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REVIEW

Economic aspects of 3D printing in restorative dentistry: a scoping review

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ABSTRACT

INTRODUCTION: The literature lacks a comprehensive evaluation of 3D printing in restorative dentistry, particularly regarding its cost-efficiency, material waste, production time, and environmental impact compared to traditional methods. This scoping review aims to systematically map current literature on the economic, environmental aspects, and clinical outcomes of traditional manufacturing compared to additive 3D printing methods for dental prosthesis materials.

EVIDENCE ACQUISITION: Following PRISMA-ScR guidelines, a literature search was conducted in March 2025 across PubMed, Embase, and Scopus. Studies investigating the costs of materials, labor, equipment, and production times of milled, pressed techniques, and 3D printing for crowns, bridges, and dentures were included. Data were independently extracted and analyzed, emphasizing cost-effectiveness, material waste, environmental impact, and clinical outcomes.

EVIDENCE SYNTHESIS: Out of 185 identified studies, 9 met the inclusion criteria, comprising in vitro, clinical trials, retrospective clinical studies, and comparative economic analyses. Evidence suggests that 3D printing exhibits lower material costs, lower initial investments, and less waste compared to the milling manufacturing method. While milling provides higher accuracy and faster production for single-unit restorations, 3D printing demonstrates superior cost-effectiveness, especially in high-volume scenarios, with notable reductions in material waste and environmental impact. Clinical performance between methods appears comparable in terms of patient satisfaction, retention, and performance, though milling achieves marginally higher precision. Furthermore, willingness to pay analysis favors milled prosthesis when it comes to patient preferences.

CONCLUSIONS: Despite milling being favored for cases demanding high precision and mechanical strength, 3D printing is advantageous for cost-efficiency and sustainability, particularly for large-scale or provisional restorations.

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KEY WORDS: Dental restoration, permanent; Cost-benefit analysis; Environment; Dental materials.

Introduction

Digital manufacturing has significantly transformed restorative dentistry, driven by the advancement of computer aided design/computer aided manufacturing (CAD/CAM) systems and three-dimensional (3D) printing technologies.[1, 2] Currently, the prevalent technique for producing dental restorations involves subtractive manufacturing, performed by automated milling units.[3, 4] However, this approach presents notable drawbacks, including material waste of the original ceramic block, tool wear, and extra energy consumption by sintering and crystallization processes required for ceramics.[5] In recent years, additive manufacturing (3D printing) has emerged as a promising alternative, offering the potential for reduced material waste and increased customization, supported by the growing availability of dental printing materials.[6-8]

Each manufacturing method has distinct advantages and limitations. Studies state that milling provides high mechanical reliability and precision but involves higher initial costs and greater material waste.[1, 4] On the other hand, 3D printing allows for more efficient material use and workflow flexibility, but still faces challenges related to the mechanical performance and aesthetics of certain restorative purposes.[3, 6, 8] Additional considerations include production time, number of clinical appointments, and laboratory or chairside complexity.[9] Although digital workflows can improve treatment efficiency and patient satisfaction, their broader implementation is often hindered by high capital investment, training requirements, and ongoing operational costs.[7, 9, 10]

Regarding methods to fabricate dental restorations, concepts of costs and economic evaluations are essential to determine the feasibility and efficiency of the process.[11] Direct costs include specific materials, such as resins or ceramics, and labor directly involved in fabrication, while indirect costs encompass overhead expenses like electricity, equipment maintenance, and administrative costs. Capital investment refers to the purchase of machines and 3D printers that will be used over many years, representing long-term expenditures. The ICER (Incremental Cost-Effectiveness Ratio) can help assess whether adopting new equipment or technologies provides meaningful improvements at justifiable costs.[12, 13] Cost-benefit analysis (CBA) compares all monetary costs and benefits of an intervention to assess whether it provides a positive net economic return.[14] Cost-effectiveness analysis (CEA), on the other hand, evaluates the relative costs and health outcomes of different interventions, often using metrics like QALYs (quality-adjusted life years), a generic measure of disease burden, including the quality and the quantity of life lived, to measure benefits. Cost-utility analysis (CUA) is a specific form of CEA that incorporates quality of life measures, such as QALYs, to assess how interventions impact both the quality and quantity of life. These analyses assist decision-makers in allocating resources efficiently to improve health outcomes, including aspects such as dental prostheses. All three approaches require specific data and metrics, such as clinical outcomes (*e.g.*, postoperative mortality, complication rates), utility weights, and costs, and face challenges like variability in data sources, including claims databases and published research, which can affect the robustness of the results.[13, 14]

Given the complexity of deciding the best manufacturing approach, it is crucial to use appropriate economic evaluation methods and evidence-based data, such as cost-benefit analysis, cost-effectiveness analysis, and cost-minimization strategies. These approaches, particularly when guided by frameworks such as the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) 2022 statement,[15] allow for a full comparison and reliable reports of costs and clinical consequences in the research field. Although several studies suggest that 3D printing may be more affordable, there remains a lack of in-depth evaluations that systematically integrate these metrics and address data to compare digital manufacturing techniques in dentistry.

In this context, the objective of this study was to conduct a scoping review of the literature, map and synthesize studies, economic variables, and results related to materials cost, production time, material waste, labor costs, and other relevant variables across traditional, subtractive, and additive manufacturing techniques for dental prostheses. This review aimed to provide evidence-based insights into which method offers greater cost-effectiveness, ultimately supporting better-informed clinical decision-making.

Evidence acquisition

This scoping review was conducted in accordance with the PRISMA-ScR guidelines.[16, 17] The protocol was made available on the Open Science Framework platform (https://osf.io/h4rc7/). The primary research question addressed was: What evidence is available regarding costs, production time, initial investments, and cost-effectiveness of different manufacturing methods, such as milling and heat-pressing techniques, compared to 3D printing, for dental prostheses (*e.g.*, inlays, crowns, bridges, and dentures)?

The PCC (Population, Concept, Context) framework was utilized to define the scope:

- population: dental prosthesis materials (*e.g.*, crowns, bridges, dentures) produced via 3D printing, traditional milling, and heat-pressed methods;
- concept: economic aspects including costs (materials, labor, equipment), production time, and measures of cost-effectiveness and comparative cost-analysis. A secondary focus was on the environmental impact, including material waste and energy consumption;
- context: the review was not limited to a specific geographic or clinical setting, aiming to encompass global literature.

