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Efeito da orientação de impressão nas propriedades físicas de resinas impressas 3D utilizadas para base de próteses totais

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Dissertação apresentada ao Programa de Pós-Graduação em Ciências Aplicadas à Saúde, da Universidade Federal de Juiz de Fora, Campus Governador Valadares, como requisito parcial à obtenção do título de Mestre em Ciências Aplicadas à Saúde, área de concentração Biociências.

Orientador: Prof. Dr. Cleidiel Aparecido Araújo Lemos

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“Em todas as circunstâncias, dai graças, porque esta é a Vontade de Deus em Jesus Cristo.” 1 Tes 5,18.

RESUMO

A utilização da impressão 3D na confecção de próteses totais é relevante por minimizar as etapas laboratoriais, reduzindo, assim, as variáveis inerentes ao processo convencional e os consequentes erros de fabricação. Assim, esse estudo teve como objetivo avaliar as características físicas de quatro marcas de resina impressa 3D (Cosmos Denture [CD], SmartPrint [SP], PriZma 3D Bio Denture [PZB], PrintaX BB Base [PXBB]) utilizadas para base de dentaduras em relação a diferentes ângulos de orientação de impressão (0°, 45° e 90°) comparadas ao grupo controle (GC) de resinas termopolimerizadas. Um total 130 amostras circulares foram confeccionadas (n=10), sendo 120 impressas e 10 convencionais com as dimensões de 10 mm de diâmetro e 3 mm de espessura. A análise de cor foi realizada através do espectrofotômetro de bancada. A análise de rugosidade superficial foi realizada utilizando o rugosímetro para mensuração dos parâmetros de Ra. As medidas de hidrofilicidade foram realizadas usando o método da gota séssil com um goniômetro. Além disso, foi realizado a análise de sorção e solubilidade das amostras com o auxílio de um dessecador e estufa. Todas as amostras foram submetidas a termociclagem de 10.000 mil ciclos, com a intenção de verificar a influência da termociclagem sobre os diferentes materiais. Os dados foram submetidos ao teste de normalidade, e para os parâmetros de cor, hidrofilicidade, e sorção foi considerado o teste paramétrico através da análise de variância (ANOVA) com pós- teste de Tukey. Para os dados não paramétricos de rugosidade e solubilidade foi considerado o teste de Kruskal-Wallis. As diferentes resinas avaliadas não afetaram as características de rugosidade superficial ($P=0,576$), hidrofilicidade ($P=0,217$), porém, diferenças significativas foram observadas para cor ($P<0,001$), sorção ($P<0.001$) e solubilidade ($P=0.003$). As resinas GC e PXBB apresentaram maior alteração de cor em comparação as resinas CD, SP e PZB ($P<0,001$), com ausência de diferença entre elas ($P=0.141$). As resinas CD apresentaram menores valores de sorção e solubilidade comparados a GC, sendo que GC apresentaram resultados similares as demais resinas impressas. Não foi observada influência da orientação de impressão para alteração de cor ($P=0,356$), rugosidade superficial ($P=0,565$), hidrofilicidade ($P=0,567$), sorção ($P=0,152$) e solubilidade ($P=0,820$). A termociclagem aumentou de forma significativa os valores de rugosidade superficial, e diminui os valores de hidroficilidade das resinas impressas 3D ($P<0.001$). Diante disso é possível concluir que as resinas impressas em 3D apresentam propriedades físicas comparáveis às das resinas convencionais termopolimerizadas, não sendo afetadas pela orientação de impressão. A termociclagem pode afetar as características de rugosidade superficial e hidrofilicidade das diferentes resinas.

Palavras-chave: Impressão 3D, Prótese total, Ângulo de orientação

ABSTRACT

The use of 3D printing in the fabrication of complete dentures is relevant as it minimizes laboratory steps, thereby reducing variables inherent to the conventional process and associated fabrication errors. This study aimed to evaluate the physical properties of four brands of 3D-printed denture base resins (Cosmos Denture [CD], SmartPrint [SP], PriZma 3D Bio Denture [PZB], PrintaX BB Base [PXBB]) at different printing orientation angles (0°, 45°, and 90°), compared to a control group (CG) using heat-polymerized resins. A total of 130 circular specimens were fabricated (n=10), including 120 printed and 10 conventional, with dimensions of 10 mm in diameter and 3 mm in thickness. Color analysis was performed using a benchtop spectrophotometer. Surface roughness was measured with a profilometer to obtain Ra values. Hydrophilicity was assessed using the sessile drop method with a goniometer. Additionally, sorption and solubility analyses were conducted using a desiccator and drying oven. All samples underwent thermocycling for 10,000 cycles to evaluate the influence of thermal aging on the materials. Data were subjected to normality testing. For color, hydrophilicity, and sorption parameters, parametric analysis of variance (ANOVA) followed by Tukey's post hoc test was applied. Non-parametric data for roughness and solubility were analyzed using the Kruskal–Wallis test. The different resins did not significantly affect surface roughness (P=0.576) or hydrophilicity (P=0.217); however, significant differences were found for color (P<0.001), sorption (P<0.001), and solubility (P=0.003). GC and PXBB resins showed greater color change compared to CD, SP, and PZB resins (P<0.001), with no significant differences among the latter (P=0.141). CD resins showed lower sorption and solubility values compared to GC, while GC presented results similar to the other printed resins. Printing orientation did not influence color change (P=0.356), surface roughness (P=0.565), hydrophilicity (P=0.567), sorption (P=0.152), or solubility (P=0.820). Thermocycling significantly increased surface roughness and decreased hydrophilicity of the 3D-printed resins (P<0.001). Therefore, it can be concluded that 3D-printed resins exhibit physical properties comparable to conventional heat-polymerized resins and are not affected by printing orientation. Thermocycling can influence surface roughness and hydrophilicity of the evaluated resins.

Keywords: 3D Printing, Complete Denture, Printing Orientation

LISTA DE ABREVIATURAS E SIGLAS

PMMA	Polimetilmetacrilato
CO	Controle
CD	Resina Cosmos Denture –Yller ©
SP	Resina 3D Smart Print Bio Denture – SmartDental ©
PZB	Resina PriZma 3D Bio Denture – Marketech ©
PXBB	PrintaX BB Base - OdontoMega ©
TC	Termociclagem

SUMÁRIO

1 INTRODUÇÃO

A prótese total ainda continua sendo uma opção de tratamento satisfatória para pacientes que perderam todos os dentes, especialmente para aqueles que não podem arcar com o custo de próteses dentárias fixas implantossuportadas (GAD et al, 2022). Embora seja amplamente utilizado na fabricação de próteses dentárias removíveis, devido à sua boa biocompatibilidade, baixo custo e facilidade de fabricação e reparo, o polimetilmetacrilato (PMMA) apresenta algumas limitações. Em primeiro lugar, o PMMA tem a tendência de absorver água, comprometendo suas propriedades físicas (KHATTAR et al, 2022). Além disso, os materiais utilizados na fabricação das bases protéticas estão sujeitos à biodegradação no meio bucal devido a fatores como hidrólise, enzimas salivares e estresse mecânico causado por alterações térmicas e químicas na dieta (VIOTTO et al, 2022). Outro aspecto a ser considerado é o processo convencional de fabricação de próteses, que envolve várias etapas clínicas e laboratoriais, tornando-o um processo laborioso e demorado (CLETO et al, 2022;GAD et al, 2022).

