Research, Society and Development, v. 12, n. 12, e126121243986, 2023
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v12i12.43986

Mechanical, chemical and biological properties of PLA 3D printer: A systematic review

Propriedades mecânicas, químicas e biológicas da impressão 3D do PLA: Uma revisão sistemática

Propiedades mecánicas, químicas y biológicas de la impresíon 3D de PLA: Una revisíon sistemática

Received: 11/02/2023 | Revised: 11/17/2023 | Accepted: 11/18/2023 | Published: 11/20/2023

Heloisa Domingues Lodi
ORCID: https://orcid.org/0009-0006-3225-8075
Universidade de São Paulo, Brazil
E-mail: heloisa.domingues.lodi@usp.br
Murilo Rodrigues de Campos
ORCID: https://orcid.org/0000-0001-8400-5332
Universidade de São Paulo, Brazil
E-mail: murilordc@usp.br
Andréa Cândido dos Reis
ORCID: https://orcid.org/0000-0002-2307-1720
Universidade de São Paulo, Brazil
E-mail: andreare73@yahoo.com.br

Abstract
The aim of this systematic review is to evaluate, through the in vitro studies included, whether PLA has mechanical, chemical and biological properties that enable its clinical use in dentistry. An electronic search was carried out in the Pubmed, Science Direct, Embase and Scopus databases containing the terms "polylactic acid", "3D printing","biomaterials","dental materials", dental prosthesis and dentistry. The objective of the inclusion criteria was to cover articles written and published in English that focused on the use of PLA in the field of dental materials and biomaterials printed using the 3D method. Any articles that did not focus on the study of PLA polymer, as well as systematic reviews, book chapters, abstracts, letters and conference articles were excluded. 1814 references were found, which after applying the exclusion criteria resulted in the final inclusion of 13 articles for the review. Based on the studies included in this systematic review, it is possible to conclude that 3D printed PLA used as a dental material and biomaterial presents favorable mechanical, chemical and biological properties that indicate its potential clinical use.
Keywords: Polylactic acid-polyglycolic; Dentistry; Printing; Systematic review.

Resumo
A presente revisão sistemática tem como objeto avaliar através dos estudos in vitro incluídos se o PLA (ácido polilático) apresenta propriedades mecânicas, químicas e biológicas que viabilizem sua utilização clínica na odontologia. Uma busca eletrônica foi realizada nas bases de dados Pubmed, Science Direct, Embase e Scopus contendo os termos ‘’ácido polilático’’ e ‘’impressão 3D’’ e ‘’biomateriais’’ e ‘’materiais dentários’’e prótese dentária e odontologia. O critério de inclusão foi abranger artigos escritos e publicados em inglês que continham como assunto o uso de PLA no campo de materiais odontológicos e biomateriais impressos pelo método 3D. Quaisquer artigos que não tinham como foco o estudo do polímero PLA, bem como revisões sistemáticas, capítulos de livros, resumos, cartas e artigos de conferências foram excluídos. Foram encontradas 1814 referências, que após a aplicação dos critérios de exclusão resultaram na inclusão final de treze artigos para a revisão. Com base nos estudos incluídos na presente revisão sistemática é possível concluir que o PLA impresso em 3D utilizado como material odontológico e biomaterial apresenta propriedades mecânicas, químicas e biológicas favoráveis que indicam seu potencial utilização clínica.
Palavras-chave: Copolímero de ácido poliláctico; Odontologia; Impressão tridimensional; Revisão sistemática.

Resumen
El objetivo de esta revisión sistemática es evaluar, a través de los estudios in vitro incluidos, si el PLA (ácido polilactico) tiene propiedades mecánicas, químicas y biológicas que permitan su uso clínico en odontología. Se realizó una búsqueda electrónica en las bases de datos Pubmed, Science Direct, Embase y Scopus que contenían los términos "ácido poliláctico" y "impresión 3D" y "biomateriales" y "materiales dentales" y prótesis dentales y odontología. El criterio de inclusión fue cubrir artículos escritos y publicados en inglés que se centraran en el uso de PLA en el campo de los materiales y biomateriales dentales impresos mediante el método 3D. Se excluyeron todos los artículos que no se centraran en el estudio del polímero PLA, así como revisiones sistemáticas, capítulos de libros, resúmenes, cartas y

artículos de congresos. Se encontraron 1814 referencias, que luego de aplicar los criterios de exclusión dieron como resultado la inclusión final de trece artículos para la revisión. Con base en los estudios incluidos en esta revisión sistemática, es posible concluir que el PLA impreso en 3D utilizado como material y biomaterial dental presenta propiedades mecánicas, químicas y biológicas favorables que indican su potencial uso clínico.
Palabras clave: Copolímero de ácido poliláctico; Odontología; Impresíon tridimensional; Revisíon sistemática.

1. Introduction

Polylactic acid (PLA), as it is produced from non-toxic renewable raw materials, such as corn and sugarcane, is widely used as an environmentally sustainable biopolymer (Su et al., 2019; Singhvi et al., 2019; Murariu & Dubois 2016).

In addition to being a biologically based material, PLA has good mechanical properties, such as high tensile strength and good flexural strength (Singhvi et al., 2019; Hamad et al., 2015), which are fundamental to its application in the health sector.

Chemically, the largest fraction of PLA is constituted by the poly-L-LA (PLLA) molecule, obtained by the polymerization of lactic acid (LA) - (CH 3 CHOHCOOH) (Su et al., 2019). PLLA, due to its excellent biocompatibility, gives PLA another advantageous attribute for its use (Su et al., 2019; Singhvi et al., 2019; Kristiawan.et al., 2021).

