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Changes in the Physicochemical Properties of 3D Printing Materials Under the Influence of Various Beverages—An In Vitro Studie

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Abstract

Background/Objectives: 3D printing of removable dentures and temporary crowns and bridges is currently one of the fastest-developing technologies in prosthetic dentistry. However, little is known about the effect of different beverage solutions on the strength and color of 3D-printed denture resins. The study aimed to determine the effect of coffee, red wine, 40% ethyl alcohol, and water (reference samples) on six 3D-printed denture resins (Denture 3D+ (Nexdent); Vita Vionic (Vita), Lucitone Digital Print 3D (Dentsply), DX Denture Flex (Dentex); Formlab Denture Base (Formlabs, Optiprint Dentona). **Materials and Methods**: Resin samples measuring 3.3 × 10 × 65 mm (144 total) and disks 1 × 20 mm (108 total) were produced using an Asiga printer. The printed materials were then stored in coffee, red wine and distilled water and vodka for 30 days. After this time, they were subjected to a flexural strength (FS) test and the measurement of color change (CC), and compared to reference samples measured before contact with the solutions. One- and two-way ANOVA were used for statistical analysis to compare samples before and after contact with the solutions. **Results**: The vodka solution affected the materials' FS—the strength was reduced from 10% (Lucitone) to 88% (Detax). For the sample with the most significant FS reduction, the elastic modulus could not be determined. The largest CCs were observed for coffee ($E = 22.66 \pm 1.26$), and red wine ($E = 21.04 \pm 0.70$), whereas vodka had the least effect on CC (Lucitone $E = 1.04 \pm 0.41$ and Form Labs $E = 1.31 \pm 0.85$). **Conclusions**: 3D-printed resins are susceptible to the effects of commonly consumed substances, such as coffee, vodka, and red wine. When designing and manufacturing removable prosthetic restorations, it is necessary to carefully consider the dietary habits of patients and the materials from which the removable prosthetics are printed.

Keywords: 3D printing; denture base; color change; mechanical properties

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1. Introduction

Nowadays, 3D printers are commonly used in dental laboratories. They are used to print materials with short contact times with the patient, such as custom trays, surgical templates, and retainers [1–3]. This technology is also increasingly used to create restorations that remain in the patient's mouth for longer periods—over 2–5 years (removable dentures, crowns, and bridges). In such cases, the impact of food intake on such materials is greater [4,5].

In the case of traditional materials used in prosthetics, such as acrylic resins and composite materials, a number of substances (the gold standards) are known to influence their color and mechanical properties. These include coffee, red wine, tea, fruit juices, and alcohol [6–10]. These solutions contain colored compounds that are deposited on surfaces. Some of these solutions also have a low pH, whereas red wine and alcohol contain ethanol, which can have a destructive effect on materials in prolonged contact [11–15].

The long-term influence on both traditional polymethyl methacrylate (PMMA) and composite materials has been observed in numerous publications, showing significant color changes in restorations and a deterioration of mechanical properties. However, printed resins differ from traditional materials in their chemical composition and processing technology [16–20].

In traditional acrylic dentures, PMMA (powder) and methyl methacrylate (MMA) liquid) are cured under pressure at high temperatures in a technical laboratory. This process results in a polymerized material with a low residual monomer content and a high degree of polymerization. Additionally, most acrylics do not contain inorganic fillers [20–22].

Some resins used in 3D printing are similar to those commonly used in composites for tooth filling in a dental clinic. However, the curing of most composite materials is different, because polymerization occurs within the oral cavity through a short exposure to a strong light source, such as a polymerization lamp. The cured material is highly cross-linked, with a monomer conversion rate of 60–80% [23–25]. Composite materials also contain various types of fillers, with a content of up to 80% [26].

According to patents and data provided by manufacturers, 3D-printed resins constitute a group of materials different in their chemical composition from both traditional acrylics and composite materials. They lack fillers (or their content is very low), and the organic component consists of monomers and oligomers similar to those used in composite materials. Furthermore, the curing technology for these types of materials varies because it involves a short exposure to a light source, rinsing in an isopropyl alcohol solution, and prolonged exposure to a polymerization lamp. Another significant difference is that the material is built using layers of approximately 50 microns, which may also affect its behavior in vivo [27–30].

Numerous studies have examined the effect of various solutions on color changes in 3D-printed materials [31–34]. However, only a few studies have examined both variables, changes in mechanical properties across a representative group of resins, because the number of products available on the market is very large [35,36]. Additionally, the current study includes comparisons of several market-leading materials tested under the same conditions.

Frequently studied solvents described in the literature include coffee, tea, fruit juices, and red wine [35,36]. To our knowledge, studies specifically addressing the effect of beverages with higher ethanol concentrations on 3D-printed denture base resins remain limited. As is known, it is used in post-processing to remove unpolymerized monomers from the surface of 3D-printed resins. Manufacturers of 3D-printed resins recommend avoiding prolonged contact with this solution, as it adversely affects the material.