Com o passar do tempo, foram implementadas diversas alterações nesse material, modificando polímeros e monômeros, visando aprimorar suas características físicas e mecânicas; mas também para melhorar suas propriedades de trabalho que facilitam as técnicas de laboratório, como cura por micro-ondas e cura por luz visível (SINGH et al., 2013; CHHABRA et al, 2022). Apesar dessas modificações, a resina acrílica ainda não alcançou um patamar de excelência como material para próteses dentárias. Assim sendo, é imprescindível continuar investindo em pesquisas e avanços tecnológicos para desenvolver um material capaz de proporcionar resultados superiores nesse contexto (CHHABRA et al, 2022). Com o objetivo de aprimorar a produção das bases de próteses e superar as limitações do processo tradicional de fabricação, surgiram os sistemas digitais (GAD et al, 2022). Uma tecnologia relativamente recente, conhecida como impressão 3D, tem mostrado um grande potencial em várias áreas, incluindo engenharia, medicina e odontologia (ANADIOTI et al, 2020; GAD et al, 2022; CLETO et al, 2022). Esse método manufatura aditiva resulta em uma redução no consumo de material durante o processo de polimerização (KHATTAR et al, 2022).

A introdução da fabricação de próteses digitais teve um marco importante com o trabalho de Goodacre et al. em 2012, onde um protótipo exemplificou o tipo de programa que poderia ser incorporado na fabricação futura de próteses digitais. A digitalização do processo de fabricação de uma prótese total é interessante, pois diminui os procedimentos laboratoriais envolvidos, assim, reduz os erros de fabricação associados ao método convencional (GAD et al, 2022; KHATTAR et al, 2022). Além de proporcionar vantagens como: armazenamento digital dos dados das próteses, reprodução mais detalhada, maior conforto para o paciente, avaliação e ajustes prévios das imagens digitalizadas, melhor vedação marginal e adaptação da prótese, custo-benefício e minimização do desperdício de material em comparação com a técnica convencional (FIORE et al, 2021; CLETO et al, 2022; VIOTTO et al, 2022). Além disso, apresenta um impacto positivo na experiência dos pacientes, pois reduz o tempo necessário para a produção protética (GAD et al, 2022).

Com o avanço do sistema digital, as próteses totais passaram a ser classificadas como fresadas ou impressas. Em uma revisão narrativa da literatura, Goodacre e Goodacre (2022) concluíram que as próteses totais impressas digitalmente apresentam diversas vantagens em comparação às fresadas e às confeccionadas pelo método convencional, incluindo menor desperdício de material, possibilidade de produção simultânea de múltiplas dentaduras e viabilidade de elaboração de designs mais complexos. Diante disso, os autores destacaram a necessidade de estudos adicionais sobre essa promissora técnica de fabricação, uma vez que ainda há muitas questões a serem esclarecidas.

Nessa mesma revisão, os autores ainda destacaram que a orientação do ângulo de impressão da prótese poderia alterar algumas propriedades físicas (Goodacre e Goodacre, 2022). Esses mesmos achados foram relatados por uma recente revisão de escopo que destacaram a necessidades de futuras pesquisas avaliando os ângulos de impressão para bases de dentaduras (Vilela et al. 2021). Isso se torna ainda mais importante, tendo em vista que no mercado pode existir uma gama muito grande de resinas utilizadas para impressão de bases de dentaduras, e cada uma dessas podem apresentar um comportamento diferente, de acordo com a variação do ângulo de impressão, o que pode interferir diretamente nas propriedades físicas (rugosidade superficial, cor, energia livre de superfície, e solubilidade/sorção). Gad e cols. (2021) relatam ser uma limitação de seu estudo usar apenas um tipo de material impresso em 3D e uma única orientação de impressão.

Esses achados indicam que ainda há uma lacuna significativa de pesquisa nesse tema na literatura. Além disso, ainda não está claro se há influência das diferentes marcas de resinas impressas em 3D disponíveis nas propriedades superficiais das bases de prótese. Dessa forma, para investigar essa questão, é possível formular a hipótese nula de que não haveria diferença de propriedades físicas entre resinas PMMA e as marcas de resinas impressas em 3D impressas sobre diferentes ângulos de orientação (0º, 45º, e 90º).

2 ARTIGO CIENTÍFICO

Artigo Científico enviado para publicação no periódico Dental Materials CAPES A1. A estruturação do artigo baseou-se nas instruções aos autores preconizados pelo periódico (ANEXO A).

Effect of printing orientation on the physical properties of 3D-printed resins for complete denture bases

ABSTRACT

This study aimed to evaluate the physical properties of four 3D-printed denture base resins—Cosmos Denture (CD), SmartPrint (SP), PriZma 3D Bio Denture (PZB), and PrintaX BB Base (PXBB)—at three print angles (0°, 45°, 90°), compared to a heat-polymerized resin control group (CG). A total of 130 circular samples (n=10 per group) were fabricated: 120 were 3D-printed, and 10 were conventionally processed (10-mm diameter, 3-mm thickness). Color analysis used a spectrophotometer, surface roughness was measured with a portable surface roughness tester, and hydrophilicity was assessed using a goniometer. Sorption and solubility were analyzed with a desiccator and oven. All samples underwent 10,000 thermocycling cycles. Data normality was tested. Color, hydrophilicity, and sorption were analyzed using ANOVA and Tukey's post hoc test, while roughness and solubility were assessed via Kruskal-Wallis test. The JAMOVI software was used for statistical analysis. No significant differences were found in surface roughness ($P=0.576$) or hydrophilicity ($P=0.217$), but color ($P<0.001$), sorption ($P<0.001$), and solubility ($P=0.003$) varied among resins. CG and PXBB resins showed the greatest color alteration ($P<0.001$), whereas CD, SP, and PZB exhibited no significant differences ($P=0.141$). CD had the lowest sorption and solubility values ($P<0.001$), while CG was comparable to other 3D-printed resins. Print orientation had no effect on color ($P=0.356$), roughness ($P=0.565$), hydrophilicity ($P=0.567$), sorption ($P=0.152$), or solubility ($P=0.820$), independently of 3D-printed resins. However, thermocycling increased roughness and decreased hydrophilicity in 3D-printed resins ($P<0.001$). In conclusion, 3D-printed resins exhibit physical properties similar to heat- polymerized resins and are unaffected by printing orientation. Thermocycling influences surface roughness and hydrophilicity.

Keywords: Printing orientation, PMMA, 3D Printing, Denture base.

1. INTRODUCTION

In 2021, edentulism affected approximately 353 million people worldwide, and projections suggest this number could nearly double by 2050, placing edentulism among the most prevalent health conditions globally [1]. In this context, rehabilitative therapies, both with or without implants, are essential for maintaining patients' quality of life, supporting psychosocial and cognitive health through improved function and aesthetics [2].

Despite the widespread use of dental implants, conventional complete dentures remain a widely used treatment for edentulous patients [3] particularly for those unable to afford the cost associated with fixed implant-supported dentures [4]. The conventional fabrication process involves a labor-intensive process using polymethyl methacrylate (PMMA) due to its biocompatibility, low cost, and ease of repair. However, PMMA has some limitations, including time-consuming fabrication, high water sorption, and low color change [4,5].

