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Comparison of tensile bond strengths of different impression materials used with custom trays fabricated by 3D printing

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Comparison of Tensile Bond Strengths of Different Impression Materials Used with Custom Trays Fabricated by 3D Printing

Title Page

Full Title of the Manuscript:
Comparison of Tensile Bond Strengths of Different Impression Materials Used with Custom Trays Fabricated by 3D Printing

Study Design:
In vitro experimental comparative study

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Abstract

Background:
This study aimed to evaluate and compare the tensile bond strength between four different impression materials and custom trays fabricated using various photopolymer-based three-dimensional (3D) printing materials and one conventional method. Additionally, the effect of three surface treatments on bond strength was investigated.

Methods:
A total of 288 custom tray specimens were fabricated using four different techniques: Stereolithography (SLA), liquid crystal display (LCD), digital light processing (DLP), and a conventional light-cured urethane dimethacrylate (UDMA)-based acrylic. Each tray type was subjected to three surface treatments: adhesive-only, perforated-only, and perforated + adhesive. Four elastomeric impression materials were tested: polyvinylsiloxane, condensation silicone, polyether, and vinylsiloxanether. A standardized CAD model was used for all trays. The impression materials were applied onto the tray surfaces, and tensile bond strength was tested using a universal testing machine. Each condition was tested with six replicates ($n = 6$). Data were recorded in Newtons and converted to megapascal (MPa) using a standardized bonding surface area of 825 mm^2. Three-way ANOVA and Tukey's post-hoc tests were conducted ($\alpha=0.05$).

Results:
All three independent variables - printing technique, surface treatment, and impression material - had a statistically significant effect on tensile bond strength ($p < 0.001$). The highest mean bond strength (0.272 MPa) was observed with the DLP-printed tray using perforated-only and polyether impression material. The lowest value (0.018 MPa) was found with the same tray type and surface treatment, but with condensation silicone. Among surface treatments, adhesive-only and adhesive + perforated trays showed significantly higher bond strengths compared to perforated-only groups ($p = 0.001$). Polyether showed significantly higher bond strength than all other impression materials, while condensation silicone yielded the lowest.

Conclusions:
Within the limitations of this in vitro study, tray fabrication method and surface treatment significantly influenced bonding with impression materials. The present findings may provide useful preliminary data for future clinical investigations evaluating retention characteristics of 3D-printed custom trays.

Keywords

Tensile bond strength, 3D printing, custom impression tray, elastomeric impression material, surface treatment, photopolymer resin.

1. Introduction

In recent years, digital technology has emerged as a cornerstone in the advancement of modern dental procedures and clinical protocols [1]. The integration of computer-aided design/computer-aided manufacturing (CAD/CAM) technology into dentistry over the past three decades has facilitated the in-office and laboratory fabrication of prosthetic restorations. These technological advances, combined with the emergence of novel biocompatible and biomimetic materials with enhanced mechanical properties, have significantly improved clinical outcomes by enabling faster and more efficient fabrication processes [2, 3]. Within CAD/CAM systems, digital fabrication may be performed using either subtractive (milling-based) or additive manufacturing approaches [4]. With the growing interest in digital dentistry, additive manufacturing (AM)—one of its emerging branches—has gained increasing attention in various domains of dental practice particularly in impression procedures [5]. Additive manufacturing enables the use of improved restorative materials within shorter production times while reducing the potential for errors and ensuring high reproducibility due to the minimization of human-related variability [6].

Accurate dental impressions are essential for producing well-fitting and functional prosthetic restorations [7]. Clinical studies have demonstrated that impression inaccuracies remain one of the most common sources of prosthetic misfit, leading to marginal discrepancies, occlusal errors, and the need for restoration remakes. Errors such as voids, tears, and incomplete recording of finish lines are frequently observed in fixed prosthodontic impressions, emphasizing the critical role of impression procedures in prosthetic success. Therefore, improving impression stability and tray–material retention is essential to minimize deformation and ensure dimensional accuracy [8-10].

Dental impression trays are expected to provide a homogeneous and uniform impression material thickness to ensure dimensional accuracy, to possess sufficient mechanical rigidity to minimize tray flexure and distortion during impression making and removal [11]. These requirements become even more critical in maxillofacial and prosthodontic rehabilitation, where the accuracy of preliminary impressions directly influences clinical outcomes.

Clinical outcomes in maxillofacial and prosthodontic rehabilitation are highly dependent on the accuracy of preliminary impressions, particularly in cases involving extensive anatomical defects or limited mouth opening. Errors in impression recording have been associated with prosthetic misfit and increased risk of clinical complications, especially in patients requiring obturator prostheses after maxillectomy or other facial defects. Several studies have highlighted the challenges of impression making in such cases, including the need for customized trays designed to accommodate irregular defect morphology and restricted access, and the benefits of advanced fabrication techniques in addressing these challenges [12-14]. In prosthodontic practice, custom impression trays offer a more precise alternative to stock trays for capturing the morphology of oral tissues [15]. While intraoral scanners have emerged as an alternative in certain clinical situations, custom trays still remain highly relevant in the literature due to their precision and adaptability [16].

As polymerization shrinkage in elastomeric impression materials correlates positively with material thickness, the use of custom trays facilitates the fabrication of accurate working models by promoting a uniform impression layer [17, 18]. Moreover, custom trays provide notable benefits over stock trays, including the ability to maintain a consistent material thickness, minimize dimensional inaccuracies, and improve surface detail accuracy [19]. Custom impression trays can be fabricated using conventional manual techniques or produced through digital workflows based on CAD/CAM technologies. Within digital manufacturing, tray fabrication is generally classified into subtractive manufacturing (milling) and additive manufacturing [20-22]. However, the traditional fabrication of custom trays is time-consuming and requires substantial manual labor, which can increase clinical chair time and cost [23]. In addition, autopolymerizing polymethyl methacrylate (PMMA), commonly used for fabricating custom trays, exhibits polymerization shrinkage, which may negatively affect the dimensional accuracy of the impression [24, 25]. Consequently, there has been a growing need to explore and develop alternative materials for the fabrication of custom trays.