The eligibility criteria

Peer-reviewed published studies that evaluated the cost-effectiveness of 3D printing for dental prostheses were included. Eligible studies had to report at least one of the following: production time, material costs, or overall manufacturing costs related to 3D printing. These data points were required to be compared with those of at least one conventional manufacturing method (*e.g.*, milling, heat-pressing) used for dental prostheses, regardless of prosthesis type, such as crowns, veneers, inlays, onlays, bridges, and dentures. The studies needed to focus specifically on restorative applications.

The exclusion criteria

Studies were excluded if they lacked extractable data on costs and production time, specifically, if the data were incomplete, unavailable, or not reported in a manner that allowed for quantitative analysis. Additionally, articles focusing on resin materials intended for non-dental applications, such as medical or industrial uses, were excluded. Studies employing experimental or non-commercial machines were excluded to ensure consistency with standard chair-side or lab-side practices. Moreover, studies limited to provisional prostheses and non-English publications were also excluded from the review.

Information on sources

The literature search was performed in March 2025 across three electronic databases: PubMed (MEDLINE), Embase, and Scopus. Search strategies were developed with a combination of

TABLE I.—*Search strategy made on 5th of March 2025 in online databases (PubMed, Scopus, and Web of Science).*

PUBMED=151 articles (05-03-2025)
(((((Printing, Three-Dimensional[MeSH Terms]) OR (3D printing)) OR (additive manufacturing)) AND ((((((Cost-Effectiveness Analysis[MeSH Terms]) OR (cost-effectiveness)) OR (cost reduction)) OR (material cost)) OR (production time)) OR (sustainability))) AND ((((((((Dental Materials[MeSH Terms]) OR (Dental Restorations, Permanent[MeSH Terms])) OR (restorative dentistry)) OR (single crowns)) OR (dental crowns)) OR (dental bridges)) OR (dentures)) OR (Denture, Partial, Fixed, Resin-Bonded[MeSH Terms]))) AND (((((milling) OR (CAD/CAM)) OR (computer-aided-machining)) OR (computer-aided-manufacturing)) OR (subtractive manufacturing))
SCOPUS=24 articles (05-03-2025)
(TITLE-ABS-KEY ((“Printing” OR “Three-Dimensional” OR “3D printing” OR “additive manufacturing”)) AND TITLE-ABS-KEY ((“Cost-Effectiveness Analysis” OR “cost-effectiveness” OR “cost reduction” OR “material cost” OR “production time” OR “sustainability”)) AND TITLE-ABS-KEY ((“Dental Materials” OR “Dental Restorations” OR “Permanent” OR “restorative dentistry” OR “single crowns” OR “dental crowns” OR “dental bridges” OR “dentures” OR “Denture, Partial” OR “Fixed” OR “Resin-Bonded”)) AND TITLE-ABS-KEY ((“milling” OR “CAD/CAM” OR “computer-aided-machining” OR “computer-aided-manufacturing” OR “subtractive manufacturing”)))
WEB OF SCIENCE=10 articles (05-03-2025)
(((ALL=((“Printing” OR “Three-Dimensional” OR “3D printing” OR “additive manufacturing”))) AND ALL=((“Cost-Effectiveness Analysis” OR “cost-effectiveness” OR “cost reduction” OR “material cost” OR “production time” OR “sustainability”))) AND ALL=((“Dental Materials” OR “Dental Restorations” OR “Permanent” OR “restorative dentistry” OR “single crowns” OR “dental crowns” OR “dental bridges” OR “dentures” OR “Denture, Partial” OR “Fixed” OR “Resin-Bonded”))) AND ALL=((“milling” OR “CAD/CAM” OR “computer-aided-machining” OR “computer-aided-manufacturing” OR “subtractive manufacturing”))

keywords related to dental prostheses, manufacturing technologies, and economic outcomes (including "cost," "cost-effectiveness," "investment," "production time," "labor," "material costs," and "environmental impact"). The detailed search syntax is provided in Table I.

Selection of sources of evidence

The evidence synthesis, original articles were systematically collected, and duplicates were identified and removed using the Rayyan QCIR platform (Qatar Computing Research Institute, Doha, Qatar). Two independent, blinded researchers (M.G.P. and J.P.M.T.) initially screened titles and abstracts to assess eligibility criteria (Phase 1). Records were classified as included, excluded, or uncertain. Subsequently, full texts of the included and uncertain articles were reviewed by the same researchers (Phase 2). When disagreements occurred during the screening process, the researchers discussed resolving discrepancies. When consensus was not reached, a third reviewer (C.J.K.) was consulted to resolve disagreements. Full texts of selected articles were then retrieved and assessed against predefined inclusion criteria.

Charting the data

Data extraction of all identified records was performed independently by two reviewers using a standardized form. A meeting was carried out to calibrate the data extraction, capturing the important information such as authors, year of publication, study design; type of technology used (3D printing *vs.* traditional method); materials and design used for restorations; costs of materials (per unit, per restoration; per material); equipment costs (printer *vs.* traditional method, initial investment and/or annual investment); time for production (time taken for manufacturing, finishing; labor hours); durability and clinical outcomes; methodology used for analysis (cost-benefit analysis, cost-effectiveness analysis); reporting guidance for health economic evaluation like Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement; material waste (in weight or percentage); study main findings. The analysis consisted of a comprehensive description of the primary characteristics of the included studies, synthesized from the collected data. A risk of bias was not conducted because scoping reviews aim to provide an overview of existing evidence. This approach aligns with the methodologies proposed for scoping reviews.[16, 17]

To enable consistent comparison of economic data across studies, all reported costs were standardized to 2025 U.S. dollars (USD). This process involved two steps: adjustment for inflation and currency conversion. First, inflation correction was performed based on the year associated with each monetary value. When the year of cost assessment was explicitly reported in a study's methodology or results, it was used for inflation adjustment; otherwise, the year of publication was assumed as a proxy. Inflation rates for the USD, euro (EUR), and Swiss franc (CHF) were sourced from In2013Dollars.com, a tool that compiles official consumer price index (CPI) data from the U.S. Bureau of Labor Statistics and Eurostat.