To overcome these limitations, digital systems have emerged, offering alternative fabrication techniques through subtractive manufacturing (milling) or additive manufacturing (3D printing) [4,6,7,8]. Among these approaches, 3D printing has gained prominence due to its material efficiency, flexible design, enhanced quality control, greater precision, and reduced clinical and manufacturing time [9,10].

Among the variables that could influence the properties of 3D-printed dentures, the printing orientation is particularly noteworthy [11]. A recent scoping review suggested that printing orientation could significantly affect the physicomechanical properties of 3D-printed resins. However, the authors also highlighted the limitations of the included studies and emphasized the need for further research on the impact of printing orientation of denture bases [12].

This aspect becomes even more relevant given the wide range of 3D-printed resins available for denture base fabrication, each potentially exhibiting different behaviors depending on the printing orientation. Therefore, the objective of this study *in vitro* was to evaluate the differences in color stability, surface roughness, hydrophilicity, sorption, and solubility among different 3D printing resins fabricated at varying printing orientation (0°, 45°, and 90°). The tested null hypotheses were as follows: 1) No significant differences existed between 3D-printed and conventional resins; 2) Printing angle orientation did not affect the evaluated parameters of 3D-printed resins; 3) Thermal cycling did not affect the optical and physical properties of the resins.

2. METHODOLOGY

2.1 EXPERIMENTAL DESIGN

Four 3D-printed resins were used for the fabrication of complete denture bases: Cosmos Denture – Yller (Pelotas/RS, Brazil), Smart Print Biodenture – Smart Dent (São Carlos, SP, Brazil), PriZma 3D Bio Denture – Makertech (Tatuí, SP, Brazil), and Printax BB Base – Odontomega (Ribeirão Preto, SP, Brazil). The 3D samples (n=10 per group) were designed using Exocad Valletta software (Darmstadt, Germany, version 2.2 6654-2017), with dimensions of 10 mm in diameter and 3 mm in thickness, following ISO 20795-1:2019 standards (ISO, 2019) and the protocol described by Carneiro Pereira et al., 2024. For the CAM software version (creation of block paths), Exocad Plovdiv CAM (Darmstadt, Germany, version 3.8.31803) was used. The samples were printed using the Elegoo Mars 4 Ultra 3D printer considering different printing orientations (0°, 45°, and 90°) [14]. After printing each brand, the NFep film was changed to avoid contamination between the resins. The taller the sample, the longer it took to print, with the 90º taking 4 hours, 45º taking 2 hours, and 0º taking 45 minutes. The resin curing was carried out according to the manufacturer's recommendations, utilizing the maximum curing time specified. (Table 1)

The control group consisted of heat polymerized acrylic resin (PMMA), that was fabricated using laboratory silicone (Zetalabor, Zhermack) molds with the same dimensions of 3D printed resins included in plastic muffles (Mufla VIPI-STG, Vipi Odonto Products) positioned between glass plates over special type IV gypsum (Durone, Dentsply Sirona), with the PMMA resins (Clássico; Clássico) handled according to the manufacturer's recommendation. The resin was inserted into the molds, maintained under a load of 1.25 t kN in a hydraulic press, and kept on a bench for 30 minutes [15]. The conventional method samples were polymerized in a water bath for 60 minutes in boiling water (100°C). After polymerization, the irregularities and excess of resins was removed using a maxicut tip attached to a straight handpiece.

After the fabrication of the samples, they were subjected to metallographic finishing and standardized polishing, using a polisher machine (Aropol E; Arotec) with silicon carbide abrasive papers (#240, #400, #600, and #1200) for 20 seconds on each side [15]. Subsequently, they were polished with disc felt and alumina in a 1 µm suspension. After finishing, the samples were immersed in an ultrasonic bath with isopropyl alcohol for 5 minutes to remove any possible debris [16]. After processing, each sample was placed in distilled water and stored in an incubator at 37 ± 1 °C [17]. All specimens were measured using digital calipers (Mitutoyo Corp., Kanagawa, Japan) to validate their length, width, thickness, and diameter.

2.3 SURFACE ROUGHNESS

The surface roughness profile for each specimen was measured after polishing using a surface roughness measurement instrument (Mitutoyo SJ-210, São Paulo, SP, Brazil). The measurement was performed on each specimen individually, and the diamond stylus has a 5 µm radius at a constant speed of 0.05 mm/s with a force of 4 mN. The cut-off value was set at 0.08 mm (Gaussian filter). Ra (µm) is the average roughness, which is determined by the arithmetic mean of the absolute values of the roughness profile ordinates. Three readings were taken on each surface sample at equidistant positions. The average of these three Ra measurements was calculated as the roughness value of the specimen [18].

2.4 COLOR

The optical properties of the specimens were evaluated using a spectrophotometer (UV-2450; Shimadzu, Kyoto, Japan). Changes were calculated using CIEDE2000 (ΔE_{00}), as established by the Commission Internationale de l'Eclairage (CIE). ΔE_{00} represents the overall color change, calculated based on the difference between initial and final L, a, and b* values. Color measurements in the CIEDE2000 system consist of coordinates representing black-white luminance (L*), red-green (a*), and blue-yellow (b*) dimensions, with the L* axis perpendicular to the a* and b* axes. The device emits a visible spectrum light source (400 to 700 nm) onto the object and measures the reflection of this spectrum. The L*, a*, and b* values of each sample were measured before and after immersion. ΔE_{00} values were calculated using the formula: $\Delta E_{00} = [(\Delta L/K L \times SL)^2 + (\Delta C/K C \times SC)^2 + (\Delta H/K H \times SH)^2 + RT \times$

$(\Delta C/KC \times SC) \times (\Delta H/KH \times SH)]^{0.5}$, where ΔL^*, ΔC^*, and ΔH^* are the differences in luminance, chroma, and hue between two specimens, and RT (rotation function) accounts for the interaction between chroma and hue differences in the blue region. SL, SC, and SH are weighting functions for the luminance, chroma, and hue components, respectively. KL, KC, and KH are parametric factors related to viewing conditions, and were set to 1 [19].

2.5 SORPTION AND SOLUBILITY

To determine the volume (V) of each sample, the diameter of the specimen was defined as the average of the measurements at three points, and the thickness was defined as the average of the measurements with a digital caliper (MDC-25M; Mitutoyo) at five points (center and four points on the contour) [20]. The specimens were dehydrated using a desiccator containing freshly dried silica gel (Sigma-Aldrich), stored in an incubator at 37 ± 1°C. After 24 hours, the specimens were removed and weighed with a precision balance to obtain a constant mass (M1). The desiccation cycle was repeated until the discrepancy between consecutive weight measurements was less than ± 0.001 g. Once the mass became constant, the specimens from each group were immersed in glass flasks containing distilled water at 37 ± 1°C for 7 days. The weight of the specimens was recorded every 24 hours until a constant weight was achieved (M2) after 7 days. Every 24 hours, the specimens were removed from the solution, gently blotted with a soft paper towel to remove excess solution, weighed, and immediately returned to the solution [20,21]. At the end of the immersion period, the specimens were desiccated again as previously mentioned, until they reached a constant mass (M3). Subsequently, the mass of the desiccator at a constant temperature bath at 37 ± 1°C was measured as m3, and the water sorption (μg/mm3) was calculated using the formula: Sorption = (m2 - m3)/V and solubility (μg/mm3) using the formula: Solubility = (m1 - m3)/V [20].