Recent advancements in digital dentistry have popularized the use of CAD and AM technologies for producing dental appliances, including custom trays [6, 26, 27]. Common AM technologies used in dentistry include stereolithography (SLA), digital light processing (DLP), and liquid crystal display-based masked stereolithography (LCD)/mSLA) printing [28]. Compared with one another, SLA has been reported to provide high printing accuracy and surface quality, DLP offers faster fabrication due to layer-wide light projection, whereas LCD/mSLA represents a more cost-effective alternative with comparable resolution but potential limitations related to light diffusion and material-dependent curing behavior [6, 29]. These methods differ in their layer formation strategies, curing mechanisms, and material compatibility. Additionally, fused deposition modeling (FDM) and conventional photopolymerized acrylics remain in use for clinical and laboratory applications.

While several studies have explored the peel bond strength between tray and impression materials, limited data exist on tensile bond strength—particularly for trays fabricated using different 3D printing techniques [30, 31]. Moreover, factors such as tray surface topography and surface treatment are known to influence retention and debonding behavior [32]. Among impression materials, polyether and polyvinylsiloxane are commonly favored for their mechanical stability and hydrophilic properties, yet their bonding performance with modern tray materials needs further elucidation [33].

Unlike previous studies that primarily focused on peel bond strength or a limited range of printing techniques, the present study exclusively evaluated photopolymer-based 3D printing technologies using a tensile testing approach and a three-factor experimental design, including the assessment of an additional LCD-based printing technology as well as adhesive-coated and perforated custom tray designs as surface treatment variables. By simultaneously analyzing printing technique, surface treatment, and impression material, this study provides a more comprehensive understanding of the complex interactions affecting tray–impression retention.

This study aimed to evaluate the tensile bond strength between four impression materials and custom trays fabricated using SLA, DLP, LCD, and a conventional light-cured urethane dimethacrylate (UDMA)-based acrylic method. Furthermore, it assessed the effect of three different surface treatments—adhesive-only, perforated-only, and combined perforated + adhesive—on bonding performance. The null hypotheses were that (1) the tray fabrication technique, (2) the surface treatment, and (3) the impression material would each have no significant effect on the tensile bond strength.

2. Materials and Methods

An a priori power analysis was performed using G*Power software (version 3.1.9.4; Heinrich-Heine University, Dusseldorf, Germany) to determine the minimum required sample size. Based on bond strength values reported in a previous study [30], an effect size of 0.86 was calculated. With a significance level of 0.05 and a desired statistical power of 95%, the minimum sample size was determined to be four specimens per group. To further increase the reliability of the results, the sample size was increased to six specimens per group (n=6 per group, 288 in total).

2.1. Test Specimen Design

Custom tray specimens were designed using a CAD program with Blender (Version 4.1, Blender Foundation, Amsterdam, Netherlands). Dimensions were standardized across all groups. Each specimen was consisted of a 25.4 mm × 25.4 mm × 6 mm cuboidal base with a central 25 mm × 25 mm square impression area [30, 31]. Impression area was recessed to a depth of 2 mm for an optimal impression thickness [34]. The perforated tray design was developed based on the design presented in a previously published study [34], consisting of 2 mm diameter holes spaced 5 mm apart. An elliptical handle with a 25 mm length and 6 mm thickness was integrated vertically into the base of the tray. The elliptical handle was incorporated to facilitate axial load application during tensile bond strength testing, in accordance with a previously reported methodology [35]. No handle failure was observed during testing. The tray designs are illustrated in **Fig. *1*.** All designs were exported in STL (Standard Triangle Language) format for compatibility with various 3D printing software platforms.

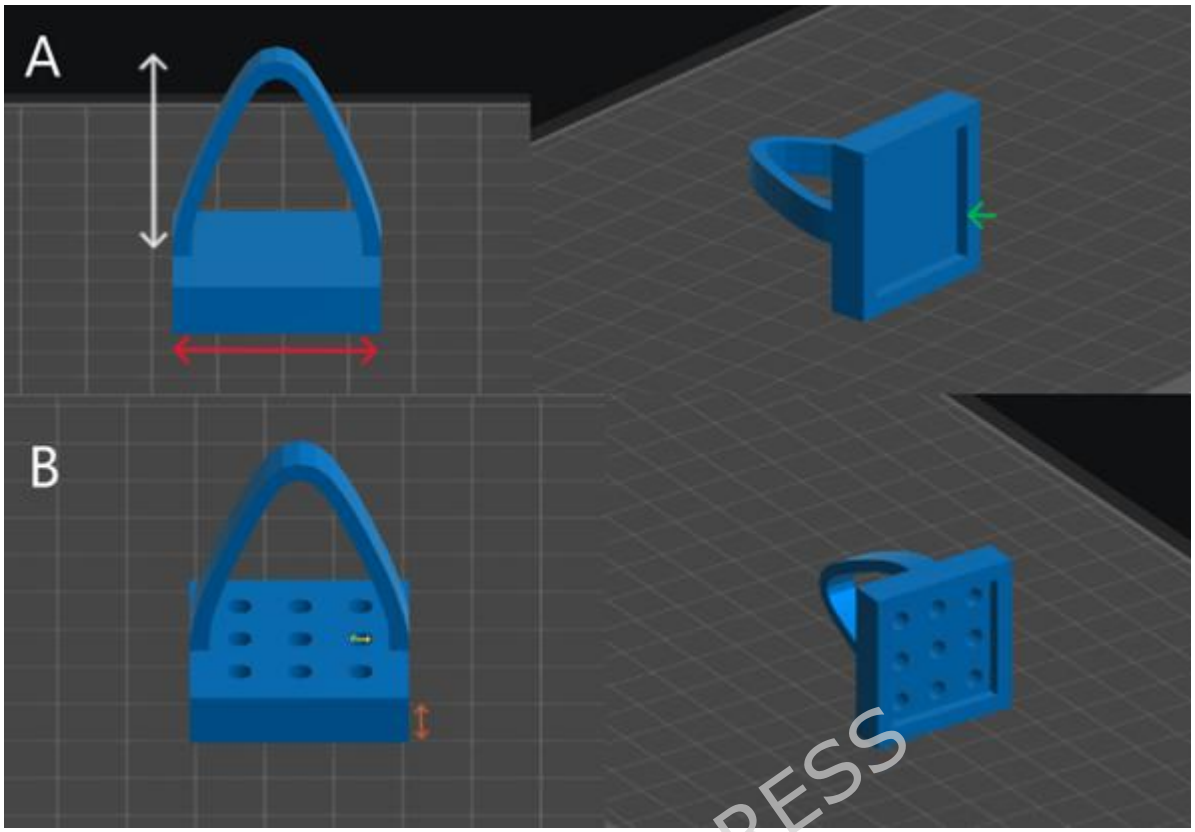

Fig. 1. CAD-designed custom impression tray specimens used for tensile bond strength testing. (A) Non-perforated and (B) perforated tray designs shown in orthogonal and isometric views. Double-headed arrows indicate key geometric dimensions: red arrows denote the cuboidal base width (25.4 mm), white arrows indicate the length of the elliptical handle (25 mm), yellow arrows represent the perforation hole diameter (2 mm), and orange arrows indicate the cuboidal base thickness (6 mm). The green single-headed arrow denotes the recessed impression depth (2 mm). All numerical dimensions are provided in the text.