Following inflation correction, all costs were converted to USD using consistent exchange rates to reflect currency values in 2025. For amounts originally reported in euros, a conversion rate of 1 EUR=1.08 USD was applied, based on the official exchange rate as of April 1, 2025. For Swiss francs, a rate of 1 CHF=1.10 USD was used, as of March 2, 2025. All exchange rates were obtained from Xe Currency Converter, a reliable source of real-time global market rates. These methodological steps ensured accuracy in comparing cost data across different currencies and timeframes.

Evidence synthesis

The flow chart of the study selection is represented in Figure 1. From the total of 185 studies detected, 36 were selected for full-text analysis. After reading the manuscripts, 9 studies were included and 27 studies were excluded, as these studies did not match the eligibility criteria.

Figure 2 illustrates a representative set of technologies to be evaluated in this analysis.

Characteristics of included studies

Different assessment methodologies were employed to assess the effectiveness of the manufac-

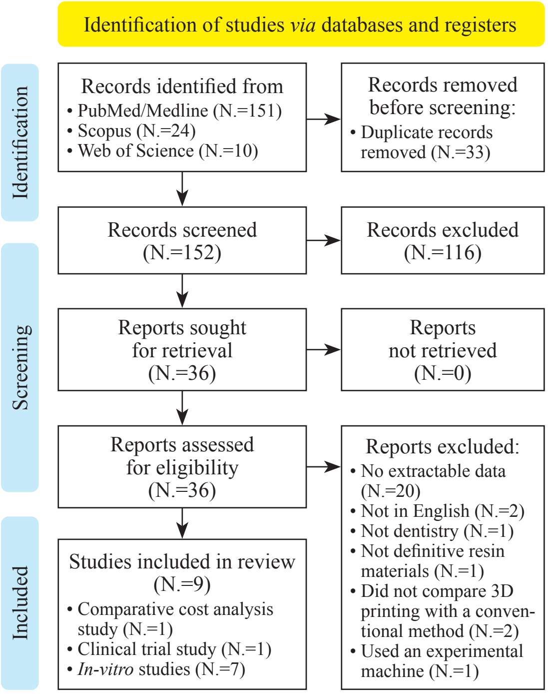

Figure 1.—Flow diagram of studies included after screening in databases and eligibility assessment.

turing methods: a retrospective study (N.=1),[18] a double-blind randomized crossover clinical trial study (N.=1),[19] a comparative cost-analysis study (N.=1),[7] and *in vitro* studies (N.=6).[3, 8, 20-23] One study evaluated costs using a cost-minimization analysis framework by using the generalized estimated equation GEE methodology,[7] one used willingness-to-pay analyses to evaluate patient preferences.[19] Just one study used the CHEERS framework to report the economic evaluation,[7] and one study used the CONSORT (Consolidated Standards of Reporting Trials) framework to report clinical trials.[19] The currencies used in the studies included were Swiss Franc (N.=1),[19] Euro (N.=3),[3, 18, 22] USD-dollar (N.=2),[7, 8] and three studies did not evaluate costs but time efficiency[20, 23] and/or waste material.[21] The most prevalent 3D printing methodology evaluated was digital light processing (DLP) (N.=3),[18, 19, 23] liquid crystal display technique (LCD) (N.=2),[8, 22] stereolithography (SLA) (N.=1),[20] lithography-based ceramics manufacturing (LCM) (N.=1),[23] multi-resin additive manufacturing (MRAM) (N.=1),[21] and direct ink writing (DIW) (N.=1).[3] The comparators were CAD/CAM milling machines (N.=8),[3, 7, 8, 18, 19, 21-23] stocked teeth (N.=1),[7] cast prosthesis,[20] heat-pressed (N.=1),[23] and heat-pressed with 3D printed template (N.=1).[23] The manufacturing techniques assessed encompassed milling (N.=8),[3, 7, 8, 18, 19, 21-23] heat-pressed methods (N.=2)[7, 23] and cast technique (N.=1)[20] as traditional methods, and 3D printing (N.=9).[3, 7, 8, 18-23] All of them compared 3D printing technologies with one traditional method. Complete conventional removable dental prostheses (CRDPs) were the most frequently evaluated design (N.=5),[7, 18-21] followed by other restorations, including crowns (N.=1),[22] onlays (N.=1),[8] ultra-thin oclusal veneers (N.=1),[23] and discs (N.=1).[3] Poly(methyl methacrylate) (PMMA) (N.=6)[7, 8, 18-21] was the most evaluated material across studies, along with other materials such as resin composite (N.=2),[8, 22] lithium disilicate (N.=2),[8, 23] and zirconia (N.=1).[3]

The evaluation of dental manufacturing methods included various critical factors. Srinivasan *et al.*[19] evaluated time, material waste,

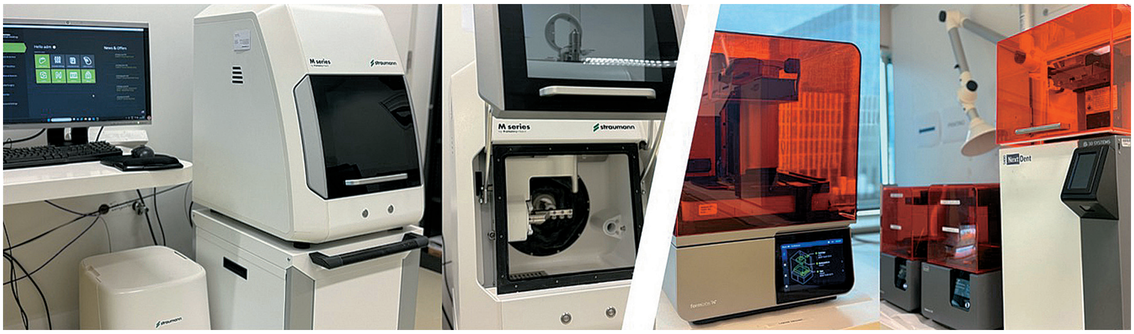

Figure 2.—Digital manufacturing methods in dentistry: CAD/CAM subtractive milling process, and additive 3D printing technology. The images depict representative equipment used in each method.