2.6 HYDROPHILICITY

Hydrophilicity measurements were performed using the sessile drop method with a goniometer (TL 100- Invoiced freight, Theta Lite, Attention, Lichfield, Staffordshire, UK). Before measurement, the samples were cleaned in an ultrasonic bath with isopropyl alcohol for 4 minutes and then air-dried at room temperature. All samples from each group were measured. The measurements were carried out by connecting to a computerized unit using specialized software for contact angle and surface energy measurement (Attension, Biolin Scientific, Stockholm, Sweden). For the measurement, a drop of deionized water was placed on the ceramic sample surface using a micrometric syringe, and the contact angle was measured for 20 seconds (30 frames per second), after an initial pause of 10 seconds. The machine and software performed the measurement through continuous photographic shots.

2.7 THERMOCYCLING

After the initial analysis, all samples were subjected to thermocycling using a thermocycler (OMC 250 TS, Odeme) in distilled water with alternating baths of 30 seconds at temperatures of 5 ± 1 °C and 55 ± 1 °C, following the recommendations of ISO 11405. A total of 10,000 cycles were performed, corresponding to an average of 2 years of intraoral use [22]. After thermocycling, the samples were measured again in all previously described analyses.

2.8 STATISTICAL ANALYSIS

Shapiro-Wilk Test confirmed the normal distribution for color, hydrophilicity, and sorption analyses. Conversely, normality was not observed for surface roughness and solubility analyses. For analyses that showed normal distribution, variance analysis (ANOVA) with Tukey's post-test was considered for comparison between 3D printed and conventional resins, as well as analysis between the printing orientation of 3D printed resins. For non-parametric distribution analyses, Kruskal-Walli’s test was considered. Data were analyzed using JAMOVI version 2.3.28 (https://www.jamovi.org), with significance values considered greater than a significance level of 5%.

3. RESULTS

The color analysis of conventional (GC) and 3D printed resins from the PXBB group showed greater color changes compared to CD, SP, and PZB (P<0.001). However, no significant differences were observed between them (P=0.141). Considering the printing angle orientation, no influence of this variable was observed on color change among the evaluated 3D printed resins (P = 0.356) (Figure 1).

In the surface roughness analysis, no influence was observed on different types of resins (P = 0.576) or printing orientation (P = 0.565). However, a significant difference in roughness was observed after thermocycling, regardless of the type of resin or printing orientation, with higher values compared to the initial analysis (P<0.001) (Figure 2).

Similarly, when analyzing hydrophilicity through the water contact angle, no influence was observed between the different types of resins (P = 0.217) or printing orientation (P = 0.567). However, there was a significant reduction in contact angle values for all evaluated groups after thermocycling (P<0.001) (Figure 3).

Regarding the sorption values, differences were observed among the evaluated resins, with lower sorption values for CD printed resins compared to the others (P<0.001). No differences were observed between CG and PXBB resins (P=0.528), and SP and PZB resins (P=0.425), which showed higher sorption values. No significant influence of thermocycling was observed (P=0.658). Specifically analyzing the printed resins, no influence of printing orientation on the sorption of 3D printed resins was observed (P=0.152) (Figure 4).

Regarding the solubility values, significant differences were observed among the resins (P=0.003) and thermocycling (P<0.001). Lower solubility values were found for CD printed resins with significant differences compared to SP, PZB, and PXBB resins (P<0.05), but no difference compared to GC (P=0.114). No differences were observed between the other printed resins and GC (P>0.05). No significant influence of printing orientation on solubility values was observed for the different 3D printed resins tested (P=0.820) (Figure 5).

4. DISCUSSION

The first null hypothesis was rejected since significant differences were observed for some 3D-printed resins compared to the heat-polymerized resin regarding color change and sorption. However, no significant differences were found among resins concerning surface roughness, hydrophilicity, and solubility. Regarding color change, CG exhibited greater color changes compared to the 3D-printed CD, SP, and PZB resins. These results align with previous studies reporting higher color changes for heat-polymerized resins than in 3D-printed resins [23-25]. Some authors attribute this to alterations in the optical properties of resin materials resulting from water absorption and other liquids that may cause color alterarion [23,26,27]. However, in our study, the sorption analysis for heat-polymerized showed higher values compared to CD but lower values than SP and PZB resins, indicating that some 3D-printed resins may exhibit greater water sorption while maintaining high color stability.

The interaction of distilled water, despite its neutral pH, can still induce changes in the polymer structure of the material. This effect is likely more related to the intrinsic properties of the material than to the influence of water sorption. It is weel established that the type and concentration of photoinitiators can significantly affect the ΔE of resin-based materials [28]. Therefore, the chemical composition of resins plays a crucial role in their interaction with water molecules, potentially impacting the color stability of denture bases. The difference between PXBB 3D-printed resins and other resins may be attributed to their material composition. 3D-printed resins contain stabilizing components, pigments, and fillers, which can influence spectrophotometric color analysis due to variations in refractive indices [4].

Although higher ΔE_{00} values were observed for GC and PXBB resins, both remained below the perceptibility (1.72) and acceptability (4.08) thresholds [29]. Perceptibility assessments are typically conducted by asking observers whether they can perceive a color difference between specimens. The perceptibility threshold is determined at the point where 50% of observers respond affirmatively and 50% negatively. Acceptability assessments involve asking whether the perceived color difference is acceptable, with the threshold defined when 50% consider the difference acceptable and 50% consider it unacceptable [29].This slight color change in the evaluated groups can be attributed to the fact that the color variation (final – initial) was assessed solely based on the effects of thermocycling in distilled water, without exposure to staining or acidic solutions, which could have led to more pronounced discoloration. This represents a limitation of the study. However, previous research has demonstrated that distilled water alone can induce color changes in resins used for denture bases [30,31], sometimes even exceeding the discoloration caused by more staining solution [23].

Regarding water sorption, CG exhibited values comparable to those of 3D-printed resins, aligning with findings from previous studies [32]. However, CD resins demonstrated lower sorption values, while PXBB showed similar results, and SP and PZB resins exhibited higher values. These variations are likely attributed to the distinct composition and characteristics of each resin [32]. Increased water sorption, particularly in 3D-printed resins, is often associated with the presence of residual monomers in resin matrix [33]. This could explain the reason for SP and PZB resins initially presented higher initial sorption but showed similar results after aging, as residual monomers may have leached out of the polymer network during thermal cycling process [34].

The results showed no significant differences between 3D-printed and conventional resins regarding surface roughness, hydrophilicity, and solubility. These findings are consistent with recent network meta-analysis of in vitro studies, which also found no differences between 3D-printed and conventional resins for these parameters. However, that study reported superior performance for milled prostheses [35]. Despite the advantages of milled complete dentures, such as improved mechanical properties, they also present limitations, including increased material waste during milling [36, 37] and constraints in fabricating complex designs [38]. Consequently, this study used heat-polymerized resin as the control group. Given the compositional variability of commercially available 3D-printed resins, future studies should also assess milled denture bases to provide a comprehensive comparison.

Printing orientation is a crucial factor in optimizing the performance of 3D-printed resins, as it determines the prosthesis alignment relative to the horizontal plane during printing. In the present study, the 90° orientation consumed less resin than the 0° and 45° orientations. However, it significantly increased printing time, and the number of layers, corroborating previous findings [39-41]. Despite differences in material consumption and time, printing orientation did not affect the evaluated outcomes, regardless of resin type, supporting the second hypothesis.

