0.294	0.176	16
Day 7	Conventional	0.576	0.179	8
	Eco-friendly	0.218	0.024	8
	Total	0.397	0.222	16
Day 14	Conventional	0.68	0.174	8
	Eco-friendly	0.251	0.038	8
	Total	0.466	0.253	16
Day 21	Conventional	0.721	0.165	8
	Eco-friendly	0.267	0.035	8
	Total	0.494	0.261	16
Day 30	Conventional	0.74	0.173	8
	Eco-friendly	0.331	0.064	8
	Total	0.535	0.246	16

Table 2. Shapiro–Wilk normality test for the two 3D printed model resins.

Resin type		Shapiro–Wilk		
	Storage period	Statistic	df	p
Conventional resin	Day 1	0.91	8	0.355
	Day 7	0.961	8	0.818
	Day 14	0.96	8	0.812
	Day 21	0.858	8	0.115
	Day 30	0.902	8	0.299
Eco-friendly resin	Day 1	0.911	8	0.362
	Day 7	0.982	8	0.971
	Day 14	0.928	8	0.502
	Day 21	0.982	8	0.972
	Day 30	0.872	8	0.156

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Table 3. Two-way ANOVA for the effects of resin type, time and their interaction on dimensional deviation.

Source	F	p	Partial η²
Resin (between-subject)	36.99	< 0.001	0.725
Time	41.9	< 0.001	0.725
Resin × time	13.3	< 0.001	0.487

Table 4. Bonferroni pairwise comparisons of dimensional deviation for the different time intervals.

(I) time	(J) time	Mean Difference (I-J)	Std. Error	p-value	95% CI for difference	
					Lower Bound	Upper Bound
Day 1	Day 7	-0.103*	0.027	0.017	-0.191	-0.015
	Day 14	-0.172*	0.029	0.000	-0.268	-0.076
	Day 21	-0.201*	0.031	0.000	-0.304	-0.097
	Day 30	-0.242*	0.032	0.000	-0.347	-0.137
Day 7	Day 1	0.103*	0.027	0.017	0.015	0.191
	Day 14	-0.069*	0.004	0.000	-0.083	-0.055
	Day 21	-0.098*	0.009	0.000	-0.128	-0.067
	Day 30	-0.139*	0.014	0.000	-0.185	-0.093
Day 14	Day 1	0.172*	0.029	0.000	0.076	0.268
	Day 7	0.069*	0.004	0.000	0.055	0.083
	Day 21	-0.029	0.009	0.087	-0.060	0.003
	Day 30	-0.07*	0.015	0.004	-0.12	-0.02
Day 21	Day 1	0.201*	0.031	0.000	0.097	0.304
	Day 7	0.098*	0.009	0.000	0.067	0.128
	Day 14	0.029	0.009	0.087	-0.003	0.06
	Day 30	-0.041	0.013	0.064	-0.084	0.002
Day 30	Day 1	0.242*	0.032	0.000	0.137	0.347
	Day 7	0.139*	0.014	0.000	0.093	0.185
	Day 14	0.07*	0.015	0.004	0.02	0.12
	Day 21	0.041	0.013	0.064	-0.002	0.084

Based on estimated marginal means. * The mean difference is significant at the 0.05 level. b Adjustment for multiple comparisons: Bonferroni.

Table 5. Estimated marginal means of RMS (mm) for the resin × time interaction.

Resin	Time	Mean RMS (mm)	Std. error	95% CI (lower–upper)
Conventional resin	Day 1	0.387	0.054	0.271–0.503
Conventional resin	Day 7	0.576	0.045	0.479–0.672
Conventional resin	Day 14	0.68	0.045	0.584–0.775
Conventional resin	Day 21	0.721	0.042	0.631–0.812
Conventional resin	Day 30	0.74	0.046	0.641–0.838
Eco-friendly resin	Day 1	0.2	0.054	0.085–0.316
Eco-friendly resin	Day 7	0.218	0.045	0.121–0.315
Eco-friendly resin	Day 14	0.251	0.045	0.156–0.347
Eco-friendly resin	Day 21	0.267	0.042	0.177–0.357
Eco-friendly resin	Day 30	0.331	0.046	0.232–0.43