However, in the everyday life of many cultures, the consumption of alcoholic beverages with higher ethanol concentrations than those found in wine is prevalent.

Therefore, it is important to examine the color changes and mechanical properties of six leading denture base materials under the influence of different beverages.

The hypotheses posed in this study define two variables. First, all resins will change color in the same way upon storage. Second, storing the materials will differentially affect their flexural strength in the same way. The similar behavior of different denture base

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materials may result from the properties of specific monomers used in their production, including their polymerization.

2. Materials and Methods

Six different types of 3D-printed resins intended for the fabrication of removable dentures were selected for the study: Denture 3D+ (Nexdent; Soesterberg, The Netherlands); Vita Vionic (Vita;Säckingen, Germany), Lucitone Digital Print 3D (Dentsply; Charlotte, NC, USA), DX Denture Flex (Dentex; Ettlingen, Germany); Formlab Denture Base (Formlabs; Somerville, MA, USA), and Optiprint (Dentona; Dormund, Germany).

When selecting the 6six resins for testing, the authors were guided by their greatest popularity on the Polish market. Information about the products (denture base resins) is presented in Table 1 and Figure 1.

Table 1. Materials used for testing.

Material	Producer	Composition	Curing Condition
Denture 3D+ (Color: Dark Pink, Lot: XG251N20)	Nexdent (Soesterberg, The Netherlands)	Ethoxylated bis GMA > 60%, methacrylic oligomer 15–25% phosphite oxide < 2.5%	RapidShape CURE lamp, layer thickness 0.050 mm, Asiga MAX 2 printer, Composer program
VITA VIONIC® DENT RESIN (Color: Pink translucent, Lot: 006352)	Vita Bad (Säckingen, Germany)	Alkoxylate phenol derivative, methacrylate terminated 40–60%, UDMA 5–20%, 1,6 HDDMA 5–20%, TPO 0.1–5%, HPMA 0.1–5%	RapidShape CURE, layer thickness 0.050 mm Asiga MAX 2 printer, Composer software 2.10.1
Lucitone Digital Print 3D Denture Base Resin (color; Shade Original, LOT: 00167075)	Dentsply (Charlotte, NC, USA)	Urethane methacrylate 40–50%, Organic methacrylate monomer 40–50%, Organic acrylate monomer 1–5%, photoinitiator < 1.5%	Dentsply Sirona Digital Cure Lamp, layer thickness 0.050 mm, Asiga MAX 2 printer, Composer software
DX Denture Flex (color: pink transparent LOT: 007741)	Detax (Ettlingen, Germany)	Ethoxylated bis GMA40–60%, UDMA 20–40%, 1,6 HDDMA 0.1–5%, TPO 0.1–5%, HPMA 0.1–5% Silanamine, 1,1,1-trimethyl-N-(trimethylsilyl)-, hydrolysis products with silica 0.1–5%	RapidShape CURE lamp layer thickness: 0.050 mm, Asiga MAX 2 printer, Composer software
Formlabs Denture Base LP V1 (color: Pink, Lot: BE24F20L)	Formlabs (Somerville, MA, USA)	Ethoxylated bis GMA 40–60%, UDMA 30–50%, Trimethylolpropane trimethacrylate 5–10%, TPO < 3%	Otoflash G171-6 lamp + Nitrogen gas shield, 2000 pulses, layer thickness 0.100 mm, Elegoo Mars 5 printer, Chitubox
Optiprint: light pink, LOT 0230568	Dentona (Dormund, Germany)	Aliphatic urethane methacrylate 40–60%, methacrylate −45%, 0. Ethyl phenyl(2,4,6-trimethylbenzoyl) phosphinate 04%	Otoflash G171-6 lamp + Nitrogen gas shield, 2000 pulses Layer thickness 0.100 mm Elegoo Mars 5 printer, Chitubox

UDMA-urethane dimethacrylate; 1,6 HDDMA-1,6 Hexanediol dimethacrylate, ethoxylated bis GMA-ethoxylated Bisphenol A-glycidyl methacrylate. HPMA-dihydroxy propyl methacrylate, TPO-Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide.