2.2. Tray Fabrication

Four groups of tray materials were fabricated based on different production techniques:

- SLA: Printer Form 3B (Formlabs Inc., USA) using Formlabs Tray Resin (Formlabs Inc., USA)
- DLP: Printer Asiga Max (Asiga, Australia) using Arma Tray Resin (Arma Dental, Turkey)
- LCD: Printer Anycubic Photon Mono M5S Pro (Anycubic Tech, Shenzhen, China) using Alias Tray Resin (Dokuz Chemistry, Turkey)
- UDMA control group (Optima Basplak, Dokuz Chemistry, Turkey)

The material characteristics of these custom tray resins are summarized in **Table 1**

All 3D-printed specimens were fabricated using different tray resins following the manufacturers' instructions and printed using the same standardized print orientation to minimize variability related to directional anisotropy. Specifically, all tray specimens were printed in a vertical orientation, with the long axis of the tray aligned perpendicular to the build platform (90° orientation). The support contact points positioned so as not to interfere with the test surface. The printing direction and layout are shown in **Fig. 2.** Screenshot of settling the tray design on printing software. . Formlabs Tray Resin specimens were printed with a layer thickness of 100 µm, washed in %99 isopropyl alcohol (IPA) for 10 minutes using a Form Wash unit (Formlabs Inc., USA), and post-cured at 80 ◦C for 30 minutes using a Form Cure unit (Formlabs Inc., USA). Arma Tray Resin specimens were printed at a layer thickness of 100 µm, washed in %99 IPA for 5 minutes using a UW-01 wash & cure unit (Creality 3D Technology Co., Ltd., Shenzhen, China), and post-cured for 7 minutes using a Asiga cure unit (Asiga, Australia). Alias Tray Resin specimens were printed with a layer thickness of 100 µm, washed in %99 IPA for 6 minutes, and post-cured for 6 minutes using a Anycubic wash & cure unit (Anycubic Tech, Shenzhen, China).

Optima Basplak (Dokuz Chemistry) specimens were polymerized for 10 minutes using a UW-01 wash&cure unit. All post-processing procedures were performed in accordance with the respective manufacturers' instructions to ensure optimal polymerization and surface quality prior to tensile bond strength testing. Specimens were stored in light-proof containers until testing.

For the production of the conventional control group, a standardized custom mold model was designed using CAD software (Blender, Blender Foundation, Netherlands) to ensure optimal reproducibility. The design was exported as an STL file and printed using high clear transparent resin (Anycubic Tech, Shenzhen, China) in 3D printer Anycubic Photon Mono M5S Pro. Additionally, a separate mold was created for the perforated variant by incorporating 2 mm diameter holes spaced 5 mm apart into the standard design. Following the manufacturer's instructions, both mold models were used to sequentially fabricate the UDMA trays. After completion of the casting and curing processes, all trays were stored in a controlled environment for subsequent testing. A representative image of the mold models is shown in **Fig. *3*.** Screenshot of mold model design

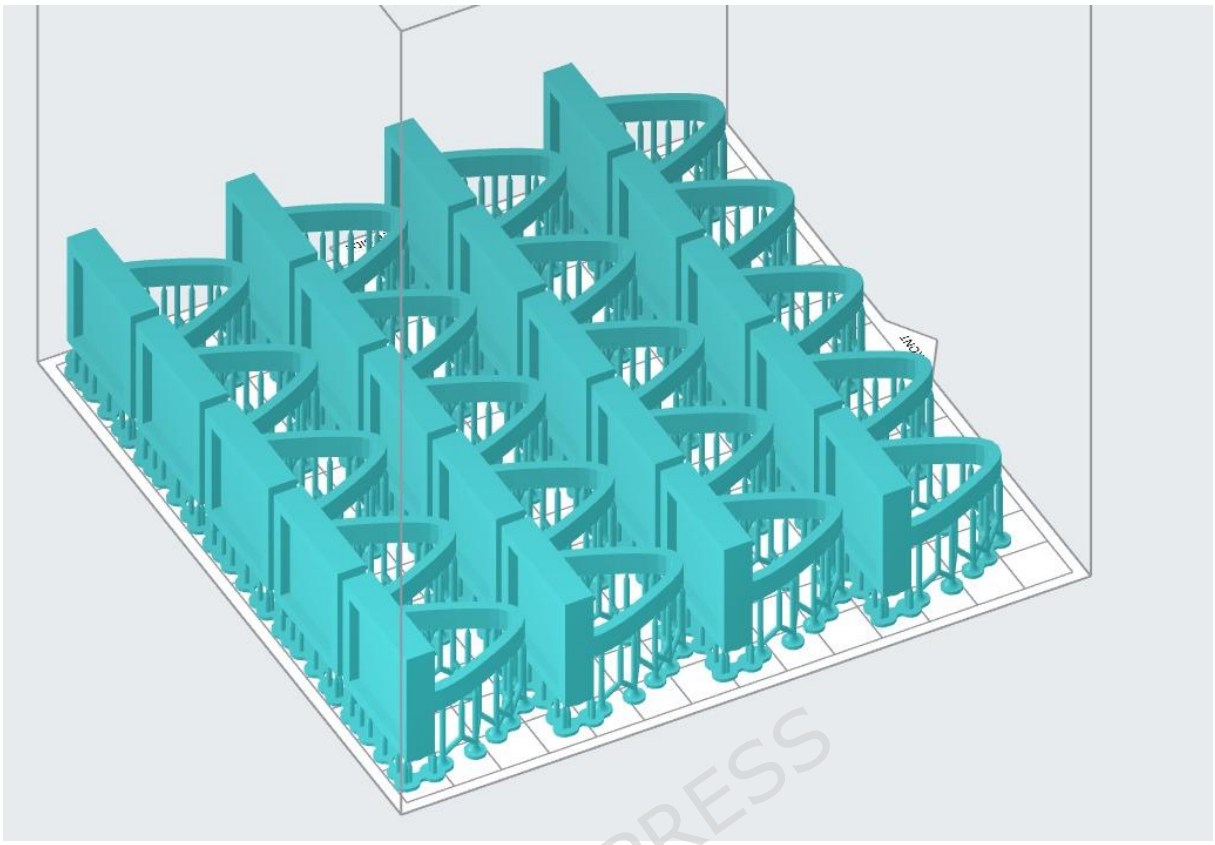

Fig. 2. Screenshot of settling the tray design on printing software. The printing direction, printing layout, and supporting materials on the build platform.

