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Research Article

In Vitro Assessment of Plant-Based 3D-Printed Resin for Dental Model Applications

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Abstract

Aims: This study aimed to assess the mechanical properties (Flexural strength, Compression strength, and hardness) and accuracy (trueness and precision) of plant-based resin as dental models in relation to conventional resin.

Materials and Methods: Sixty specimens for mechanical properties (20 specimens for each test) evaluation and 20 dental models were fabricated using two types of 3D printing resins (plant-based and conventional) printed by an LCD 3D printer with 75 µm layer thickness and zero-degree printing orientation. The mechanical performance was assessed through flexural strength, compressive strength, and hardness testing. Dimensional accuracy was evaluated by digitally scanning the printed models with a lab scanner and analyzing the datasets using Geomagic Control X software.

Results: Descriptive analysis and an independent samples t-test were performed. The results show that the plant-based resin exhibited equivalent values to those of the conventional model resin for flexural strengths (49.81±3.47 MP, 48.41±4.14 MP respectively), compressive strengths (4127.39±1.1MP, 127.3±0.59 MP respectively), and hardness (70.68±0.49 and 70.72± 1.12 respectively). No statistically significant differences (p=0.105) were observed between the two resin types in terms of model trueness, whereas the plant-based resin demonstrated higher precision than the conventional resin (0.184±0.04 and 0.257± 0.09 mm, respectively).

Conclusion: Plant-based resins demonstrate mechanical and dimensional properties comparable to those of conventional 3D-printed model resin. Plant-based resin shows superior precision to conventional resin.

Keywords: Accuracy, Dental model, Eco-friendly resin, Plant-based resin, 3D printed, Mechanical properties.

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INTRODUCTION

Dental models are essential for different dental practices, and gold standard gypsum dental models are still widely used as patient replicas for prosthodontic treatment diagnosis, planning, and appliance manufacturing. This requires extended manufacturing time and care for handling to prevent fracture and deformation (1–3) Currently, oral structures can be digitally captured by intraoral scanners for dental planning via CAD and the construction of dental models and appliances via computer-aided manufacturing, such as additive and subtractive technology. (4)

3D-printed dental casts are widely used for oral diagnosis, providing the teeth position, arch discrepancies, jaw, and occlusion form in a three-dimensional interpretation. Furthermore, the storage of physical models was eliminated, as they could be produced from scanned data when required (2,5). They have been confirmed to have clinically acceptable accuracy and reproducibility when compared with a gypsum cast (6).

Conventional photopolymer resins used in dental 3D printing are predominantly derived from petrochemical sources, incorporating methacrylate-based monomers such as bisphenol A-glycidyl methacrylate (BIS-GMA) and urethane dimethacrylate (UDMA) (7). While these materials have demonstrated acceptable mechanical and dimensional properties for dental model applications, growing concerns regarding their environmental impact and cytotoxicity of residual monomers have prompted the search for more sustainable and biologically favorable alternatives.

In response to these concerns, plant-based and bio-derived resins have generated increasing attention as eco-friendly substitutes in polymer science and dental material research (8). 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 (9).

These bio-based monomers offer potential advantages including reduced toxicity, improved biodegradability, and a lower carbon footprint compared to their petrochemical counterparts(10,11).

Donmez et al. (12) concluded that plant-based 3D-printed resin removable model dies have better trueness and stability than conventional resin. While Pauls and Hornberg(13) stated that there are no significant differences between the accuracy of soy bean 3D-printed orthodontic models and conventional dental resin and plaster models.

Donmez et al. (14) explored that corn-based 3D resin printed by a DLP printer displayed dimensional stability equivalent to or higher than that of the conventional dental model printed with a similar printer

Despite these promising attributes, the clinical translation of plant-based resin into dental model fabrication remains largely unexplored. Dental models must satisfy stringent requirements in terms of dimensional accuracy, trueness, precision, flexural and compressive strength, and surface hardness to reliably support downstream clinical workflows.