and accuracy, oral health-related quality of life (OHRQOL), Maximum voluntary bite force (MBF), chewing efficiency (CE), Clinician's denture quality assessment (CDQE), Patient's final choice of the complete removable dental prostheses, willingness-to-pay analysis (WTPA). Lo Russo *et al.*[7] compared clinical and laboratory costs. Jiang *et al.*[21] evaluated time, material waste (g), and accuracy. Teegen *et al.*[3] evaluated mechanical properties, cost efficiency by reporting time and costs. Casucci *et al.*[18] investigated clinical effectiveness (laboratory costs, chairside time, follow-up time, and number of follow-ups), bite force, masticatory performance, and OHIP-14 scores. Paqué *et al.*[23] assessed load-bearing capacity, marginal and internal accuracy, and time efficiency. Daher *et al.*[8] evaluated marginal integrity, costs, production time, and material waste. Chen *et al.*[20] evaluated the trueness and time efficiency of conventional and digital methods. No-cortes *et al.*[22] investigated trueness, 3D deviation, production time, and costs of CAD-CAM resin single crowns produced via milling and 3D-printing methods (Supplementary Digital Material 1: Supplementary Table I).[3, 7, 8, 18-23]

Cost analysis and economic implications

The economic evaluation across the included studies consistently indicates that 3D printing tends to be more cost-effective than traditional milling, especially when considering material expenses, waste reduction, initial investment costs, and average annual cost (Figure 3, 4, 5).[3, 7, 8, 18, 22]

Regarding cost analysis between manufacturing methods, Daher *et al.*[8] highlight that the consumables cost per crown for 3D printed

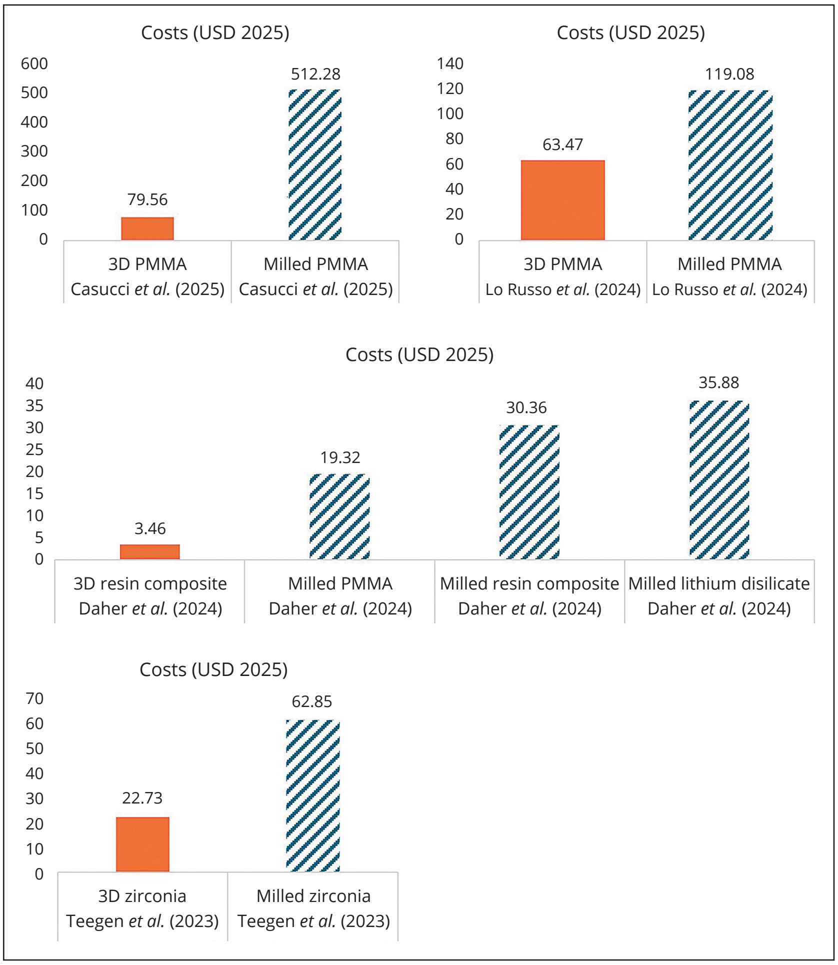

Figure 3.—Costs in USD for 2025, illustrating the increase in milling costs within each study. Values were adjusted for inflation and currency fluctuations based on each report, considering unit costs, material expenses, and labor, according to the restoration design and materials used. PMMA: polymethyl methacrylate.[3, 7, 8, 18]

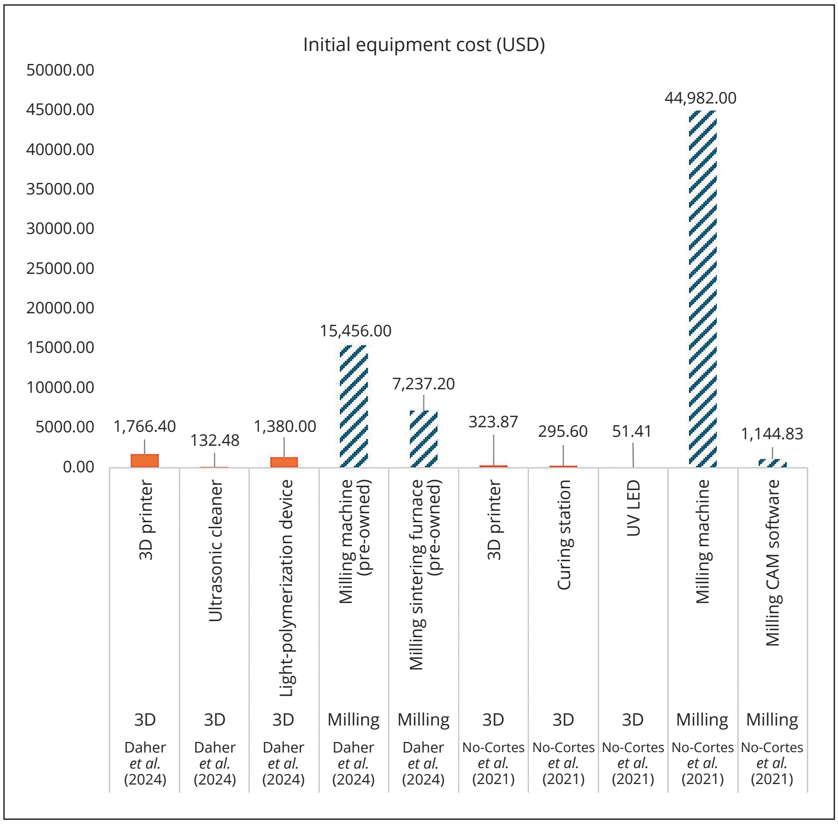

Figure 4.—Initial equipment costs (USD 2025) across studies for different manufacturing methods used in prostheses. The figure compares the initial investments required for each technology, illustrating their financial variability and investment trends over time.[8, 22]