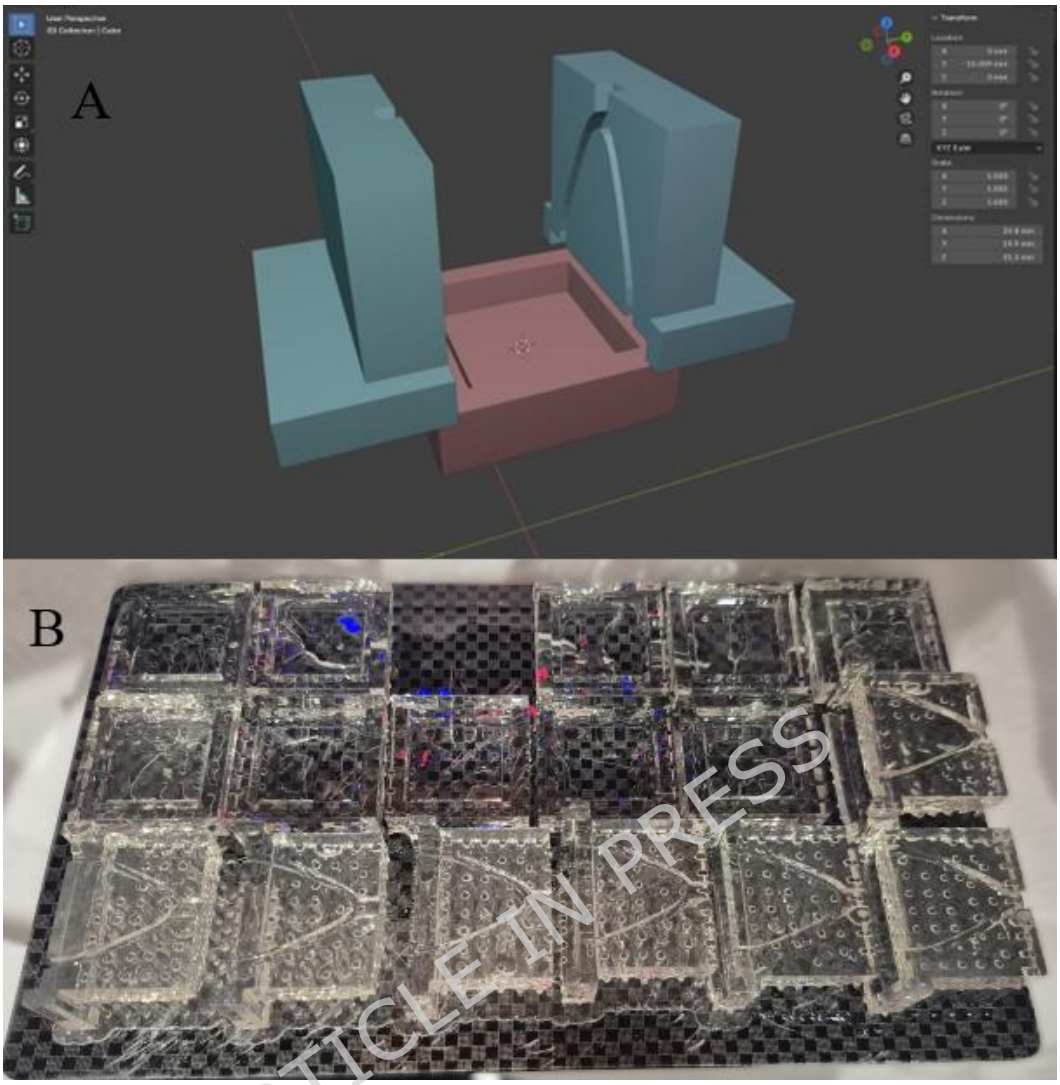

Fig. 3. Screenshot of mold model design (A), and photo of after mold printing (B).

Table 1

Properties of custom tray resins used in this study.

Tray Resin (Manufacturer)	AM Technique	Component
Formlabs Custom Tray Resin (Formlabs, USA) **[36]**	SLA	(Meth)acrylate-based
Arma Tray Resin (Arma, Turkey) **[37]**	DLP	(Meth)acrylate-based
Alias Tray Resin (Alias, Turkey) **[38]**	LCD	(Meth)acrylate-based
Optima Basplak (Dokuz Kimya, Turkey) **[39]**	Conventional (UV cure)	UDMA-based acrylic

2.3. Surface Treatments

Each tray material group was subdivided into three surface treatment subgroups:

- Adhesive-only (3M Polyether Tray Adhesive, 3M Healthcare, USA)
- Perforated-only: 2 mm-diameter holes were uniformly distributed across the bonding surface [34]
- Perforated + Adhesive

The tray adhesive was applied according to the manufacturer's instructions and allowed to dry under ambient conditions.

2.4. Impression Materials

Four elastomeric impression materials commonly used in clinical dentistry were tested:

- Polyvinylsiloxane (a-silicone): Zhermack Elite HD Putty (Zhermack S.p.A., Badia Polesine, Italy)
- Condensation Silicone (c-silicone): Zhermack Zetaplus Putty (Zhermack S.p.A., Badia Polesine, Italy)
- Polyether: 3M Impregum Penta Soft (3M ESPE, Seefeld, Germany)
- Vinylsiloxanether (VSXE): Kettenbach Identium Heavy (Kettenbach GmbH & Co., Eschenburg, Germany)

Following the application of each impression material onto the tray surface, a force was applied using a universal testing machine, pressing the tray against a flat reference platform produced via 3D printing. Any excess material was carefully trimmed using a sharp scalpel. In this manner, a standardized impression thickness of 2 mm was achieved.