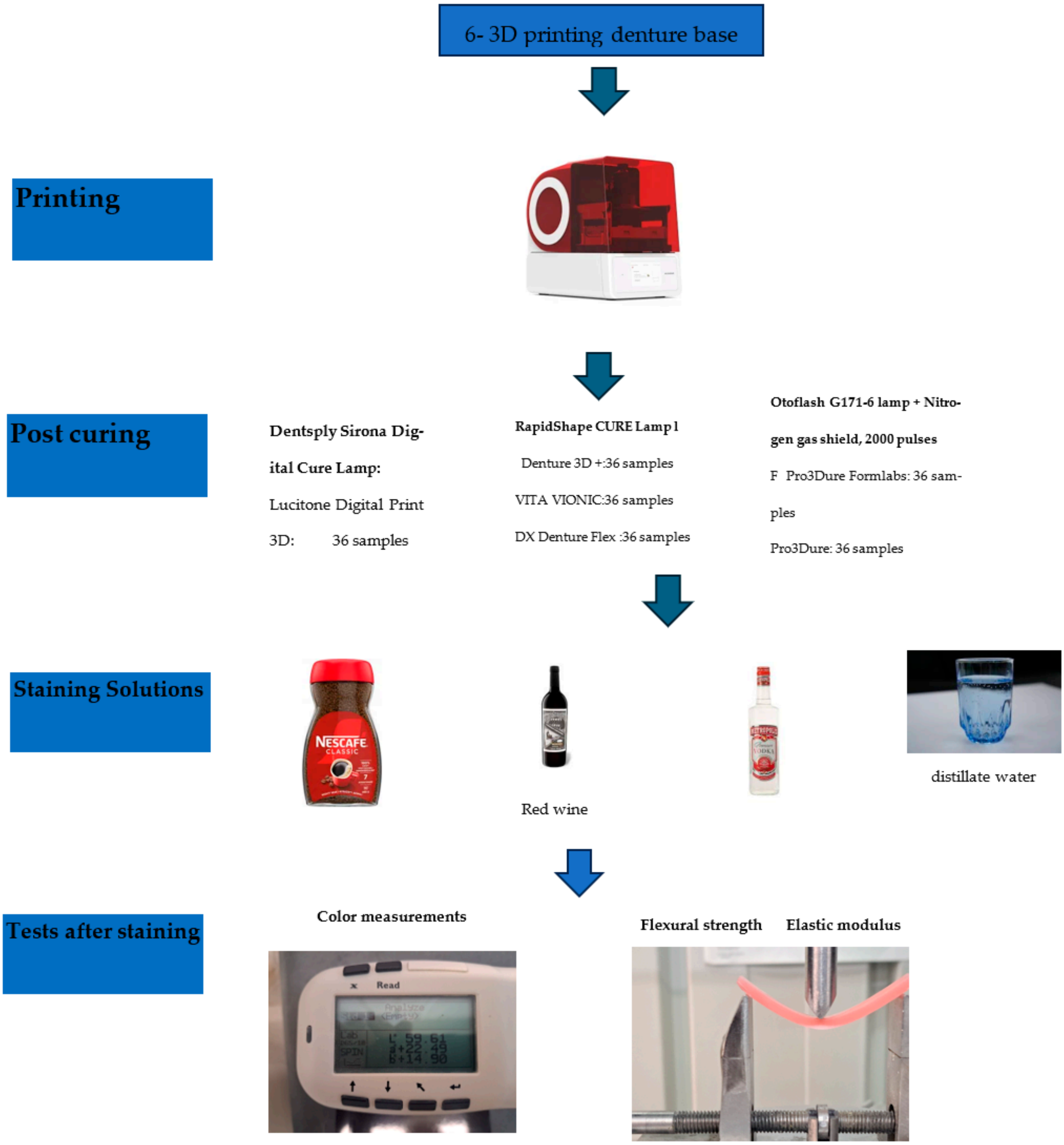

Figure 1. Graphical abstract of the tests performing during the study.

Before printing, the resins were mixed by placing the closed resin bottle on a roller mixer (Nextdent, Soesterberg, The Netherlands) for 10 min, according to the manufacturer's recommendations, to obtain a homogeneous material.

Test samples were designed using the Composer (Asiga, Sidney, Australia) software program. The data was then exported as an STL file to an Asiga Max 2 printer (Asiga, Sydney, Australia) (manufacturer's recommendations). The thickness of the printed single layer was 0.05 mm.

Formlabs and Optipring resins were cured using an Elegoo Mars 5 printer, as recommended by the manufacturers. Horizontal sample geometry was used during printing, and supports were not used [37].

After printing, the samples were washed with isopropyl alcohol (Cleanser, Microchip Electronic cleaning solution, Katowice, Poland) for 5 min using an ultrasonic cleaner (Bandelin Sigma Aldrich, Poznan, Poland). The samples were then cured in polymerization lamps (Table 1) for 10 min [38].

The sample size used for testing is strictly defined according to Choi et al. [35].

2.1. Solutions

The following solutions were used for the tests: instant coffee (Nescafe Classic, Vevey, Switzerland). The solution was prepared by adding 2 teaspoons of coffee to 200 mL of water at 90 °C. The mixture was thoroughly mixed.

The second coloring solution was red wine (Barrel Smuglers, Cabernet Sauvignon 2022; Mendoza, Argentina, with an alcohol content of 13.5%). This material was used for the tests without modification.

The third solution was 40% ethyl alcohol (Metropolis, Warsaw Vodka Factory Koneser, Warsaw, Poland). The substance was used for the tests without modification. Distilled water was used as a reference solution [39].