The mechanical and dimensional performance of plant-based 3D-printed resin relative to conventional resins has not been comprehensively characterized, reporting a critical gap in the literature.

Therefore, this study aimed to evaluate and compare the mechanical properties (flexural strength, compressive strength, and surface hardness) as well as the dimensional accuracy, in terms of trueness and precision, of plant-based 3D-printed resin against a conventional model resin in an in vitro setting.

This study aims to inspect whether dental models fabricated by plant-based 3D-printed resin offer viable substitutes to those fabricated through conventional 3D-printed model resin, with an explicit focus on model accuracy (trueness and precision) and mechanical properties (compressive strength, flexural strength, and hardness).

The null hypothesis proposed that no significant differences would exist between the two resin types across all tested parameters.

MATERIALS AND METHODS

Specimen preparation

Eighty specimens were prepared from two types of 3D-printed resin (40 specimens for each); the first one was conventional resin (DM12, dental model resin, Shining 3D Tech, Chania, lot:20240720-05) and the second one was plant-based resin (Plant-Based UV Resin 2.0, Anycubic Technology Co., Shenzhen, China, lot: RZW2HU2504C0802). The specimens subdivide to four groups of each resin type (10 specimens for subgroups) to be tested for flexural strength, compressive strength, hardness, and dimensional accuracy.

Specimens were virtually designed using open-source CAD software (freeCAD1.0.2, Belgium). with the following dimensions for each test: compressive strength (CS) tests a cylindrical shape with 6mm diameter ×12mm height(15) , bar shape with 64 × 10 × 3.3 ± 0.2mm (length, width and thickness respectively) for flexural strength (FS) test(16) and disk shaped 12 mm diameter and 6mm thickness for dura d hardness (H) teat(17), the generated designs were exported as STL files. Dental model (DM) STL files were generated by scanning a standard mandibular typodont dental model (Frasaco GmbH, Germany) using a lab scanner (3Shape E2, Copenhagen, Denmark) to obtain a CAD STL file for an accuracy test.

The resins were well blended for 5 min with an automatic electrical free-hand mixer (Phrozen Resin Mixing Station, Phrozen Tech Co, Taiwan) for evenly mixed viscous and composite-filled resins, to ensure flawless and homogeneous prints. The STL file was then transferred to a high-precision resin LCD technology 3D-printer (AccuFab- L4K, Shining 3D Tech, Chania) for specimen printing with a 405 nm UV wavelength, 75 μm layer thickness, and zero-degree printing orientation based on accuracy assessments from a former study (18). The completed printed specimens were removed from the printer table and washed with 95% isopropyl alcohol (IPA) for 2 min in a washing bath (Fabwash; Shining 3D Tech, Chania) to eliminate uncured resin (according to the manufacturer's instructions), then left to dry and IPA to evaporate in air at ambient room conditions. The specimens were post-cured for 7 min using a 405-wavelength UV LED post-polymerization unit at 30 °C (FabCure 2; Shining 3D Tech, Chania) as manufacturer's recommendation. Subsequently, the supporting structures of the specimens were removed manually and finished using a low-speed dental engine with 800, 1500, and 2000 grit silicon carbide paper, then cleaned with IPA (19,20).

The tested specimens were stored at room temperature in a dry and dark box for 48 hours to preserve their dimensional accuracy and simulate dental cast storage conditions before tests were performed(21–24).

Flexural strength

The three-point bending test for flexural strength was performed using a universal testing machine (GESTER GT-UA03, China) at a crosshead speed of 5 mm/min. Each specimen was seated on two round supports with a 50 mm distance between them, and a vertical load was applied at the center of the specimen. Data were obtained when the samples were fractured. The flexural strength was calculated according to equations (25,26):

FS(MPa) = 3 FL/(2bd2).