2.5. Tensile Bond Strength Testing

Each specimen was cleaned with steam and allowed to air dry. For the groups involving adhesive application, the adhesive agent was applied according to the manufacturer's instructions and left to dry for 15 min before impression material placement. The drying time was determined based on protocols reported in previous studies [40-42]. After the impression material set, any excess material was removed with a sharp scalpel, and then the test specimens were subjected to tensile bond strength testing using a universal testing machine (Trapezium X, Shimadzu, Japan) at a crosshead speed of 300 mm/min. A hook was inserted through the opening beneath the elliptical handle to apply a vertical tensile force perpendicular to the tray base. The force at failure was recorded in Newtons (N) and converted to megapascal (MPa) using the bonded surface area of 825 mm^2. The testing setup is illustrated in **Fig. *4*.** Photo of the testing complex

Each group consisted of six specimens (n = 6), yielding a total of 288 tested samples.

2.6. Statistical Analysis

Data were analyzed using IBM SPSS Statistics 26.0. Descriptive statistics (mean and standard deviation) were computed for each subgroup. The effects of the three independent variables—printing technique, surface treatment, and impression material—on tensile bond strength were evaluated using three-way ANOVA. Interaction effects were also assessed. Where significant differences were found, Tukey's HSD post-hoc tests were applied. Statistical significance was set at $\alpha = 0.05$.

Fig. 4. Photo of the testing complex.

3. Results

A three-factor ANOVA revealed that tray fabrication technique, tray surface treatment, and impression material each had a statistically significant effect on tensile bond strength ($p < 0.001$). All two-way interactions between factors were also significant ($p < 0.001$), as was the three-way interaction, indicating that bond strength depended on specific combinations of technique, surface treatment, and impression material. Tensile bond strengths across the 48 test groups ranged widely, from as low as 0.018 MPa for a DLP-printed tray with a perforated surface and c-silicone impression up to 0.272 MPa for a DLP tray with a perforated surface and polyether impression, highlighting the substantial influence of the experimental factors.

The choice of tray manufacturing method significantly affected bond strength. Among the four tray types, SLA-printed trays produced the highest mean bond strength, while the conventional UDMA-based acrylic trays yielded the lowest. DLP and LCD tray groups showed intermediate bond values. Post-hoc Tukey comparisons (**Table 2**) confirmed that SLA-printed trays had significantly higher bond strength than DLP and also higher than LCD. SLA was also significantly higher than UDMA. Conversely, UDMA trays gave significantly lower bond strength than DLP and LCD. Notably, there was no statistically significant difference between the DLP and LCD tray groups, indicating these two 3D printing techniques performed comparably in terms of impression bond. These results demonstrate that the SLA technique provided superior impression retention, whereas UDMA trays showed the poorest retention of impression material.

The method of surface treatment on the tray had a pronounced impact on bonding. Results are shown in **Table 3**. Trays with perforated-only showed significantly lower bond strength compared to trays treated with adhesive-only. Adding adhesive to perforated trays (Adhesive + Perforated) significantly improved strength relative to perforated alone. There was no significant difference between adhesive-only trays and perforated + adhesive trays. Thus, the application of tray adhesive (with or without perforations) yielded higher bond values than perforated-only, which by itself produced the weakest bond among surface treatments.

Significant differences were also found among elastomeric impression materials. Polyether produced the highest mean bond strength of all impression materials. In fact, polyether's bonding performance was significantly greater than that of both a-silicone and c-silicone. On the other end, c-silicone exhibited the lowest bond strength on average, which was significantly lower than the bond strength of the other materials. For instance, c-silicone's bond strength was statistically inferior to a-silicone's, and also lower than that of VSXE. The two systems – a-silicone and VSXE – showed no significant difference from each other in mean bond strength, clustering as intermediate performers between polyether and c-silicone (see

). These results can be summarized as: Polyether > VSXE ≈ a-silicone > c-silicone in terms of tensile bond strength. The superior outcome for polyether is evident in that the highest individual group mean (0.272 MPa) was observed with polyether in a perforated tray, whereas the lowest (0.018 MPa) involved c-silicone in a similar tray condition.

Given the significant interaction terms, some notable combined effects were observed. The technique × impression material interaction ($p < 0.001$) (**Fig. 5.** This figure illustrates the interactions (A) between different fabricating techniques and impression materials, (B) surface treatments and fabricating techniques, and (C) surface treatments and impression materials.) manifested in differing material performance depending on tray type. For example, polyether consistently yielded the highest bond strength with almost all tray fabrication methods, but its advantage was most pronounced with DLP tray. In contrast, the UDMA acrylic tray tended to yield the lowest bond strengths regardless of the impression material used; even with polyether, the UDMA tray's bond was lower than the bonds achieved by polyether on the printed trays. Meanwhile, the technique × surface interaction (**Fig. 5.** This figure illustrates the interactions (A) between different fabricating techniques and impression materials, (B) surface treatments and fabricating techniques, and (C) surface treatments and impression materials.) showed that the benefit of perforations varied by tray type: SLA-printed trays with adhesive + perforated and adhesive-only surfaces showed especially high bond strengths, whereas the UDMA tray's bond remained low with any surface condition. LCD trays showed a similar pattern: both attained relatively high bond strengths when perforated, but their performance dropped with perforated-only surfaces. Finally, a significant surface × material interaction (**Fig. 5.** This figure illustrates the interactions (A) between different fabricating techniques and impression materials, (B) surface treatments and fabricating techniques, and (C) surface treatments and impression materials.) was observed as well. In general, only polyether benefited from tray perforations compared to adhesive alone, but the magnitude of this benefit differed. Polyether in particular saw a dramatic increase with perforated trays, achieving the highest overall bonds. By contrast, c-silicone remained the worst performer under every surface condition, but with adhesive usage bonding performance increased. Notably, for some materials like a-silicone and VSXE, the difference between using adhesive-only versus perforated + adhesive was minimal (overlapping bond values).