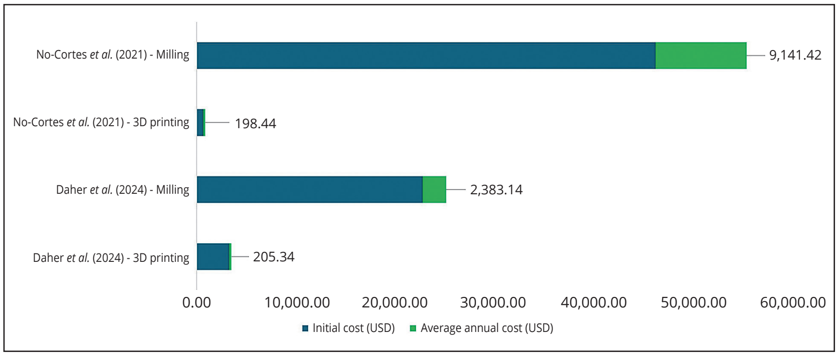

Figure 5.—Average annual and initial costs according to the manufacturing method and the reported studies. The annual average costs were calculated by dividing the total raw investment costs by the assumed five-year lifespan of each device, providing an estimate of the yearly depreciation expense for economic evaluation purposes.[8, 22]

resin composite material is significantly lower at $3.46 compared to milled options, where PMMA milled costs $19.32, resin composite milled is $30.36, and lithium disilicate milled is $35.88. Casucci *et al.*[18] found that the milling manufacturing method had higher costs, $512.28±$169.40, compared to 3D printing, $379.56±154.23 (P=0.0496). Besides, Casucci *et al.*[18] found that laboratory costs were statistically lower for digital dentures, $445.92 *vs.* $540.52, P=0.0059) compared to conventional dentures. Teegen *et al.*[3] found a total cost of $22.73 per crown for 3D printing zirconia by DIW technique compared to $62.85 per crown for the milling approach.

Regarding initial investment costs for 3D printing, the total amount is considerably lower ($3278.88 for the printer, cleaner, and polymerization device) compared to the milling system costs ($20,650 for a used milling machine and sintering furnace).[8] The average annual costs further emphasize the cost-effectiveness of 3D printing, which totals $205.34, while milled methods (PMMA and resin composite) are $966.00, and lithium disilicate milling manufacturing is $1,417.14, considering the crystallization furnace. According to No-Cortes *et al.*[22] the capital costs for equipment substantially influence overarching economics. The initial expense for a 3D printer set-up (about $670.88) is markedly lower than that for a milling system (over $46,126.83), including the necessary sintering and post-processing units. This lower barrier to entry makes 3D printing particularly attractive for smaller practices or laboratories to implement digital workflows without high capital outlay. Patient preference and willingness to pay, as reported in Srinivasan's *et al.*[19] study, affect perceived value. Milled dentures were favored by patients willing to pay more (Milled $3872.00±1466.34 *vs.* 3D Printed $3137.93±935.55),[19] which can influence pricing strategies and economic implications (Supplementary Digital Material 2: Supplementary Table II).[3, 7, 8, 18-23]

Time efficiency and production time

The efficiency in time is an essential factor in cost-effectiveness; the findings across studies can be visualized in Figure 6.[7, 8, 20, 22] Analysis of manufacturing times across studies reveals that, within each study, additive manufacturing (3D printing) generally requires longer fabrication times for dental restorations compared to subtractive manufacturing (milling). While 3D printing offers lower per-unit costs, production speed can vary depending on workflow scale and complexity. Daher *et al.*[8] found that while milling methods are faster for small batches (up to 8 restorations), 3D printing becomes advantageous for larger productions, reducing overall labor time. For 50 restorations, the production time for 3D printing was 64 min for printing, 10 min for cleaning, and final polymerization of 8 min; in contrast milling method was 10 min per restoration for grinding (composite, lithium disilicate, and PMMA) and 24 min for crystallizing lithium disilicate (for up to 2 restorations). Jiang *et al.*[21] found that the speed of the additive manufacturing multi-resin method is 3 times faster than CAD/CAM for complete dentures. Teegen *et al.*[3] findings are 30 min for printing by the DIW technique, with a total manufacturing time of 34 min per crown; however, the time for the milling manufacturing method was not reported. Paqué *et al.*[23] found that CAD/CAM milling is the most efficient fabrication method (67 min), compared to the 3D printing process, 701±8 min for fabricating lithium disilicate ultra-thin