2.2. pH Measurement of the Test Solutions

The prepared solutions were measured using a Mettler Toledo F20 pH meter with an InLab Solids Go-ISM food-grade combination electrode (Mettler Toledo, Warsaw, Poland), which was calibrated with pH 4 and pH 8 buffer solutions (from the same company) prior to measurement. Three measurements of each solution were taken and the arithmetic mean was calculated [15].

2.3. Color Change

Twenty-four hours after curing, the color of the samples of the printed resins was measured using an X Rite Spectrophotometer (X Rite, Grand Rapids, MI, USA) at coordinates L, a, b. Three measurements were taken at different locations on each sample, and the average was taken as the result. These values were designated as the reference sample.

Six samples (2 × 20 mm diameter disks) of each resin (18 in total) were placed in 200 mL coffee solution. Similarly, 108 samples were prepared and divided for testing in red wine, vodka and distilled water.

The vessels and solutions were tightly sealed and stored at 37 °C. The test solutions were replaced every seven days. The total exposure time of the samples to the test solutions was 30 days. After this period, the sample surface was washed with distilled water and a soft brush to remove deposits from the material surfaces. The resin surface was dried using a soft laboratory tissue. The color of the samples was measured again using a spectrophotometer. Similarly to the previous test, three selected points on the surface were measured, and the average of these 3 points was calculated, yielding 54 measurements for one resin [7,9,11].

The color change in the 3D-printed resins was calculated using the following formula (Equation (1)).

$$\Delta E_{ab}{}^{*} = \sqrt{\left(L_2{}^{*} - L^{*}{}_1\right)^2 + \left(a_2{}^{*} - a^{*}{}_1\right)^2 + \left(b_2{}^{*} - b^{*}{}_1\right)^2} \quad (1)$$

where L_2 indicates the (black/white) coordinate after immersion (the period in the staining solution); L_1 is the coordinate before testing.

a_2—(red/green) is the value after the staining solution; a_1 is before placement in the environment;

b_2—(yellow/blue) is a coordinate after staining solution use; b_1 is an initial value before testing.

2.4. Flexural Strength Testing

Samples measuring 3.3 × 10 × 65 mm (6 samples of each tested resin) were placed in solutions of coffee, red wine, ethanol, and distilled water. These solutions were changed every 7 days, and the total exposure time for the materials was 30 days at 37 °C. The infrequent changes in staining solutions were intended to simulate a group of patients who do not maintain regular hygiene practices while wearing dentures. The samples were stored in tightly closed containers, which were scalded with boiling water before use to prevent contamination with microorganisms [40,41]. For comparison, samples stored at room temperature (23 °C) and 50% humidity for 24 h were used as reference samples. For this study, 144 samples were prepared from 6 resins in 4 solutions.

After this period, the samples were subjected to a 3-point deflection test according to the method described in ISO 20795-1:2013 Dentistry—Base polymers Part 1: Denture base polymers [42]. Namely, the distance between the supports during the fracture test was 50 mm, and the fracture head travel speed was 5 mm/min. The test ended when the sample fractured. A Shimadzu device (ASG-X) was used for the tests. This device calculated the FS [MPa] (Equation (2)) and the modulus of elasticity E [MPa] (Equation (3)), along with the standard deviation [43,44].

$$\sigma = \frac{3FL}{2bh^2} \tag{2}$$

with F: fracture load (N); l: span (mm); b: specimen width (mm); h: specimen height (mm).

$$E = \frac{F1l^3}{4bh^3d} \tag{3}$$

E: elastic modulus (MPa); F_1: load (N) at a point in the straight portion (at the maximum slope) of the load-deflection curve; d: deflection at F_1 (mm); l: span (mm); b: specimen width (mm); h: specimen height (mm).

2.5. Statistical Analysis

One-way ANOVA with a post hoc Tukey HSD test was used to analyze the color change and mechanical resistance during each resin test, using the calculator available at https://astatsa.com/OneWay_Anova_with_TukeyHSD (accessed on 16 April 2026). The comparison was made between the samples before storage (references) in staining solutions and after the test was completed. Two-way ANOVA was used to examine statistical differences between resins and the media in which they were stored, using the calculator available at https://www.statskingdom.com/two-way-anova-calculator.html (accessed on 16 April 2026).

3. Results

Color change solutions used for testing had the following pH values: coffee 4.8 ± 0.1; red wine pH = 3.60 ± 0.05., and vodka pH = 7.11 ± 0.1.

The following tables (Tables 2–4) present the results obtained for samples stored in solutions of acid, red wine and alcohol.

Table 2. Color change of 3D-printed resins intended for the fabrication of removable dentures after 30 days, calculated as ΔE.