Table 2

Results of comparisons of tensile bond strength among different techniques. *Statistically significant at $\alpha = 0.05$

Group 1	Group 2	Mean Difference (MPa)	95% CI Lower	95% CI Upper	p-value
DLP	LCD	0.0136	-0.0102	0.0373	.453
DLP	SLA	0.0455	0.0218	0.0692	< .001*
DLP	UDMA	-0.0292	-0.0529	-0.0055	.009*
LCD	SLA	0.0319	0.0082	0.0556	.003*
LCD	UDMA	-0.0428	-0.0665	-0.0191	< .001*
UDMA	SLA	0.0747	0.0568	0.0926	< .001*

Table 3

The results of the Tukey HSD post-hoc test performed to determine significant differences in tensile bond strength among surface treatment types. *Statistically significant at $\alpha = 0.05$

Group 1	Group 2	Mean Difference (MPa)	95% CI Lower	95% CI Upper	p-value
Adhesive	Perforated	-0.0308	-0.0510	-0.0107	.001*
Adhesive	Perforated + Adhesive	0.0024	-0.0178	0.0226	.957
Perforated	Perforated + Adhesive	0.0333	0.0131	0.0534	< .001*

Table 4

The results of the Tukey HSD post-hoc analysis conducted to evaluate differences in tensile bond strength among the impression materials. *Statistically significant at α = 0.05

Group 1	Group 2	Mean Difference (MPa)	95% CI Lower	95% CI Upper	p-value
A-Silicone	C-Silicone	-0.0267	-0.0499	-0.0036	.016*
A-Silicone	Polyether	0.0540	0.0308	0.0772	< .001*
A-Silicone	Vinylsiloxanether	0.0016	-0.0216	0.0247	.998
C-Silicone	Polyether	0.0807	0.0576	0.1039	< .001*
C-Silicone	Vinylsiloxanether	0.0283	0.0051	0.0515	.010*
Vinysiloxanether	Polyether	0.0524	0.0325	0.0724	< .001*

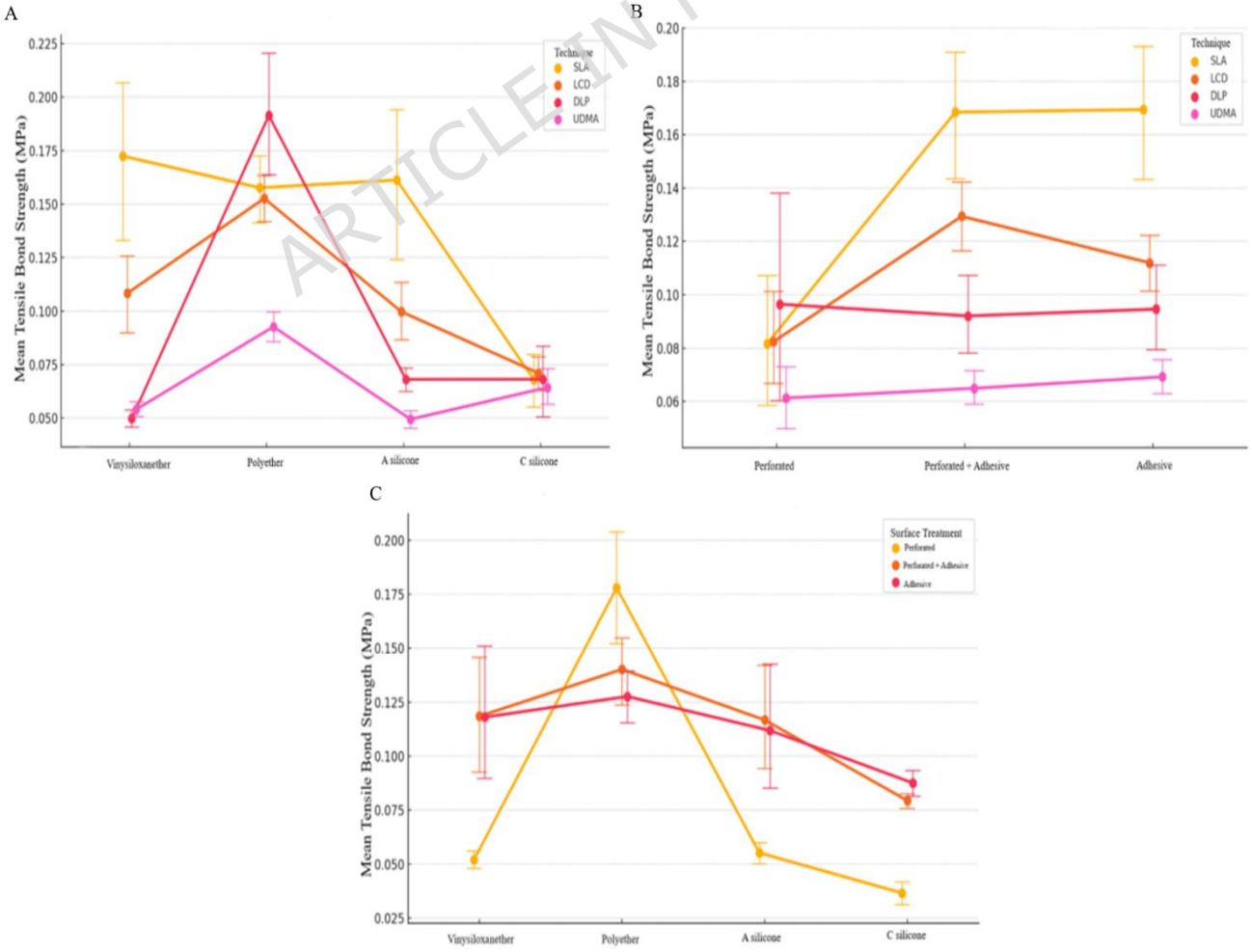

Fig. 5. This figure illustrates the interactions (A) between different fabricating techniques and impression materials, (B) surface treatments and fabricating techniques, and (C) surface treatments and impression materials.

4. Discussion

This study represents the systematic investigation of the combined effects of photoplymer-based 3D printing techniques, tray surface modifications, and various elastomeric impression materials on the tensile bond strength between trays and impressions. The results confirmed that each factor individually, as well as their interactions, significantly affect retention. All three null hypotheses were rejected ($p < 0.05$), demonstrating statistically significant differences across the investigated variables.