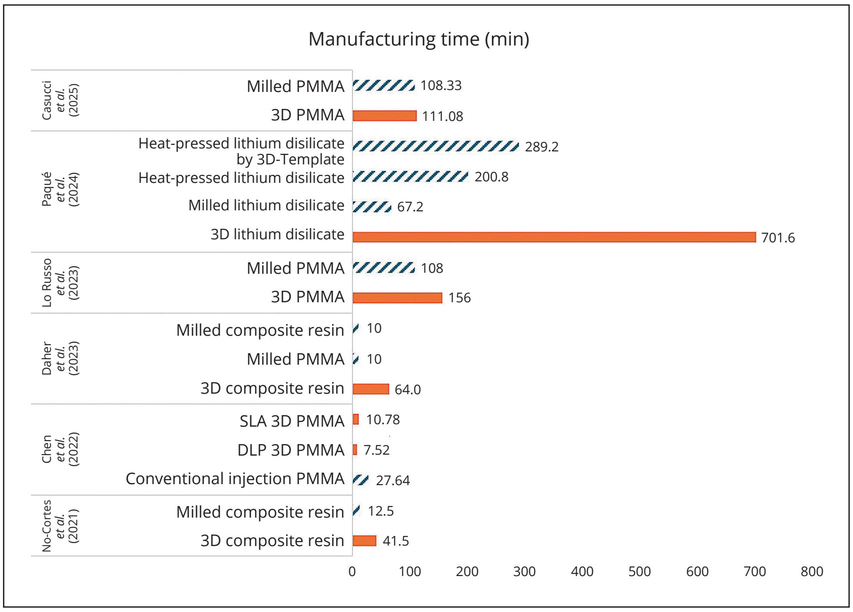

Figure 6.—Manufacturing time in minutes (min) per prosthesis type, arranged from the most recent to the oldest study. The figure compares method efficiency, highlighting more and less time-consuming manufacturing techniques for economic and operational assessment.[7, 8, 20, 22]

occlusal veneers; also, more efficient than the heat-pressed method. According to No-Cortes *et al.*,[22] mean times required by the milling device were 13 min, and by the 3D printer, it was 42 min to produce only one resin single crown. Chen *et al.*[20] found that conventional methods require a total time of 28 min for manual post-processing after manufacturing, which is longer than the 3D Printing DLP method, with a total time of 8 min, considering digitalization, trimming, and finishing time, and the SLA method, 11 min. Lo Russo *et al.*[7] found a manufacturing time in hours of 1.4 h for 3D printing compared to 2.2 h for milling for denture-based resins, with a completely digital workflow using intraoral scanners.

Casucci *et al.*[18] evaluated chairside and follow-up time. According to the findings, digital dentures significantly cut chairside time (154 min for digital *vs.* 218 min for conventional; $P<0.0001$), which can reduce labor costs and improve workflow efficiency. However, regarding follow-up time and number of follow-ups, there were no statistical differences between the digital and conventional fabrication methods. Srinivasan *et al.*[19] evaluate the time spent to perform clinical adjustments in completed removable dental prostheses (CRDPs) after manufacturing methods, suggesting more extensive adjustments or ongoing care requirements in aftercare settings for 3D-printing (17 min) compared to the average clinical time per visit for milling (11 min) during planned recall visits. Srinivasan *et al.*[19] findings show that 3D-printed CRDPs require more clinical visits for adjustments; clinical time ($P=0.0003$) and higher adjustment costs ($P=0.021$) than milled CRDPs, which could offset some cost benefits through higher maintenance expenses.

Material waste and environmental cost savings

Material waste is a critical factor affecting overall costs and sustainability. Jiang *et al.*[21] found that 3D printing reduces material waste by approximately 87%, 20 g *versus* 434 g for milling, 14 times less material waste than CAD/CAM, resulting in lower acquisition costs and environmental impact. Daher *et al.*[8] found a waste factor for 3D printing being 73% and for a subtractive method of 90% (Figure 7).[8, 21] Lower waste production translates to material savings, enhancing cost-effectiveness. Reduction in waste not only decreases resource consumption but also diminishes waste disposal costs and contributes to environmental sustainability.

Clinical-related outcomes

Srinivasan *et al.*[19] found that milled and 3D-printed complete removable dental prostheses (CRDPs) demonstrated comparable clinical performance regarding patients' denture satisfaction, patients' oral health quality of life, final choice, clinician's denture quality assessment, chewing efficiency, and maximum voluntary bite force ($P>0.05$) between the two CRDPs groups, being both valid treatments for edentulous patients. However, 3D-printed dentures required more maintenance, adjustments, and incurred higher aftercare costs. Additionally, patients expressed lower willingness-to-pay for 3D-printed dentures compared to milled ones.

Casucci *et al.*[18] observed no statistically significant differences in bite force, masticatory performance, and OHIP-14 scores between digital complete dentures and conventional dentures ($P>0.05$). Digital complete dentures significantly reduced chairside time compared to conventional dentures ($P<0.0001$) and costs ($P=0.0059$). In the

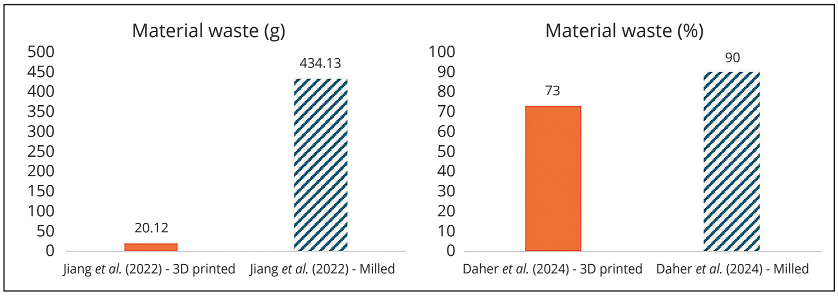

Figure 7.—Material waste in grams (g) and percentage (%) across studies.[8, 21]

matter of comparison between milled and 3D-printed dentures, Casucci *et al.*[18] found no significant differences in clinical outcomes between the two fabrication methods, suggesting equivalent performance. Besides, 3D printing allows a substantial reduction in costs compared to the milling fabrication methods ($379.56±$154.23 *vs.* $512.28±$169.40).

According to Teegen *et al.*[3] DIW-printed zirconia demonstrates promising mechanical properties with a biaxial strength above 822 MPa, comparable to cast and milled zirconia.

Lo Russo *et al.*[7] results show that 3D-printed dentures demonstrated superior manufacturing efficiency, less material waste, shorter production time, and comparable or better mechanical strength, though slightly less accurate than milled versions. Clinically, both are valid options, with 3D-printed dentures being a more sustainable and cost-effective choice for large productions. According to Jiang *et al.*,[21] using a laboratory-developed multi-resin additive manufacturing (MRAM) system to create complete dentures, the printed dentures are fabricated three times faster and generate 14 times less material waste than CAD/CAM systems, with a 35.08% reduction in inaccuracy. The use of a tenon joint significantly increases bending strength by approximately 32%, enhancing the durability of the denture, while the overall accuracy, though slightly less precise than milled options, remains clinically acceptable.