The selection of 0°, 45°, and 90° printing orientations was based on their frequent application in denture fabrication [42, 31]. Although the 45° orientation represents a relatively large angular difference, it was insufficient to alter the physical properties of the evaluated 3D-printed resins. A possible explanation is that printing orientation may be more closely related to volumetric alterations in the dentures rather than changes in their physical-mechanical properties [41]. Regarding color stability, PXBB resin, which exhibited the highest color change values among 3D-printed resins, maintained this pattern across all printing angles. A similar trend was observed for the other 3D-printed resins, suggesting that color stability is primarily influenced by the type and concentration of photoinitiators rather than by printing orientation [27].

Previous studies have also reported that printing orientation does not affect surface roughness [43,44]. This may be attributed to the sample shape used in this study, which differs from the original design of a complete denture [44]. Another contributing factor is the standardized polishing performed on all samples after printing, which eliminated minor imperfections caused by the staircase effect in inclined orientations, thereby preventing significant alterations in surface roughness [45]. Consequently, all samples exhibited roughness values below the clinical threshold limit of 0.2 µm [46].

Print orientation also did not affect the hydrophilicity of 3D-printed resins. The literature includes only one study evaluating printing orientation in relation to contact angle [14], which reported lower hydrophilicity for samples printed at 45° compared to those at 0° and 90°. A possible inverse correlation between hydrophilicity and roughness can be observed in this study, as samples printed at 45° exhibited higher roughness values. This finding aligns with our results, where samples initially exhibited lower roughness and higher hydrophilicity before thermocycling, but this pattern reversed after thermocycling. It is well established that surface roughness influences hydrophilicity, by modifying surface area and increasing liquid affinity [13]. Given that no significant differences in surface roughness were found, this may explain the absence of significant differences in hydrophilicity.

Sorption and solubility parameters were also not influenced by printing orientation. As previously reported, variations in these characteristics are likely attributed to the individual properties and compositions of the evaluated resins, rather than print orientation. Sorption refers to the absorption of water molecules within the polymer, while solubility represents the dissolution of unreacted monomers and other soluble components [47]. This study corroborates previous research indicating that printing orientation does not affect solubility in 3D-printed resins. However, the authors reported that the 90° orientation exhibited lower sorption than the 0° and 45°

orientations, attributing this difference to a higher degree conversion of monomer in the 90° printed resin [47].

The third hypothesis was rejected, as thermocycling significantly affected surface roughness and hydrophilicity properties, regardless of denture base resin. Since complete dentures are subjected to thermal stress during daily use [43], evaluating aging behavior of 3D-printed resins is critical. This study employed a thermocycling protocol of 10,000 thermal cycles, simulating two years of intraoral temperature variations [48,49].

3D-printed resins are fabricated layer by layer, followed by polymerization. This process may result in weak interlayer bonding due to unreacted residual monomers, leading to a lower degree of polymerization, increased void formation, and greater spacing between layers, ultimately creating a rougher surface [50-52]. Additionally, clinical factors such as toothbrushing and the use of abrasive agents can further exacerbate surface roughness in these materials[53].

Consequently, the decrease in hydrophilicity observed after thermocycling could be attributed to the increased in surface roughness, which enhances the interaction between water droplets and the functional groups of 3D-printed resins, thereby increasing their hydrophobicity [51]. However, a similar increase in roughness and decrease in hydrophilicity were also observed in the heat-polymerized resins after thermocycling, indicating that this effect is not exclusive to 3D-printed resins and does not compromise their durability as denture bases materials.

The findings of this study should be interpreted with caution, as in vitro assessments inherently present limitations. The study focused exclusively on the physical properties of restorative materials, without evaluating their accuracy and mechanical behavior, highlighting the need for further research to complement these findings. Additionally, not all evaluated resins had detailed information regarding their chemical composition, which may have influenced the interpretation of differences in results. The standardized sample design was fabricated to facilitate the analyses; however, its behavior may differ when applied to a complete denture. Although thermocycling was performed, the absence of factors presents in the oral environment—such as salivary fluids, pH variations, and intrinsic and extrinsic staining agents—may lead to different outcomes. Therefore, future clinical studies, including in situ and in vivo evaluations, are recommended to provide a more comprehensive understanding of the assessed properties.

5. CONCLUSION

Based on the findings of this in vitro study the conclusions can be drawn:

- 3D-printed resins exhibit physical properties comparable to those of conventional heat-polymerized resins.
- Print orientation did not affect color, roughness, hydrophilicity, sorption, or solubility properties, regardless of 3D-printed resin.
- Thermocycling contributed to color alteration, increased surface roughness, and reduced hydrophilicity in the denture base resins.

Declaration of Competing Interests

We appreciate the donation of resins provided by the companies, but the authors declare that they have no competing interests related to the research, authorship, and/or publication of this article.

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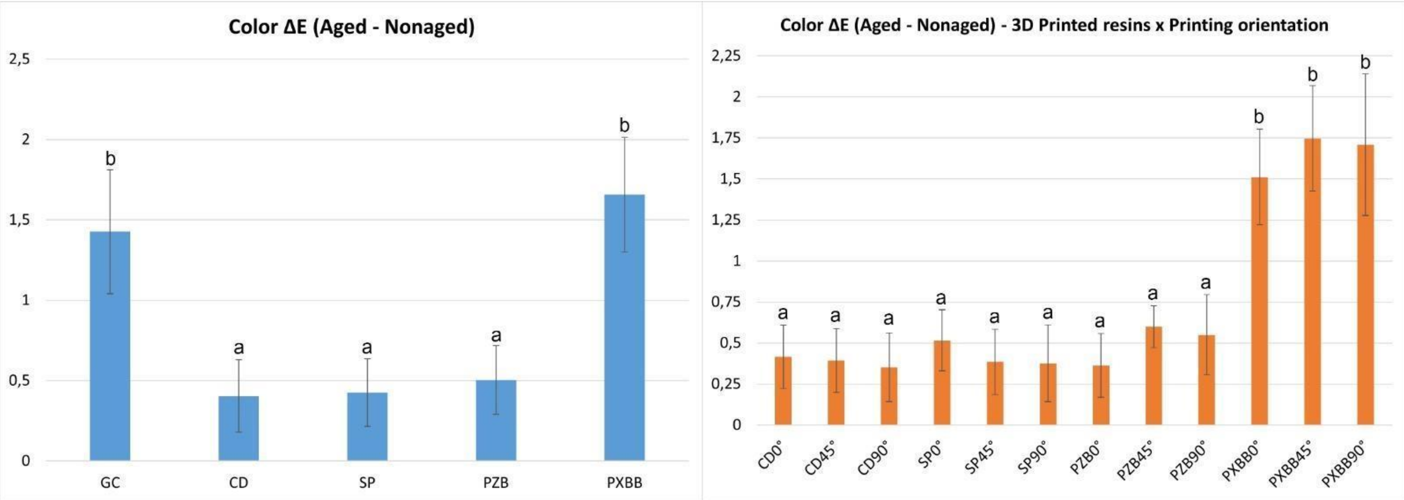
Tables

Table 1. Experimental design of the groups evaluated.