Resin	Distilled Water	Vodka	Red Wine	Coffee
Denture 3D + (Color: Dark Pink, Lot: XG251N20)	0.83 ± 0.25	1.04 ± 0.41	3.22 ± 0.47 *F	3.37 ± 0.13 *F
VITA VIONIC® DENT RESIN (Color: Pink translucent, Lot: 006352)	0.78 ± 0.36 *D	2.33 ± 0.72 *D	4.94 ± 0.99 *D	3.11 ± 0.47 *D
Lucitone Digital Print 3D Denture Base Resin (color; Shade Original, LOT: 00167075)	0.82 ± 0.14	1.36 ± 0.15 *C	3.30 ± 0.44 *C	1.34 ± 0.38 *C **
DX Denture Flex (Color: pink transparent LOT: 007741)	1.11 ± 0.45	2.05 ± 0.26 *E	15.56 ± 3.55 *E **	7.38 ± 1.31 *E
Formlabs Denture Base LP V1 (color: pik, Lot: BE24F20L)	1.31 ± 0.85	1.38 ± 0.65	5.86 ± 2.02 *A	6.01 ± 0.83 *A
Optiprint color: light pink, LOT 0230568	1.58 ± 0.38	3.11 ± 0.80 *B	21.04 ± 0.70 *B **	22.66 ± 1.26 *B **

*A $p < 0.0010053$ significance compared to distilled water *E $p < 0.0021162$ significance compared to distilled water. *B $p < 0.0085826$ significance compared to distilled water *F $p << 0.0010053$ significance compared to distilled water. *C $p << 0.0010053$ significance compared to distilled water ** statistically significant compared to other resins $p << 0.0010053$. *D $p < 0.0100456$ significance compared to distilled water.

Table 3. Flexural strength of the sample after storage in different media [MPa].

Resin	Water [MPa]	Red Wine [MPa]	Coffee [MPa]	Vodka [MPa]	Air [MPa]
Denture 3D + (Color: Dark Pink, Lot: XG251N20)	74.23 ± 6.58 *A	71.50 ± 10.20 *A	66.20 ± 5.94 *A	60.88 ± 6.83 *A	93.31 ± 5.90
VITA VIONIC® DENT RESIN (Color: Pink translucent, Lot: 006352)	87.42 ± 9.67	80.38 ± 3.58 *B	78.88 ± 2.44 *B	54.20 ± 4.57 *B	95.33 ± 4.11
Lucitone Digital Print 3D Denture Base Resin (color; Shade Original, LOT: 00167075)	96.87 ± 6.52	87.28 ± 3.91 *C	79.75 ± 2.13 *C	63.02 ± 2.38 *C	106.57 ± 7.52
DX Denture Flex (Color: pink transparent LOT: 007741)	26.75 ± 2.51 *D	16.50 ± 2.33 *D	21.52 ± 1.97 *D	3.23 ± 0.41 *D	38.67 ± 3.11
Formlabs Denture Base LP V1 (color: pik, Lot: BE24F20L)	40.27 ± 6.31	33.42 ± 6.90 *E	34.43 ± 6.34 *E	19.90 ± 2.63 *E	48.38 ± 3.56
Optiprint color: light pink, LOT 0230568	16.57 ± 0.65 *F	11.50 ± 1.26 *F	12.72 ± 1.24 *F	4.50 ± 0.42 *F	37.91 ± 4.76

*A $p < 0.0010053$ significance compared to sample storage in lab conditions. *E $p < 0.0020973$ significance compared to lab conditions. *B $p < 0.0010053$ significance compared to sample storage in lab conditions. *F $p < 0.0032603$ significance compared to lab conditions. *C $p < 0.0020973$ significance compared to sample storage in lab conditions. *D $p < 0.0010053$ significance compared to sample storage in lab conditions.

The resin samples showed the least color change after storage in distilled water and vodka. However, after being stored in 40% alcohol, some samples became flexible and easily changed their shape under finger pressure, allowing them to be molded. This was particularly noticeable for the Detax and Optiprint samples. The color change values were statistically significant (at the confidence level of $p < 0.01$) for the samples stored in red wine and coffee staining solutions compared to the untreated samples. Resins stored in the coffee solutions turned brown, while those stored in red wine changed color toward reddish-brown. Samples stored in vodka were lighter than their original color. The least significant color changes were observed for the Lucitone material in distilled water and coloring foodstuffs: Delta E = 3.30 ± 0.44 in red wine solution and Delta E = 1.34 ± 0.38 for vodka. For comparison, the most significant color changes were obtained for Resin Pro3Dcure: Delta E = 21.04 ± 0.70 and 22.66 ± 1.26 for the red wine and coffee solutions (Figure 2).

Table 4. Elastic modulus of the sample after storage in different media [MPa].