Regarding trueness analysis, Chen *et al.*[20] found that digital 3D printing methods produced more accurate dentures than the conventional method. Digital duplication methods (cone-beam computed tomography [CBCT], laboratory scanner, 3D printing) produced dentures with similar trueness; however, conventional duplication was less accurate. Digital methods were more time-efficient and less labor-intensive, with DLP 3D printing showing shorter finishing times compared to SLA.[20]

Paqué *et al.*[23] found no significant differences across groups comparing lithium disilicate veneers by distinct methods (Milled, 3D-Printed, and Heat-Pressed) regarding load bearing capacity (initial and maximum load for failure), P=0.5795. For marginal accuracy, milled and heat-pressed methods had discrepancies of <43 µm. 3D-printed veneers showed larger marginal gaps but minor internal discrepancies (P<0.001). Milled, heat-pressed, and 3D-printed lithium disilicate veneers exhibited high load-bearing capacity (>1687 N) and acceptable marginal fit. Milled and heat-pressed veneers had smaller marginal gaps, while 3D-printed veneers showed slightly larger gaps but had comparable internal accuracy. Milling was faster, but 3D printing was more cost-effective overall, despite longer processing times.[23]

Daher *et al.*[8] reported no statistical differences for marginal adaptation (%CM) before fatigue of milled composite (75.9%), 3D printed composite (69.8%), and milled lithium disilicate (63.1%), while milled PMMA (45.1%) was statistically worse from the 3 other groups (milled PMMA *versus* milled composite P<.001, PMMA *versus* 3D P=.001, PMMA *versus* milled lithium disilicate P=.002). For the analysis after fatigue, the milled composite (68.5%) presented the highest mean %CM, and the milled PMMA (20.5%) showed the lowest values. No statistically significant difference was found between 3D resin composite (44.7%) and milled lithium disilicate (43.7%) (P=0.45). 3D printed resin composite onlays demonstrated similar marginal integrity before and after fatigue compared to milled resin composite and lithium disilicate restorations, with digital groups showing better accuracy than conventional ones. They were also more time-efficient and cost-effective, especially when producing larger quantities, and showed comparable clinical performance with better efficiency and lower costs.[8]

The main clinical outcomes from No-Cortes *et al.*[22] indicate that milled crowns demonstrate smaller deviations and higher precision, particularly at the cervical margin, and are faster to produce, making them suitable for chairside workflows. In contrast, 3D-printed crowns, although showing slightly greater deviations regarding trueness and accuracy, especially at margins, are significantly more cost-effective and have a higher production rate, making them a viable option for high-volume or interim restorations.

Overall, milling offers superior accuracy and speed, while 3D printing provides a more economical and efficient alternative for clinical use (Supplementary Digital Material 3: Supplementary Table III).[3, 7, 8, 18-23]

Discussion

This scoping review aimed to explore the potential of 3D printing technologies in reducing costs associated with dental treatments without compromising quality. Significant differences in cost-effectiveness between milling, conventional, and 3D printing in the production of dental prostheses were found among studies. The findings of this review suggest that 3D printing does offer several advantages in terms of cost and efficiency, though the complete survey varies based on different studies.

Data from Casucci *et al.*[18] supported the cost-effectiveness of digital dentures, showcasing lower laboratory costs for 3D printed solutions. Daher *et al.*[8] underlined the financial advantages of 3D printing in the long run and in initial investment costs. Srinivasan *et al.*[19] indicated a significant difference in willingness-to-pay costs, with milled dentures being willing to pay more ($3872.00) compared to 3D printed options ($3137.93), but noted the higher clinical time required in the 3D printing process. Jiang *et al.*[21] emphasized the superiority of the 3D printing method in speed and material waste reduction when compared to CAD/CAM systems. Teegen *et al.*[3] provided compelling evidence concerning overall cost savings, showing that the DIW (Direct Ink Writing) 3D printing technique could save substantially per crown compared to traditional milling methods, although an innovative manufacturing method. The studies generally suggest that 3D printing is becoming a cost-competitive alternative to milling for various dental restorations, especially when considering the material waste and equipment investment.[3, 7, 8, 22] Regardless of the difference in digital methods, both 3D printing and milling often show advantages over conventional analog methods,[18, 20] which was also reported in a recent review evaluating digital CAD/CAM milling and conventional manufacturing methods.[10]

3D printing often demonstrates lower material costs per unit/restoration compared to milling, mainly due to reduced material waste.[7, 8, 21] Initial equipment costs for 3D printers are often lower than those for milling machines.[7, 8, 19] Studies comparing 3D printed dentures to milled ones have found that 3D printing can lead to substantial cost reductions in laboratory expenses.[18] No-Cortes *et al.*[22] compared the production of single crowns using LCD 3D printing and 5-axis milling. The results indicated that LCD 3D printers offer lower costs and higher production rates, which are especially relevant for clinics with high demands for interim single crowns.[22] The total raw cost for 3D printing was $991.19, with a cost per unit of approximately $1.99.[22] In contrast, the milling process involved higher total raw costs of $45,701.71, leading to a cost per crown of about $13.66. This could make dental prostheses more affordable for the patient as well, considering the significantly lower cost per unit with 3D printing compared to milling.[22]

Regarding production time for single restorations or small batches, milling can sometimes be faster.[8, 24] For larger production quantities, 3D printing can be more time-efficient.[8] Chen *et al.*[20] states that digital workflows, especially with 3D printing, reduce labor time compared to conventional methods. Besides, digital dentures (both 3D printed and milled) often require less chairside time compared to conventional dentures.[18] It is important to emphasize, however, that conventional denture fabrication primarily involves manual, laboratory-based techniques, including impression taking, wax try-ins, and acrylic processing.[18] No-Cortes *et al.*,[22] evaluating processing times showed a significant difference; milling required an average of 13 min per resin crown, whereas 3D printing took approximately 42 min, with statistically significant differences (P=0.001), which can be explained by all the post-processing steps required for achieve the final aspect of the resin composite crown using the printing approach *versus* subtractive milling, which does not requires crystallization/sintering. When it comes to milling ceramics, the difference would be smaller considering firing and cooling, however, this study reported only resin composite metrics for the manufacturing methods.[22]