Group	Brands	Priting orientation	Composition	Cleaning and post-curing protocol
CO	Thermo-Polymerizing Acrylic Resin (Classic – Dental Articles – Classic ©)		Acrylic Liquid: Methyl Methacrylate Monomer, DMT, CrossLink Acrylic Resin-Powder: Methyl Ethyl Methacrylate Copolymer, Peroxide, Organic Pigments.	
CD0	Cosmos Denture Resin – Yller ©	0º	Oligomers ≥90%, Monomers, Photoinitiators, Stabilizer, Pigment <10%	Cleaning with isopropyl alcohol for 10 minutes and drying, post-curing: 72 W UV chamber for 10 minutes.
CD45		45°		
CD90		90º		
SP0	3D Resin Smart Print Bio Denture – SmartDent ©	0º	Monomers, Oligomers, Photoinitiators, Pigments, Stabilizers	Cleaning with isopropyl alcohol for 15 minutes, post-curing for 9 minutes.
SP45		45°		
SP90		90º		
PZB0	PriZma 3D Bio Denture Resin – Marketech©	0º	Acrylated Monomers >10%, Pigmentation and Filler ≤ 10%, Acrylic Oligomers < 65 %, Diphenyl (2,4,6-trimethylbenzoyl)-phosphine oxide < 5 %	Cleaning with isopropyl alcohol for 3 minutes, post-curing for 20 minutes.
PZB45		45°		
PZB90		90º		
PXBB0	PrintaX BB Base - OdontoMega ©	0º	Aromatic methacrylic oligomer <80% Aliphatic methacrylic oligomer <30% Phosphine oxide <5%	Cleaning with isopropyl alcohol for 5 minutes, post-curing BB base and CC tray (60 W-405 nm oven) 5 cycles of 1 minute each.
PXBB45		45°		
PXBB90		90º		

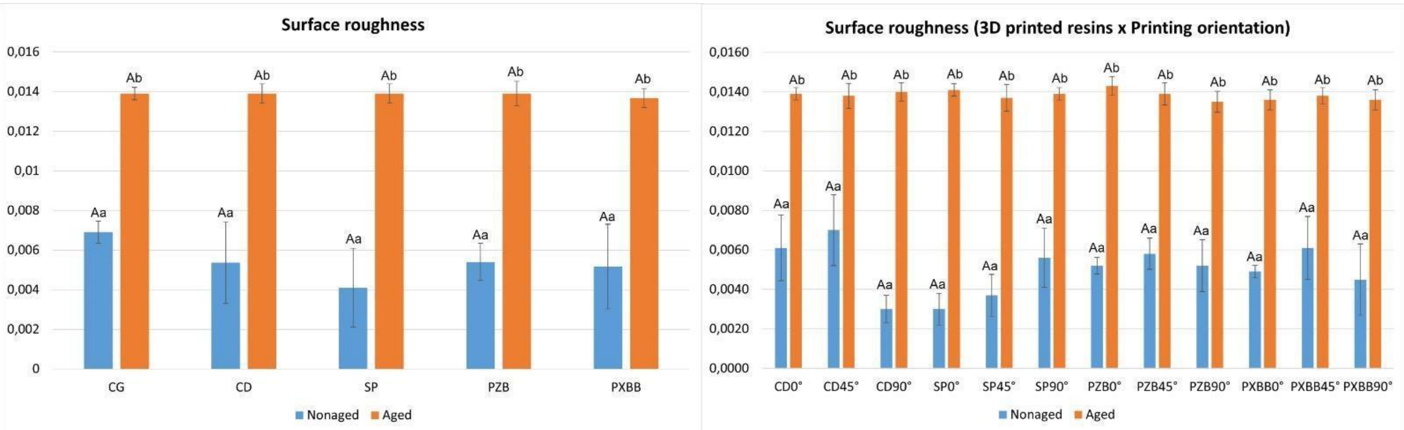
Figures

Figure 1. Color analysis of conventional and 3D printed resins



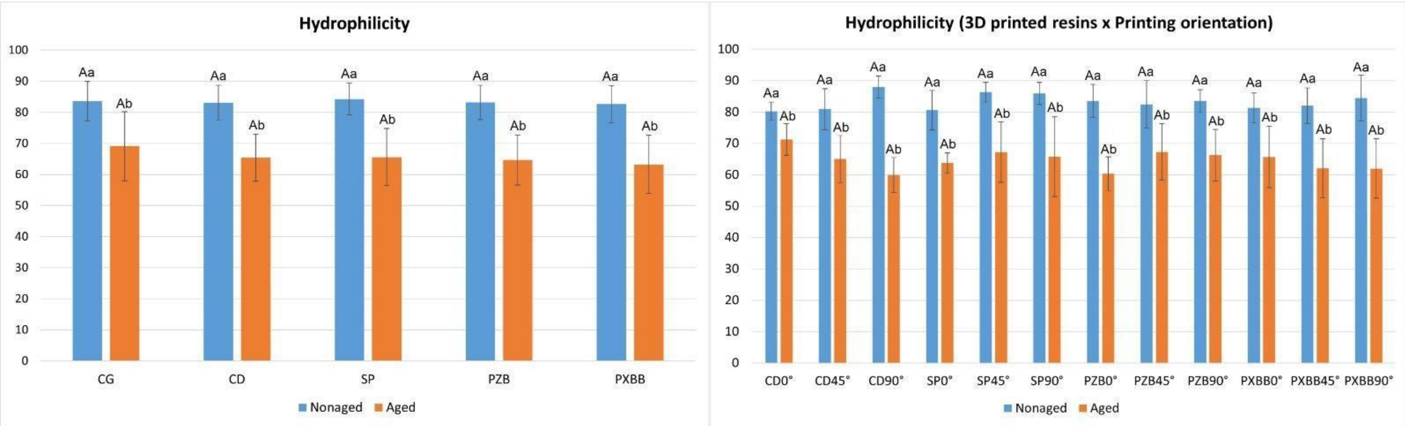
Different lowercase letters indicated significant differences between evaluated resins and printing orientation.

Figure 2. Surface roughness of conventional resin and different 3D printed resins, before and after thermocycling.



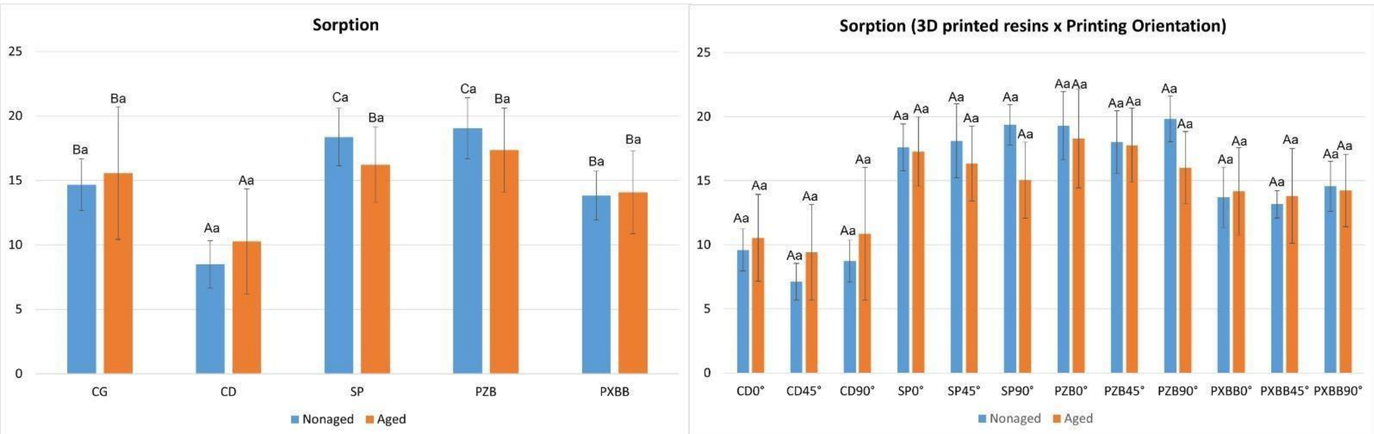
First graph: Equal capital letters indicate no significant differences between resins under the same thermocycling condition. Equal lower case letters indicate no significant differences within the same resin. Second graph: Equal capital letters indicate no significant differences between the 0°, 45° and 90° angles within the same resin and cycling condition. Equal lower case letters indicate no significant differences in the thermocycling ratio within the same resin.