Compression strength

A compressive strength test was performed using a universal testing machine (GESTER GT-UA03, China) with a crosshead speed of 1.3 mm/min at room temperature. The compressive strength of the specimens under the crushing load was calculated using the following equation(27).

CS (MPa) = load/area

Hardness

A Shore D durometer tester (Shore D, LD –YJ, Dongguan Lonroy Equipment Co., China) was used to measure the hardness of the specimens. The measurement was performed by applying an indenter over the specimens under 5 kg (50 Newtons load) for 5 sec. The mean of five readings at different sites of the specimen was calculated for the hardness test(28,29).

Accuracy test.

The test was performed by comparing the STL file for the 3D-printed dental model and the CAD STL file from which the dental model was printed. Printed dental models (10 models for each resin) were digitized to obtain an STL file by scanning with a lab scanner (3Shape E2 Copenhagen K, Denmark) that was calibrated prior to the scanning process. The scanning procedure was performed under ambient room conditions. The accuracy was achieved based on trueness and precision.

The trueness is deviation between the printed model and the CAD object's dimensions, while precision is closeness of repeated print produced by the same object, so for trueness evaluation each scanned DM surface was compared with the CAD STL file from which the dental model was printed from, whereas the precision of DM were achieved by comparing STL file of dental model for same group with each other via Geomagic Control X software (Hexagon AB, Stockholm, Sweden) with 0.01 mm tolerance bands(30).

The dental models were labeled (1to10) for each resin. To assess the trueness of the model, the STL file of the standard mandibular model was set as the reference CAD file in Geomagic Control X software. The scanned STL file was initially alignment to superimposed onto the CAD file, which automatically detect the anatomical land mark of the model (cusp tips and incisal edges), followed by a best-fit alignment that based on iterative closest point algorithm for dental models (minimizing distance between point cloud over the model surface). A 3D measurement was performed for each group separately, in which the software calculated point-to-surface distances across the entire model. The Root Mean Square (RMS) values (to quantify the overall deviation between the scanned and reference CAD model) and associated color-coded deviation maps were obtained from the analysis. In the precision test, model No.1 was set as the CAD reference file, and an identical area of interest was selected. Thereafter, models 2 to 10 were separately processed to calculate the RMS values. Subsequently, model No. 2 was selected as the CAD's new reference file, and models No. 3 to 10 were independently uploaded for comparison to calculate their root mean square (RMS) values. This procedure was repeated iteratively, yielding a total of 45 RMS values for each resin(31,32).

Statistical analysis

The normality test (Shapiro–Wilk test) was performed to assess the distribution of the specimen; descriptive statistics (mean and standard deviation) were reported; and an independent t-test was performed to assess inter-group differences. Data were collected and calculated using Microsoft Excel 2021, and SPSS Statistical software (IBM SPSS Statistics, v27, IBM Corp., USA) was used to perform statistical analyses. Statistical significance was set at $p \leq 0.05$.

RESULTS

Mechanical properties:

Table (1) demonstrates the descriptive analysis of the mechanical properties of the two different resins (plant-based and conventional) evaluated in this study. The mean flexural strength of the plant-based resin was 49.81 (±3.470) MPa, whereas that of the conventional resin was 48.41 (±4.147) MPa. The compression strength means for plant-based and conventional resins were 127.034 (±1.102) and 127.392(±0.597) MPa, respectively. The mean Shore D hardness was 70.68 (±0.49) for plant-based resin and 70.72(±1.128) for conventional resin.

Table (1): Descriptive analysis of mechanical properties of plant-based and conventional resins.

Mechanical properties	Resin type	N	Minimum	Maximum	Mean	Std. Deviation
Flexural strength (MPa)	Plant-based resin	10	43.56	56.56	49.81	3.470
	Conventional resin	10	41.36	53.69	48.41	4.147
Compression strength (MPa)	Plant-based resin	10	124.420	128.367	127.034	1.102
	Conventional resin	10	126.757	128.332	127.392	0.597
Hardness (Shore D)	Plant-based resin	10	69.8	71.6	70.68	0.491
	Conventional resin	10	69.6	72.6	70.72	1.128

Table (2): Test of normality (Shapiro-Wilk test) for mechanical properties.