For durability, clinical outcomes, and accuracy, some studies found comparable marginal adaptation between 3D-printed resin composites and milled resin composites/lithium disilicate before fatigue.[8] After fatigue, 3D printed resin composites were comparable to lithium disilicate. Digital methods, including 3D printing, generally offer better trueness and accuracy compared to conventional methods in denture duplication.[20] Daher *et al.*[8] assessed marginal adaptation before and after fatigue, finding differences between materials, with PMMA performing less favorably. Casucci *et al.*[18] used the OHIP-14 index and found no significant differences in patient-reported oral health impacts between milled and 3D-printed dentures. The study by No-Cortes *et al.*[22] also noted that milling provided higher precision and smaller deviations than 3D printing, although at a higher cost and lower throughput. Overall, milling produced crowns with marginally higher accuracy but was less cost-efficient, making 3D printing a viable alternative for high-volume clinical scenarios where cost is prioritized over the highest precision.[22] There may be differences in the clinical lifetime of milled *versus* printed prostheses, as studies show milled composites tend to have higher mechanical strength and fatigue resistance than printed resins.[25, 26] However, when materials are identical, these differences are likely minimal. Compared to ceramics, which exhibit superior mechanical properties and long-term stability,[27] digital and milled resin products can vary greatly in durability due to differences in microstructure and fabrication quality.

When speaking of economic models and frameworks, some studies explicitly used economic models such as cost-effectiveness analysis, cost-benefit analysis, or cost-minimization analysis.[7, 8] The studies analyzed demonstrate that both 3D printing and milling are viable manufacturing methods for dental prostheses, with each offering distinct benefits. Notably, milling consistently provides higher precision and superior mechanical properties, especially for single crowns and ultrathin veneers, as highlighted by No-Cortes *et al.*[22] and Paqué *et al.*[23] Milling also tends to require fewer adjustments post-fabrication, contributing to greater clinical reliability and long-term durability.[21] Moreover, certain cases, such as single crowns and ultrathin veneers, are produced more quickly via milling after initial digital setup, due to their higher accuracy and streamlined workflow efficiency.[22, 23]

In addition to technical advantages, willingness to pay data indicate that patients and clinicians often favor the higher precision and robustness of milled restorations compared to 3D-printed options.[19] However, these benefits come with higher material and equipment costs, making milling less cost-effective in certain scenarios but justified by expectations of better long-term clinical performance. Conversely, 3D printing tends to excel in cost-effectiveness for less complex restorations, showing comparable clinical outcomes, such as marginal adaptation, bite force, and patient satisfaction, to milled restorations.[8, 18] Studies indicate that 3D printing can significantly reduce costs, particularly with advancements in digital workflows, making it suitable for high-volume or provisional restorations. Nonetheless, in cases demanding high precision and mechanical strength, milling remains the preferred choice due to its reliability, and time-efficiency for specific prostheses.

Regarding material waste, both the percentage data and absolute mass show that 3D printing is more efficient, using less raw material and generating less waste. This supports claims that 3D printing is a more sustainable and material-efficient method for prosthetic fabrication. To estimate the efficiency, the material used for the final product, the following formula can be used: Yield=100%-Material Waste (%). According to the findings from Daher *et al.*[8] 3D printing presents 27% efficiency, and milling exhibits 10% efficiency (3D printing: 73% waste and milling: 90% waste). Even though we don't know the initial material mass, the pattern is clear and consistent across both studies: Milling generates significantly more waste than 3D printing. According to Jiang *et al.*,[21] 3D printing presents 20.12g of waste, and milling 434.13g of waste when it comes to acrylic-based resins for complete dentures. Milling produces over 20× more waste in absolute terms.

Despite the promising outcomes reported, limitations must be acknowledged. There were few studies available regarding economic comparisons; furthermore, they used varied methodologies and materials under evaluation, which can complicate direct comparisons across the literature. Moreover, while the cost-effectiveness of 3D printing is highlighted, the majority of the studies didn't use the CHEERS guideline. This tool could minimize the risk of bias in reporting and performing the studies. It is important to highlight that scoping reviews don't test hypotheses and do not measure the effectiveness directly; however, it does systematically map the current literature available. In this study, we explore costs, time, and manufacturing methods to guide future decision-making based on scientific data as a secondary economic evaluation. This scoping review takes into consideration aspects such as patient outcomes and satisfaction, which have not been extensively covered with costs and time benefits of each manufacturing method in the existing literature, to the best of the author's knowledge. Furthermore, there are some reviews reporting the cost-effectiveness of 3D printing, however, they do not accurately address values and costs. Future research should focus on larger-scale studies that compare patient outcomes associated with both treatment methods to provide a more comprehensive assessment of their cost-effectiveness, aesthetics, and long-term behavior. There is also a strong need for investigations into the long-term sustainability of both practices beyond material waste, potentially examining the lifecycle impacts of dental prosthetics.

Conclusions

The conclusions that can be drawn from the review are as follows:

- 3D printing tends to be more economical than milling, especially considering lower material costs, reduced waste, and initial investment expenses. This makes it particularly suitable for high-volume or provisional prostheses for all types of design;
- milling generally provides higher precision and mechanical reliability, making it the preferred method for final, high-precision restorations such as crowns and veneers;
- both techniques improve workflow efficiency in digital dentistry, but milling might be faster for small batches, whereas 3D printing offers advantages in large-scale production;
- clinical performance and patient satisfaction between the two methods are comparable, although milling might need fewer adjustments post-fabrication;
- the choice between milling and 3D printing should be based on specific clinical requirements, considering factors such as precision needs, production volume, cost constraints, and sustainability goals.

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Conflicts of interest
The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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Authors' contributions
Maria G. Packaeser: conceptualization, literature search, data curation, writing – original draft; Amanda Dal Piva: methodology, writing – review and editing; Cornelis Johannes Kleverlaan: methodology, writing – review and editing, validation; João P. Mendes Tribst: conceptualization, supervision, methodology, writing – review and editing, final approval. All authors read and approved the final version of the manuscript.

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Supplementary data
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