A limited number of studies in the literature have compared the bond strengths between different impression materials and various 3D printed tray substrates. The majority of these investigations have focused on 3D printed tray materials, most commonly those produced via FDM. To the best of our knowledge, the present study is the first to directly compare exclusively photopolymer-based 3D printing technologies with respect to their tensile bond strength to elastomeric impression materials, incorporating different surface treatments.

4.1. Influence of Tray Material and 3D Printing Method on Bond Strength

The present results indicate that the tray material and fabrication method can impact the retention of the impression; however, the majority of 3D-printed tray–impression combinations provided bond strength values within clinically acceptable ranges (i.e., >0.05 MPa) as reported in previous literature [30, 43]. This finding aligns with recent studies showing that additive manufactured (AM) custom trays achieve bonding performance comparable to conventional trays [30, 31].

Trays produced by SLA technology possess a high degree of cross-linking and elevated surface energy. These properties improve the wettability of certain impression materials, particularly polyether [44]. The good bonding performance observed in the SLA group in the present study is consistent with the findings reported by Katheng et al. [44] In the same study, similar mechanical properties were reported for DLP and LCD prints, which may explain the comparable bond strengths observed between these two methods in our investigation [44]. Similarly, another study reported comparable results under analogous conditions [45].

In the present study, DLP-printed trays demonstrated higher tensile bond strength than UDMA trays. This trend is in agreement with the findings of Priyadarshini et al. [46], Clarkson et al. [47].

These findings, however, should be interpreted in the context of material-dependent variability reported in the literature. For example, Rues et al. reported lower bond strength values for polyether on DLP-printed trays compared to UDMA trays [48], indicating that material interactions may vary depending on resin formulation and testing protocols.

The UDMA-based custom tray material used in our study demonstrated lower tensile bond strength compared to values reported in previous studies employing other visible light-cured acrylic trays [49]. These discrepancies may be attributed to intrinsic differences in resin composition, filler content, and surface properties. While some UDMA tray materials incorporate co-monomers and high filler fractions that enhance surface energy, stiffness, and micro-mechanical retention, the tray material used in our study may consist primarily of unfilled or lightly filled UDMA resin. Such a composition could yield a smoother, chemically inert surface with lower surface energy, reducing adhesive wettability and interfacial bonding [50]. Despite these material-related differences, the practical relevance of small numerical variations should be interpreted cautiously.

Although several statistically significant differences were detected, not all of these differences may be clinically meaningful. Previous studies have suggested that bond strength values above approximately 0.05 MPa may be considered clinically acceptable for tray–impression retention [30, 32]. Therefore, small numerical differences within this range should be interpreted with caution and primarily as indicators of relative material performance rather than definitive clinical superiority.

In addition to material composition and printing technology, manufacturing parameters may also influence bonding behavior. In the present study, all specimens were printed using a standardized vertical orientation with a consistent alignment relative to the tensile loading axis. This approach was adopted to control the effects of layer-dependent anisotropy, as printing orientation has been shown to affect the mechanical behavior of photopolymer-based 3D-printed resin materials [51-53]. By maintaining a uniform printing orientation across all groups, the potential influence of orientation-induced mechanical variability was minimized, ensuring that differences in tensile bond strength could be attributed primarily to tray fabrication technique, surface treatment, and impression material. Similar orientation standardization strategies have been recommended in previous studies to enhance the comparability and reliability of mechanical testing outcomes in additively manufactured dental materials [52, 53].

Although printing orientation was not evaluated as an independent variable in the present study, controlling this parameter allowed a more reliable comparison among different printing technologies and tray materials. Future studies specifically designed to investigate the effect of printing orientation on tray–impression bond strength would further clarify its clinical relevance.

4.2. Influence of Post-processing Parameters on Bond Strength

In the present study, no separate analysis was performed to evaluate the direct effect of different washing times on tensile bond strength, which should be considered a limitation of the study. However, Hwangbo et al. reported that variations in washing solution and washing duration did not result in significant differences in surface defects of 3D-printed resin materials [54].

In another study, it was reported that increasing the application time of isopropyl alcohol on SLA-printed specimens led to statistically significant reductions in surface roughness values. However, the authors also noted that their findings differed from those reported in other studies and therefore emphasized that the effect of IPA washing time on surface characteristics should be evaluated separately for each material [55].

Similarly, no separate analysis was conducted to evaluate the isolated effect of different post-curing times on tensile bond strength, representing another limitation of the present study. Nevertheless, a parallel may be drawn with the findings of Karademir et al., who reported that increasing post-curing time significantly improved the mechanical properties of 3D-printed resin materials [56]. In addition, another study reported that increasing post-curing time led to a corresponding increase in microhardness [57], and similarly demonstrated that higher light intensity combined with prolonged post-curing duration was associated with improvements in certain mechanical properties, particularly microhardness [58].

In one study, it was reported that mechanical properties differed when post-curing was performed under two different atmospheres, namely nitrogen (N_2) and air [59]. While these findings suggest that post-processing parameters may influence the mechanical behavior of 3D-printed materials, the authors emphasized that adherence to the manufacturer's recommended post-processing protocols remains appropriate to ensure methodological consistency and clinical relevance.

In line with these observations, the SLA-printed trays in the present study, which were subjected to the longest post-curing protocol, demonstrated the most reliable and consistent bond strength results overall. This indirect agreement suggests that extended post-curing may contribute to enhanced material integrity and interfacial stability, although further studies specifically designed to isolate this variable are required to confirm its direct influence on bond strength.

4.3. Role of Surface Treatments

The role of surface treatments had a measurable effect on tray bond strength. Using a tray adhesive dramatically increased tensile bond strength compared to having no adhesive, which is in line with a vast body of evidence dating back several decades [60, 61]. Our results concur with that recommendation to a notable extent. For example, in our study the perforated trays with polyether consistently outperformed all others. However, adding adhesive to perforated trays did not enhance retention, possibly because the adhesive film obstructed mechanical undercuts, especially with inherently stiff and sticky materials like polyether.

4.4. Influence of Elastomeric Impression Material on Retention

In the present experimental setting, the impression material type showed a pronounced influence on tray–impression bond strength. Overall, polyether, a-silicone, and VSXE all showed high adhesion to the tray. In our study, polyether impression material tended to produce slightly higher tensile bond values than other impression materials under the

conditions of the present study, which is understandable given polyether's inherently more adhesive nature and high stiffness [62].