Resin	Water [MPa]	Red Wine [MPa]	Coffee [MPa]	Vodka [MPa]	Air [MPa]
Denture 3D + (Color: Dark Pink, Lot: XG251N20)	2471.60 ± 118.96 *A	2342.62 ± 247.88 *A	2056.73 ± 208.02 *A	1813.13 ± 159.65 *A	3085.45 ± 75.89
VITA VIONIC® DENT RESIN (Color: Pink translucent, Lot: 006352)	2388.30 ± 231.14	2138.97 ± 138.64 *B	1997.98 ± 56.73 *B	1421.67 ± 205.31 *B	2695.33 ± 54.34
Lucitone Digital Print 3D Denture Base Resin (color; Shade Original, LOT: 00167075)	2999.65 ± 58.80 *C	2270.82 ± 63.20 *C	2121.22 ± 4320 *C	1877.10 ± 126.55 *C	3225.67 ± 56.53 **
DX Denture Flex (Color: pink transparent LOT: 007741)	767.95 ± 64.32	401.62 ± 29.08 *D	599.28 ± 75.86 *D	-	888.67 ± 23.11
Formlabs Denture Base LP V1 (color: pik, Lot: BE24F20L)	1404.42 ± 79.58	1137.83 ± 144.69 *E	1115.71 ± 58.80 *E	626.03 ± 39.10 *E	1568.21 ± 46.56
Optiprint color: light pink, LOT 0230568	278.57 ± 43.34 *F	-	187.97 ± 19.58 *F **	-	379.45 ± 33.76

*A $p < 0.0010053$ significance compared to sample storage in lab conditions *E $p < 0.0010053$ significance compared to lab condition. *B $p < 0.0016457$ significance compared to d sample storage in lab conditions *F $p < 0.0010053$ significance compared to lab conditions. *C $p < 0.0018854$ significance compared to sample storage in lab conditions ** statistically significant compared to other resins $p < 0.0010053$. *D $p < 0.0016457$ significance compared to sample storage in lab conditions.

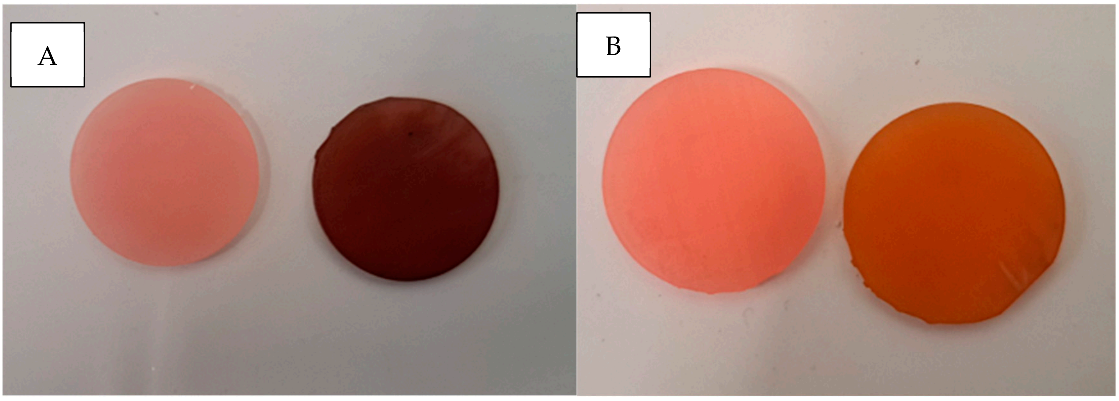

Figure 2. Optiprint (**A**) (left) sample before being stored in staining solution, (right) 30 days in red wine. (**B**) Color change in the material sample after storage in coffee.

Storing resin samples for printing denture bases in various testing solutions significantly affects their fracture resistance. The FS changed most significantly when the materials were stored in vodka. Materials from Detax and Optiprint were most susceptible to this solution. Samples of these materials became very flexible, did not break under the influence of force, and the maximum force at which the samples deformed was 80% lower than the force used to deform samples stored under reference conditions. The least significant changes were observed for the Vita and Dentsply materials stored in vodka (a reduction of about 20%).

Samples stored in distilled water had the least noticeable change in FS compared to the same materials stored in dry conditions at room temperature. These changes were approximately 10% lower compared to the original values.

During the FS testing, it was also possible to determine the elastic modulus (E), which indicates the material's flexibility and elasticity. The results of these calculations, performed by the Shimazu Flexural Strength instrument computer program, are presented in Table 4.

High elastic moduli (E) were calculated for the resins tested under laboratory conditions, exceeding 3000 MPa for the Lucitone and Denture 3D resins. Placing the samples in water or alcohol reduced this modulus, making them more elastic. The greatest reduction in this value was observed for Denture Flex in vodka and Optiprint (alcohol and red wine). The samples were so flexible that it was impossible to determine the straight-line portion where the increase in force was directly proportional to the deflection. Therefore, the Shimadzu tensile tester software 2.0 could not calculate the elastic modulus.