Mechanical properties	Resin type	statistic	df	Significant
Flexural strength	Plant-based resin	0.952	10	0.694
	Conventional resin	0.907	10	0.263
Compression strength	Plant-based resin	0.853	10	0.063
	Conventional resin	0.879	10	0.127
Hardness (Shore D)	Plant-based resin	0.976	10	0.938
	Conventional resin	0.876	10	0.119

Table 3 (Independent Samples Test) showed that flexural strength has no significant differences between conventional and plant-based resin (*p*= 0.426) with a mean difference of 1.391(±1.71) MPa; also, there were no significant differences for compression strength (*p*=0.378) and hardness test (*p*=0.920) with mean difference -0.358 (±0.396) MPa and -0.04 (±0.389), respectively. Overall, the results indicated that the two resins did not significantly differ in the studied mechanical properties.

Table (3): Comparison of mechanical properties of plant-based and conventional resins.

	Mean Difference	Std. Error Difference	t-value	df	Sig. (2-tailed)	Significance
Flexural strength	1.391	1.71	0.814	18	0.426	NS
Compression strength	-0.358	0.396	-0.904	18	0.378	NS
Hardness (shore D) test	-0.04	0.389	-0.103	18	0.920	NS

df: degree of freedom, NS: not statistically significant (p>0.05)

Accuracy test

The normality test results (Table 4) showed that the data for trueness and precision followed a normal distribution for both resin types (*p*>0.05), justifying the use of parametric statistical analysis.

Table (4): Test of normality (Shapiro-Wilk test) for accuracy test.

Accuracy	Resin type	statistic	df	Significant
Trueness	Plant-based resin	0.924	10	0.392
	Conventional resin	0.952	10	0.692
precision	Plant-based resin	0.956	45	0.082
	Conventional resin	0.964	45	0.178

The mean of the RMS value, as determined by trueness measurement (Table 5), for plant-based 3D printed resin was 0.156 (±0.043) mm, while that for conventional resin was 0.13 (±0.021) mm.

Table (5): Comparison of accuracy between plant-based and conventional resins.

		Mean (mm)	Std. Deviation	t-value	df	Sig. (2-tailed)	Significance
Trueness	Plant-based resin	0.156	0.043	1.706	18	0.105	NS
	Conventional resin	0.13	0.021				
precision	Plant-based resin	0.184	0.048	-4.605	88	0.000	S
	Conventional resin	0.257	0.094				

df: degree of freedom, NS: not statistically significant, S: statistically significant (p>0.05)

A lower RMS value indicates higher trueness and minimal deviation from the reference STL file. Overall, no significant difference in trueness was identified between the two resins (p>0.05), as revealed by the Independent Samples Test (Table 5).

The resin type significantly affected repeatability, as demonstrated by precision (p<0.05). Table 5 revealed that plant-based resin displayed significantly higher (lower RMS) precision (0.184 ±0.048 mm) related to conventional resin (0.257± 0.094mm)

Color map

The 3D color map (Figure 1) demonstrates a heterogeneous deviation pattern between the tested and reference models for both resins. Expansion is represented by yellow/red areas, while blue regions indicate shrinkage. The lingual and buccal gum surfaces primarily showed expansion, the lingual frenum area showed shrinkage, and the occlusal and incisal areas displayed both expansion and contraction.