Figure 3. Analysis of water contact angle of conventional resin and different 3D printed resins, before and after thermocycling



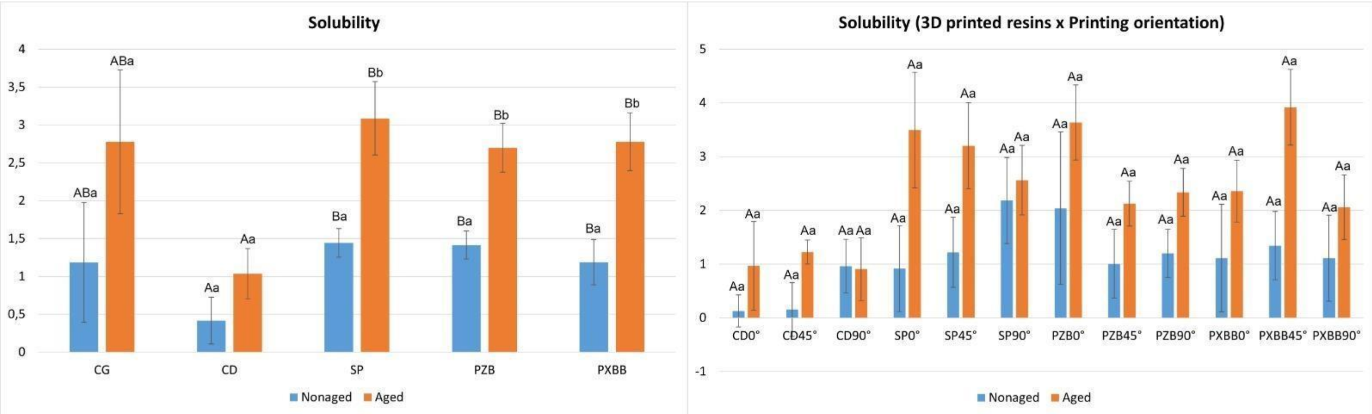
First graph: Equal capital letters indicate no significant differences between resins under the same thermocycling condition. Equal lower case letters indicate no significant differences within the same resin. Second graph: Equal capital letters indicate no significant differences between the 0°, 45° and 90° angles within the same resin and cycling condition. Equal lower case letters indicate no significant differences in the thermocycling ratio within the same resin.

Figure 4. Analysis of the sorption of conventional resin and different 3D printed resins, before and after thermocycling.



First graph: Equal capital letters indicate no significant differences between resins under the same thermocycling condition. Equal lower case letters indicate no significant differences within the same resin. Second graph: Equal capital letters indicate no significant differences between the 0°, 45° and 90° angles within the same resin and cycling condition. Equal lower case letters indicate no significant differences in the thermocycling ratio within the same resin.

Figure 5. Solubility analysis of conventional resin and different 3D printed resins, before and after thermocycling.



First graph: Equal capital letters indicate no significant differences between resins under the same thermocycling condition. Equal lower case letters indicate no significant differences within the same resin. Second graph: Equal capital letters indicate no significant differences between the 0°, 45° and 90° angles within the same resin and cycling condition. Equal lower case letters indicate no significant differences in the thermocycling ratio within the same resin.

3 CONCLUSÃO

As resinas impressas em 3D possuem propriedades físicas similares às das resinas convencionais termopolimerizadas, enquanto a orientação de impressão não influenciou fatores como cor, rugosidade, hidrofobicidade, sorção ou solubilidade.

O processo de termociclagem, que envolve alternar entre temperaturas altas e baixas, causou mudanças na cor, aumento da rugosidade da superfície e diminuição da hidrofilicidade das resinas utilizadas na base de próteses dentárias.

Esses achados indicam que a confecção de próteses totais através da manufatura aditiva por meio das resinas impressas em 3D podem ser uma alternativa viável às próteses totais convencionais para reabilitação de pacientes totalmente desdentados.

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ANEXO A – Instruções e normas Dental Materials

Instruções para submissão no periódico “Dental Materials”, disponível em: https://www.sciencedirect.com/journal/dental-materials/publish/guide-for-authors

ANEXO B – Imagens dos ensaios

Imagem 1: Amostras de impressão 3D antes do polimento (0°, 45° e 90°, respectivamente).