4. Discussion

Although the initial thesis of these studies was not confirmed, samples of various materials intended for denture base printing had significantly different mechanical properties. They also varied in resistance to color change in solutions with strong discoloring properties. This is primarily due to the different compositions of the resins used to produce 3D-printed resins. Regarding materials based on traditional MMA/PMMA and thermally cured materials, their chemical composition is similar. Powders from different manufacturers can be PMMA polymers with varying molecular weights and polymer bead diameters, or copolymers with ethyl or butyl methacrylate. The monomer is a mixture of methyl methacrylate and ethylene glycol dimethacrylate or 1,4-butanediol dimethacrylate. Their fracture toughness also depends on the length of the polymerization process [43]. However, 3D-printed resins differ in this regard. The number of monomers used is large. The most common are various types of urethane dimethacrylates, bis-GMA (Bisphenol A-glycidyl methacrylate) resin derivatives, and a whole range of acrylates. Therefore, the use of different monomer mixtures significantly affects, for example, FS [4,5]. Among the materials tested, we can distinguish two groups. First, Lucitone and Denture 3D Vita Vionic, which behave similarly to traditional heat-polymerized PMMA/MMA resins. They have an FS and elastic modulus similar to traditional materials, or even greater. They meet the ISO Denture Base Materials standard, as their resistance is above 60 MPa and their elastic modulus is above 2000 MPa.

Lucitone material was also tested for FS and elastic modulus by Coldea et al. The authors subjected the material to 10,000 aging tests in 5–55 °C thermocycling, demonstrating that this thermocycling had a destructive effect on the mechanical properties of the material, reducing them by approximately 40% [45,46]. The tests showed strong plasticization of the material, which was visible as strain increased while the load decreased, continuing either until fracture occurred or a 10 mm deflection was reached. During accelerated aging, chemical processes such as water sorption, solubility, and leaching of residual monomers may occur, affecting the mechanical properties of resin-based materials used for 3D printing [4,6,44,45].

When stored in water and coffee, these materials will undergo some plasticization due to water absorption. This will reduce their FS and modulus, but they still meet the standard requirements. When stored in alcohol, their mechanical resistance is reduced by approximately 30–40%. This occurs due to alcohol absorption and its plasticizing effect.

The second group of acrylic resins includes DX Denture Flex and Optiprint. They are very flexible and do not crack during the FS test. However, they do not meet the standard requirements.

Storing these two materials in a solution containing alcohol causes increased plasticization, leading to material deformation and easy bending under pressure. Some samples then crack easily. This can be explained by their chemical composition. They contain urethane methacrylates, which can absorb water or alcohol more readily than materials containing bis-GMA derivatives [2–5].

The explanation for these phenomena can be attributed to several factors. Alcohol can have a destructive effect through its short-term action, leaching out unpolymerized monomers and catalysts. This creates micro-voids within the materials. Water or ethanol can penetrate these voids. This has a plasticizing effect on the resin, which is manifested as a reduction in the elastic modulus (samples exposed to 40% ethanol) and a lower FS [2,5,7]. The color change of 3D-printed resins in the presence of coffee and red wine occurs via a two-step mechanism: absorption and adsorption. Liquid components penetrate the resin's polymer matrix, while chromogenic compounds adhere to the surface and fill the microscopic pores created by the leaching of monomers and oligomers from the cured resin.

Coffee and red wine contain highly pigmented polyphenols (tannins) and chlorogenic acids. These substances are attracted to the resin surface through polar interactions, van der Waals forces, and hydrogen bonding. They become physically trapped in the voids created by the absorbed water [7,8,12].

Additionally, both solutions have a pH of 4, which can cause the slow hydrolysis of methacrylate and acrylic esters, the main components of the resins [7].

For the second group of materials with highly flexible, malleable denture bases, alternative strength testing methods, such as tensile testing, should be considered and incorporated into the standards for testing dental materials. The latest ISO 20795-1 standard from 2013 does not include new materials such as 3D-printed resins. Therefore, a newer version should describe testing methods specific to printing materials [46,47].

The problem of prolonged exposure of denture base materials to a low pH (5) and alkaline pH (8) has been described in the literature. The tested red wine and coffee solutions had a pH < 4 [48]—acidic solutions can adversely affect the mechanical properties of 3D-printed resins. This is consistent with the present results—red wine, with its low pH, reduces the FS and elastic modulus of all resins. This is explained by the fact that methacrylate esters, which are the main components of resins, are easily hydrolyzed by acids, as the polymer chain bonds are interrupted, leading to the formation of numerous cracks in the resin surface [48]. The rate of hydrolysis depends on many factors: hydrophilicity, water diffusivity within the matrix, functional groups present in the polymer chains, sample geometry, and printing the sample in a vertical or horizontal direction [49,50].

However, when attempting to analyze the effect of various agents on 3D-printed materials, one may encounter an issue related to their composition. Some manufacturers do not provide the composition of their materials, despite this being a legal requirement. The information provided is general. For example, the term urethane methacrylate, without providing a CAS number, does not clearly define the specific substance we are dealing with [18,19].