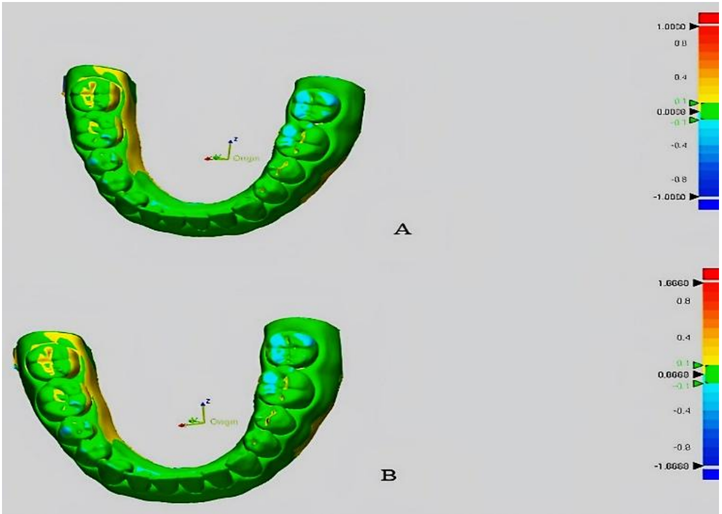

Figure (1): Color map illustrating the deviation in different dental model surfaces between the reference and test models for conventional resin(A) and plant-based resin(B).

DISCUSSION

Limited investigations have focused on the mechanical properties of plant-based resins in relation to conventional 3D-printed dental models. The null hypothesis that there are no significant differences in the mechanical properties of the two types of resins was accepted.

Mechanical performance is essential for dental model resins to achieve reliable printability, accuracy, and clinical success(28,33). Accordingly, this study evaluated the flexural properties, compressive strength, and hardness, which are among the most widely examined mechanical characteristics of 3D-printed dental resin(33). Accurate and precise replication of anatomical structures is fundamental to achieving the treatment objectives.

Additively manufactured dental resins have been reported to show that extended post-curing increases flexural strength due to polymer network development (34,35), which is consistent with previous reports indicating that plant-based monomers can achieve mechanical behavior similar to conventional resin. This indicates that plant-based monomers can achieve mechanical behaviors similar to conventional resin (36–38).

The compressive strength found in this study was consistent with that previously reported for 3D-printed model resins (39). Plant-based resins demonstrated a slight reduction in compressive strength in relation to conventional ones, which is in line with findings reported in previous studies (40,41).

Surface hardness influences wear resistance and detail preservation. The hardness (Shore D) of the plant-based resin was comparable to that of conventional dental model resins. Consistent with previous reports (38,40,42).

The null hypothesis that there are no significant differences in the accuracy of plant-based and conventional resins was accepted for the trueness of the printed model and rejected for precision.

Accuracy (trueness and precision) of a 3D-printed dental model is multi-factorial, driven by the digital workflow rather than the printer alone. Trueness is primarily influenced by factors such as polymerization shrinkage, layer thickness, and build-up orientation, and the resin viscosity to ensure adequate flow between the printer platform and the bottom of the vat after the deposition of each layer, rather than chemical composition of the resin per se (43). As the two resins had comparable viscosity and filler content and were printed with similar parameters and post-curing conditions, there was no statistical difference in the trueness of the dental models. This result was consistent with finding that conducted by Pauls and Hornberg (13).

To the best of the author's knowledge, limited data are currently available regarding the precision of plant based 3d- printed resin as a dental model, and this study contributes additional evidence to this relatively unexplored area.

The results indicate superior measurement consistency for plant-based resins compared to conventional resins.

The common range of researchers presently accepts a deviation of <100–500 μm for clinically acceptable 3D- printed dental models. In a further study, clinically acceptable deviation for an orthodontic 3D-printed model was <300 μm, while for prosthodontics application, the acceptable margin deviations were 100–150 μm (44,45).