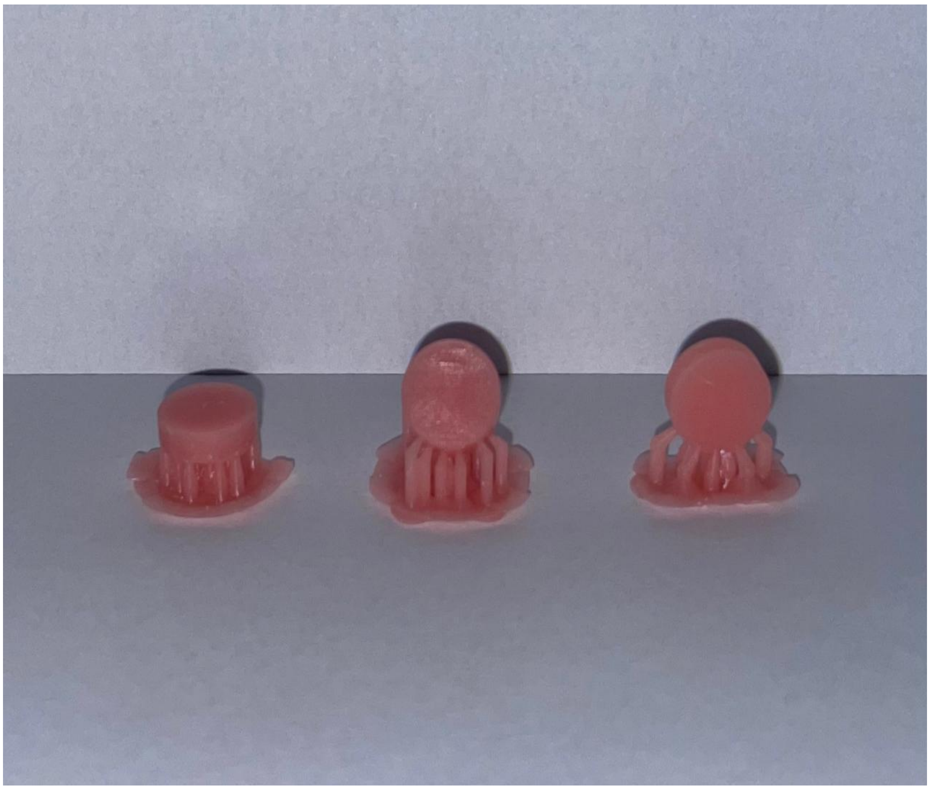

Imagem 2: Análise de rugosidade superficial

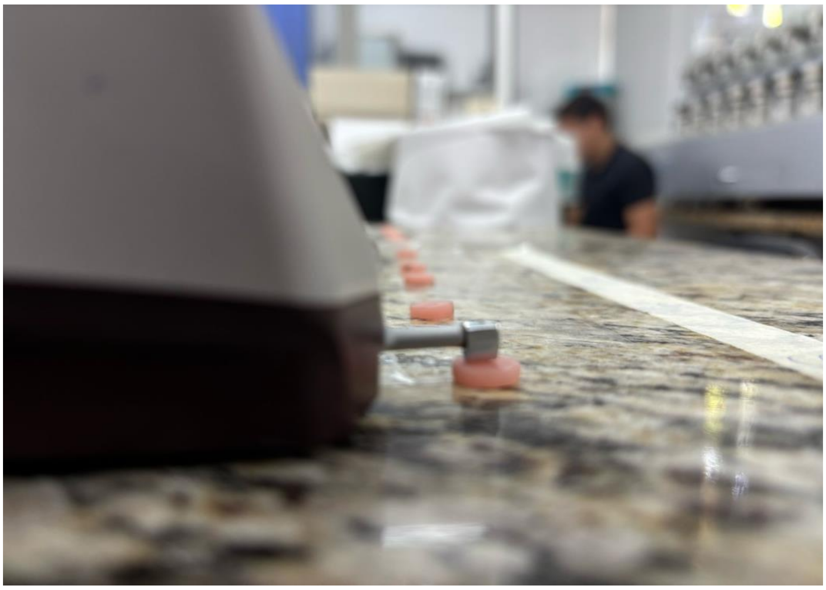

Imagem 3: Teste de hidrofilicidade superficial (Goniômetro)

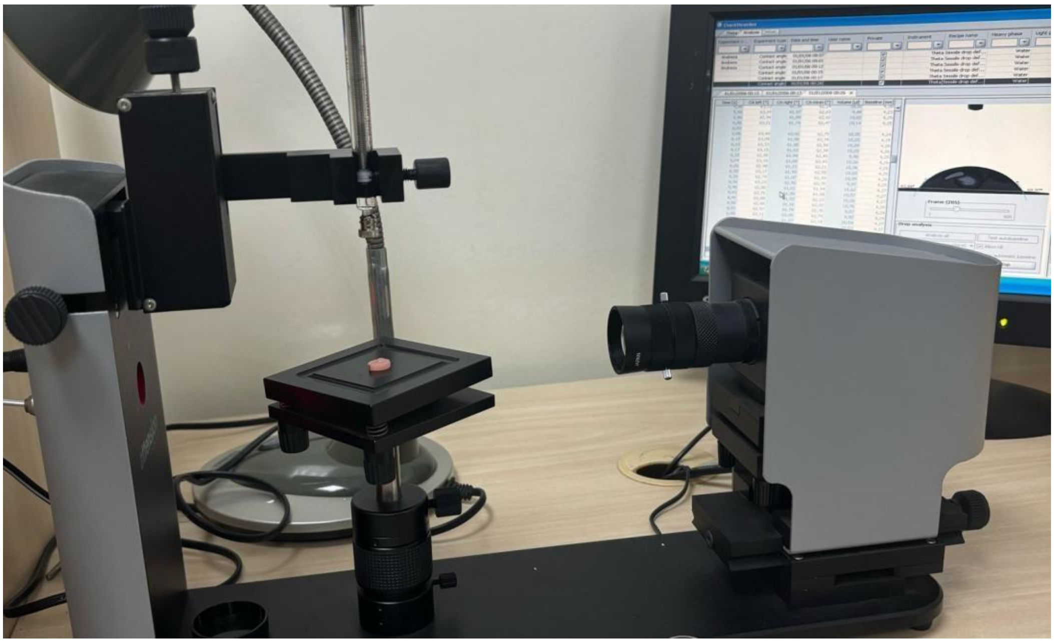

Imagem 4: Amostras dentro do dessecador para realização de teste de sorção/solubilidade

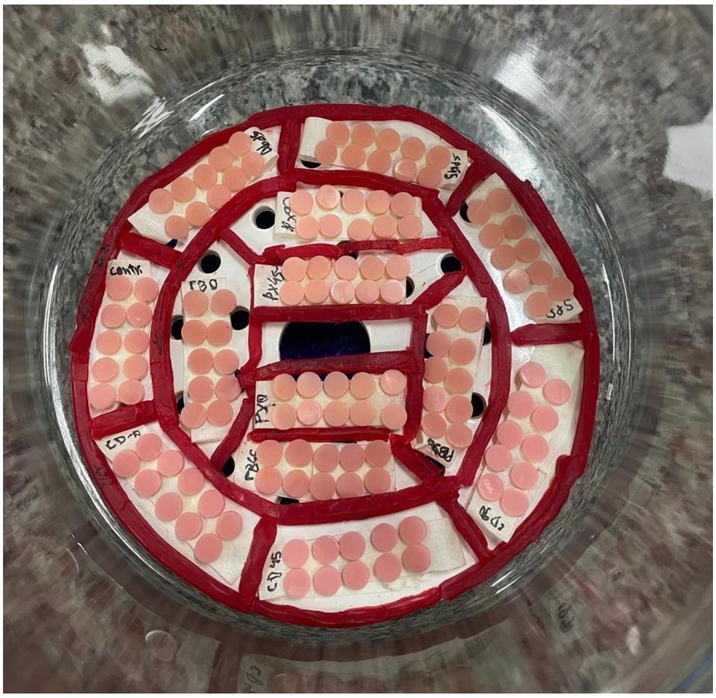

Imagem 5: Amostra sendo pesada por uma balança de precisão.

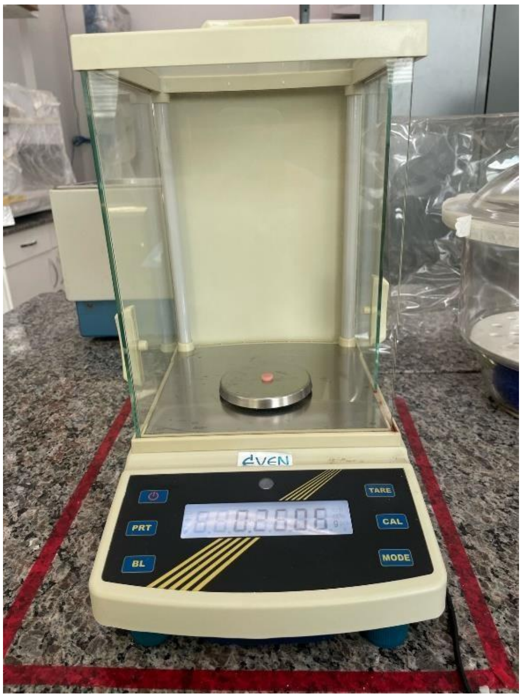

Imagem 6: Resumo das amostras e testes realizados.