The findings of the present study are consistent with the results of the analysis/testing by Greiger [46]. In this study, the material Denture 3D+, obtained an FS = 98.3 ± 9.5 MPa in air, while in the present study, it was 93.31 ± 5.90 MPa. Samples stored in water had lower fracture resistance values: 72.9 ± 3.4 [51] versus 74.23 ± 6.58 MPa.

Flexural strength may depend on many factors: the nature of the material itself, the orientation in which the samples were cured (vertical or horizontal), the curing time, the atmosphere (contact with oxygen) or an anaerobic environment (inert gas such as glycerin), and the presence of fillers in the 3D-printed resin [51]. In the present study, the manufacturers' recommendations for the tested materials were strictly followed. Consequently, future research studies can test the same group of resins, but polymerized with different polymers, as mentioned by Gad et al. [51]. Therefore, in similar future studies, the authors should focus on determining the exact chemical composition of the tested resins.

The color changes in the resins stored in various solutions also suggest dividing the resins into two groups. First, harder materials (Lucitone, Vita Vionic, Denture 3D) are less susceptible to color changes. In modern dentistry, color changes can be considered in terms of two components: the perceptibility threshold, which is the point at which 50% of observers can successfully see a color difference, widely accepted as $\Delta E \approx 1.2.$, and the acceptability threshold, at which 50% of observers consider a color mismatch to be clinically unacceptable and requiring correction. This is typically recognized to be in the range of $\Delta E \approx 2.7$ according to ISO/TR 28642:2016(en) Dentistry—Guidance on color measurement [52]. Minor color changes will therefore be clinically acceptable for these materials.

The low color change in the coffee solution for the Lucitone material was confirmed in the studies of Lawson et al. [53] and NextDent [54].

Materials belonging to the first group are 1–2 units lighter after exposure to alcohol and distilled water than the samples measured before the tests. Coffee and red wine solutions change the color of the materials by 2–4 units, shifting toward a more brownish (coffee) and brownish-red color (red wine).

For the second group of materials, that is, elastic materials, the measurable color changes are significant. DX Denture Flex stored in red wine had a Delta E of 15.56 ± 3.55. The second material tested, Optiprint, stored in coffee, had a Delta E of 22.66 ± 1.26. These are significant color changes; thus, they are clinically unacceptable for the dentist, the patient or the denture wearer. Such significant color changes may result from the strong absorption of the materials, which is derived from their chemical structures and the high content of UDMA and hydroxypropyl methacrylate (DX Denture Flex). This monomer has an OH group, which increases its affinity for water [51]. Such significant color changes may also raise questions about the changes in the surface roughness of materials by washing out some of the unpolymerized monomers or hydrolyzed products. This causes, at a later stage, the absorption of water or other nutrients, creating conditions that may favor biofilm formation [55]. This should be considered by future research.

Samples stored in distilled water show the least color change. This was concluded by previous studies [56,57].

Resin color changes after contact with various dye solutions result from water absorption. This process leads to the absorption of other liquids containing substances that cause discoloration. As water is absorbed, the 3D-printed resin matrix stretches and splits the polymer chains, facilitating the penetration of dyes into the material. Furthermore, the 3D printing process makes individual printed layers visible in microscopic images, which affects the occurrence of porosity, enabling water sorption without hygroscopic expansion [58].

The present study has some limitations. Testing was conducted in vitro, where the period of exposure to dye solutions and alcohol was continuous. Under normal denture wearing conditions, patients take greater or lesser care of their prosthetic restorations, performing various types of hygiene procedures. The effect of strong dye solutions, such as coffee or red wine, is short-lived, similarly to that of alcohol. Moreover, saliva has buffering properties, and the consumption of solid food components, through mechanical interaction with the denture surface, reduces the deposition of dyes on the surface.

The current study was conducted under static conditions. In the future, it will be worthwhile to also perform tests in solutions stirred using a magnetic stirrer rotating at 40 rpm, along with a model of artificial saliva [59].

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Although the present study covered a relatively large group of denture base resins (six), it needs to be considered that a wide range of these types of product is available on the market from different manufacturers—other materials may behave differently, which is worth examining.

5. Conclusions

- The present study identified two groups of 3D-printed resins: the first group exhibited mechanical properties (FS and E) similar to traditional thermally polymerized materials, while the second group comprised materials with greater flexibility.
- Materials belonging to the first group are less susceptible to color changes in dye solutions (coffee and red wine).
- A 40% alcohol causes significant reductions in the FS and elastic modulus of flexible resins compared to harder materials.

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Abbreviations

The following abbreviations are used in this manuscript:

1,6 HDDMA	1,6 Hexanediol dimethacrylate
Bis-GMA	Bisphenol A-glycidyl methacrylate
ethoxylated bis GMA	Ethoxylated Bisphenol A-glycidyl methacrylate
HPMA	Dihydroxy propyl methacrylate
MMA	Methyl methacrylate
PMMA	Polymethyl methacrylate
TPO	Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide

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