In the study conducted by Xu et al., polyether exhibited lower bond strength compared to VSXE and a-silicone [30]. However, in our study, polyether demonstrated higher bond strength values. This discrepancy may be attributed to differences in adhesive selection. In our protocol, a single type of polyether adhesive was applied uniformly across all impression materials, whereas Xu et al. used material-specific adhesives recommended by each manufacturer.

Among silicones, we observed that a-silicone generally had higher bond strengths than c-silicone when using the same adhesive [63, 64]. This is supported by Kambiranda et al., who found that a-silicone exhibited significantly greater bond strength than c-silicone with both tested universal adhesives [61]. Polyvinylsiloxane materials have largely replaced condensation types in clinical practice due to their superior stability and lower shrinkage [65], and our findings suggest they also have an edge in tray adhesion. The higher bonding could be due to the composition of adhesives which are optimally formulated for a-silicone, whereas c-silicones might not achieve as strong a chemical interaction with the adhesives [66]. Indeed, Kambiranda (2019) noted the strongest combination was a universal adhesive with a-silicone, while the weakest was a similar adhesive with c-silicone [61]. Our results echo this trend.

Although this study did not specifically categorize the modes of failure (adhesive, cohesive, or mixed), one notable observation warrants explicit mention. In all subgroups involving VSXE used with SLA-printed trays—specifically those with adhesive-only and those with perforated + adhesive— cohesive failures were observed in VSXE groups with SLA-printed trays, consistent with reports noting similar behavior under high-retention conditions [67, 68].

4.5. Methodological Considerations and Study Limitations

One important methodological consideration of the present study relates to the selection of tensile bond strength testing as the primary outcome measure. Although tensile bond testing provides standardized and reproducible comparative data, it does not fully replicate clinical impression removal, which is predominantly governed by peel-type stresses initiating at one edge of the tray [31]. Peel tests, as reported in previous studies, generally yield lower bond strength values because stress is concentrated at a progressing interface [30, 31].

Nevertheless, tensile testing offers a conservative and controlled evaluation of the overall adhesive integrity across the entire bonded surface. Therefore, while the absolute values may differ from clinical conditions, the tensile test remains a valid method for comparing relative bonding performance among different tray–impression combinations.

The use of simplified cuboidal tray specimens instead of anatomically shaped trays represents a limitation of the present study. This design choice was primarily dictated by the requirements of tensile bond strength testing, which necessitates uniform geometry, parallel bonding surfaces, and controlled load application to ensure reliable and reproducible measurements. Although tray geometry has been shown to influence impression accuracy and

material distribution [19, 24], a standardized cuboidal geometry was intentionally employed to eliminate geometric variability, minimize confounding factors, and enable direct comparison of material- and surface-related effects on tensile bonding performance. A separate limitation of the present study is that only a single polyether adhesive was used for all impression materials. Since tray adhesives are generally material-specific [61, 63], this methodological choice may have introduced bias and influenced the relative bonding performance of the tested impression materials. Another limitation is that failure mode analysis (adhesive, cohesive, or mixed) was not performed in the present study. Since failure pattern evaluation may provide valuable insight into interfacial bonding mechanisms [67], its absence should be considered a limitation. Future studies incorporating failure mode analysis are recommended.

Finally, the present study was conducted under in vitro conditions. Clinical variables such as saliva or blood contamination of the tray, incomplete adhesive drying, or improper tray seating may reduce bond effectiveness. Future studies incorporating such variables, as well as different adhesive drying times or wet environments, would provide a more comprehensive assessment of tray–impression bonding under clinically realistic conditions.

5. Conclusion

Within the limitations of this in vitro study, it was concluded that surface treatment, printing technique, and impression material significantly influenced tensile bond strength. Among all methods, SLA-printed trays demonstrated more consistent bonding performance under the tested conditions, while the light-cured acrylic tray yielded the weakest retention. The use of tray adhesive improved bond strength. Regarding impression materials, polyether exhibited higher bond strength values in the present experimental setting, while c-silicone resulted in the weakest adhesion. These results provide practical guidance for optimizing tray–impression systems in clinical prosthodontic workflows.

List of abbreviations

CAD/CAM: Computer-aided design/Computer-aided manufacturing

C-silicone: Condensation silicone

FDM: Fused deposition modeling

DLP: Digital light processing

LCD: Liquid crystal display

A-silicone: Polyvinylsiloxane

SLA: Stereolithography

mSLA : Masked stereolithography

UDMA: Urethane dimethacrylate

PMMA: Polymethyl methacrylate

STL: Standard Triangle Language

AM: Additive manufacturing

VSXE: Vinylsiloxaneether

MPa: Megapascal

IPA: Isopropyl alcohol

Declarations

Ethics approval and consent to participate

Not applicable. This study did not involve human participants or animals.

Consent for publication

Not applicable.

Availability of data and materials

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

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Study Design and Conceptualization: Onur Topalan conceived the research idea and study objectives. Özgün Yusuf Özyılmaz contributed to refining the research design and ensuring the scientific relevance of the study.

Methodology: Onur Topalan designed the experimental protocol, while Özgün Yusuf Özyılmaz reviewed and optimized the methodology for accuracy and feasibility.

Investigation: Onur Topalan performed the majority of laboratory experiments, including the fabrication of custom trays and the tensile bond strength tests, while Özgün Yusuf Özyılmaz contributed to overseeing experimental procedures and validating critical steps.

Data Curation: Onur Topalan organized and prepared the raw data, while Özgün Yusuf Özyılmaz verified the datasets for accuracy and completeness.

Formal Analysis: Onur Topalan conducted the statistical analyses, with Özgün Yusuf Özyılmaz reviewing the results and ensuring correct interpretation.

Writing – Original Draft: Onur Topalan prepared the initial manuscript draft, including figures and tables, with contributions from Özgün Yusuf Özyılmaz particularly in structuring and developing the Introduction and Discussion sections.

Writing – Review & Editing: Onur Topalan and Özgün Yusuf Özyılmaz revised the manuscript for clarity, technical accuracy, and consistency with journal guidelines.

Supervision: Özgün Yusuf Özyılmaz provided academic supervision, guided the research process, and oversaw the final approval of the study.

Resources: Onur Topalan arranged and provided all necessary materials and equipment for the experiments.

Validation: Onur Topalan and Özgün Yusuf Özyılmaz verified the reproducibility of the experimental results and confirmed the validity of the conclusions.

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