This study has several limitations. The specimens were not subjected to aging protocols, thermocycling, or water sorption analysis, which are important for simulating the long-term performance of resins under clinical conditions. No biocompatibility testing was performed, and physicochemical characterization of the resins (such as degree of conversion, cross-linking density, or filler content) was not conducted, which limits the ability to correlate the observed mechanical and dimensional outcomes with underlying material composition. Additionally, this study evaluates only one plant-based resin type, one printing technology, and one printing orientation. Future studies are warranted to validate and extend these limitations

CONCLUSIONS

Within the limitations of this study:

- The mechanical properties of plant-based resin (soybean resin) were comparable to those of conventional resin.
- Soy-based resin demonstrated comparable trueness and, in terms of precision, a superior alternative to conventional model resin. It may be considered a viable material for the fabrication of prosthetic and orthodontic models.

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Authors' Contribution

Sadoon M contributed to conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, validation, visualization, writing–original draft, writing–review and editing.

Ethical statement:

The protocol of this study was approved by the Research Ethical Committee at the College of Dentistry at the University of Mosul.

Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this manuscript.

Availability of data and materials: All data generated or analyzed during this study are included in this published article.

Declaration of Generative AI and AI-assisted technologies

The author declares that during the preparation of this work, the author used consensus AI to collect related review articles. The author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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تقييم مختبري لراتنج نباتي المنشأ مطبوع بتقنية الطباعة ثلاثية الأبعاد لاستخدامه في نماذج قوالب الأسنان

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الملخص

الأهداف: هدفت هذه الدراسة إلى تقييم الخصائص الميكانيكية (مقاومة الانحناء، ومقاومة الضغط، والصلابة) والدقة (الصحة والدقة الإحصائية/الاتساق) للراتنج (الريزن) النباتي المستخدم في نماذج الأسنان، وذلك مقارنةً بالراتنج التقليدي.**المواد وطرائق العمل:** تم تصنيع ستين عينة لتقييم الخصائص الميكانيكية (20 عينة لكل اختبار) و20 نموذجاً سنياً باستخدام نوعين من راتنجات الطباعة ثلاثية الأبعاد (راتنجات نباتية وأخرى تقليدية)، وطُبعت هذه النماذج باستخدام طابعة ثلاثية الأبعاد بتقنية LCD، مع ضبط سُمك الطبقة عند 75 ميكرومتراً واتجاه طباعة بزاوية صفر درجة. وجرى تقييم الأداء الميكانيكي من خلال اختبارات مقاومة الانحناء، ومقاومة الانضغاط، والصلابة؛ كما تم تقييم الدقة الأبعادية عن طريق المسح الرقمي للنماذج المطبوعة باستخدام ماسح ضوئي مخبري وتحليل البيانات المجمعة باستخدام برنامج "Geomagic Control X". **النتائج:** أُجري التحليل الوصفي واختبار "ت" (t-test) للعينات المستقلة. وأظهرت النتائج أن الراتنج النباتي أظهر قيماً مكافئة لتلك الخاصة بالراتنج التقليدي المستخدم في النماذج من حيث مقاومة الانحناء (3.47±49.81 ميجا باسكال و4.14±48.41 ميجا باسكال على التوالي)، ومقاومة الضغط (1.1±127.39 ميجا باسكال و0.59±127.3 ميجا باسكال على التوالي)، والصلابة (0.49±70.68 و1.12±70.72 على التوالي). ولم تُلاحظ فروق ذات دلالة إحصائية (p=0.105) بين نوعي الراتنج من حيث "صحة النموذج" (trueness)، في حين أظهر الراتنج النباتي دقة (precision) أعلى مقارنة بالراتنج التقليدي (0.04±0.184 مم و0.09±0.257 مم على التوالي). **الاستنتاجات:** تُظهر الراتنجات النباتية خصائص ميكانيكية وأبعاداً مماثلة لتلك الخاصة بالراتنج التقليدي المستخدم في الطباعة ثلاثية الأبعاد للنماذج. كما يُظهر الراتنج النباتي دقةً تتفوق على دقة الراتنج التقليدي.

الكلمات المفتاحية: الدقة، نموذج الأسنان، راتنج صديق للبيئة، راتنج نباتي، طباعة ثلاثية الأبعاد، خصائص ميكانيكية..