The applications of polylactic acid are numerous and covers areas like the industrial, packaging manufacturing, containers and stationery items (Singhvi et al., 2019; Ilyas et al.,2021), biomedical and dental, the manufacturing of scaffold tissue engineering, delivery system materials, covering membranes, bio-absorbable medical implants, cosmetics, sutures in dermatology (Doi, Steinbüchel, 2002) and prosthetic components (de Campos et al.,2023).

In the field of dentistry, polylactic acid is widely used, through the 3D printing method, by additive manufacturing, which consists of adding the material, layer by layer, until the desired geometric object is obtained (Park & Shin, 2018; Zimmermann et al., 2020; Van Noort 2012; Horn & Harryson, 2012; Dawood et al., 2015; Caviezel et al., 2017; Kessles et al., 2020; Kieschnick et al., 2020). Another advantage of this procedure is that there is the possibility of presenting complex shapes (Reverte et al.,2020), customization and design freedom, as they do not have previous manufacturer definitions for their use, low material waste (Dawood et al., 2016) and relatively short development time (Valerga et al.,201; Wach et al., 2018; Cuan-Urquizo et al., 2019).

This polymer is used in one of the most common 3D printing methods, called fused filament manufacturing (FFF) (Brounstein et al., 2021), which guarantees simplicity of handling, low cost and waste in equipment and materials (Reverte et al.,2020). The biopolymer in question is the most popular with this method because it is biodegradable, a thermoplastic, semi-crystalline and it has a melting point of 150–160 °C, which allows printing on cheaper equipment, as well as its lower toxicity compared to other thermoplastics, such as ABS (Behzadnasab et al., 2020).

The operation of FFF ensures that the desired dental piece is obtained by heating the PLA (Reverte et al.,2020) beyond its glass transition temperature or melting point. With 3D extrusion of the softened material through a nozzle, the material is positioned on a platform where the filament cools slowly enough to adhere to the layers placed below and above it (Brounstein et al., 2021; Thompson et al., 2016).

In the field of dentistry, the FFF method is used in the manufacture of obturator prostheses (Ye et al., 2020); surgical screws; pins; orthopedic plates (Tappa et al.,2019); complete dentures (Lo Russo et al., 2021); teeth and their structures (Cresswell-Boyes et al.,2018); implants (Liu et al., 2019), crowns (Nagata et al., 2022) and temporary fixed prostheses (Park et al., 2020), for example. However, there is still no consensus in the literature on the effectiveness of these materials, their behavior under different circumstances and mechanical and microstructural analysis that prove their effectiveness. Therefore, the objective of this investigation is to analyze, through the studies carried out, whether PLA, printed in 3D and used as dental materials and biomaterials, presents adequate mechanical, chemical and biological properties that indicate its feasibility for clinical use.

2. Material and Methods

Protocol and Registration

This systematic review was structured according to the items of the Preferred Reporting Items for Systematic Review and Meta-Analyses Protocols (PRISMA) (Page et al., 2021).

Eligibility Criteria

The criteria of the present systematic review were applied using the PICOs structure: population, polylactic acid (PLA) used in the field of dental materials; intervention, additive manufacturing printing; comparison, mechanical, chemical and biological properties; results, possibility of clinical use. The main objective of this research was to answer the following question: Does 3D-printed PLA have adequate mechanical, chemical and biological properties to be used as dental materials and biomaterials, which enable their clinical use?

The inclusion criteria were articles written and published in English that were limited to the use of PLA in dental materials. Exclusion criteria included articles whose focus was not the study of the polymer in question, as well as book chapters, abstracts, letters, reviews and conference articles.

Information and Search Strategy

A data search was performed using Pubmed, Science Direct, Embase and Scopus. The terms used on each of the digital platforms were: ‘’polylactic acid’’, ‘’3D printing’’, ‘’biomaterials’’, “dentistry”; ‘’polylactic acid’’, ‘’3D printing’’, ‘’dental materials’’, ‘’polylactic acid’’, ‘’3D printing’’ and “prosthodontics.” All terms were searched in double quotes, except for Embase, where single quotes were used. A referencing program (Rayyan Systems Inc.2022.Qatar Foundation) was used to check and delete duplicate references to facilitate reading and the final selection of articles.

Study Selection

Two phases were used to select the studies. In the first phase, two reviewers (H.D.L and M.R.C) independently read the titles and abstracts in order to identify possible studies for inclusion. In the second phase, references that did not meet the selection criteria were excluded and articles with the potential to be included were read in full by two reviewers (H.D.L and M.R.C). For final inclusion, all articles from the last selection phase were discussed with the research coordinator (A.C.R) to finalize the inclusion list. Thus, table 1, was created, containing information on the articles included in the systematic review in question, such as: Author and year, objective, polymers used, analysis performed, and outcomes.

Data Collection Process

The data extracted from the included articles are presented in Table 1, which includes the author, year of publication, objective, polymer used, data analysis and results found for each publication.

Assessment of Risk of Bias

The articles were qualitatively evaluated to analyze the risk of bias, promoting a more reliable result of the studies. The risk of bias classification presents three results: Low risk, when the article is clear, easy to understand or no bias can alter the results; uncertainty, when the study presents moderate risk because the object of study is not clear and there is a need to justify it to evaluate it; and high risk when results cannot be obtained faithfully.

(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v12i12.43986

3. Results

Study Selection and Characteristics

The search for the articles is detailed in the diagrammatic model of PRISMA (Figure 1). We found 1814 references from the period between 1996 and 2023. After excluding 338 references that were abstracts, book chapters, and conference papers, 1476 remained. Duplicates were then checked and excluded, which left 948 articles. After reading the abstracts, 923 were excluded for not meeting the inclusion criteria, while the remaining 25 articles were read in full. After this reading, 12 articles were further excluded, leaving 13 articles for the final inclusion in this review.

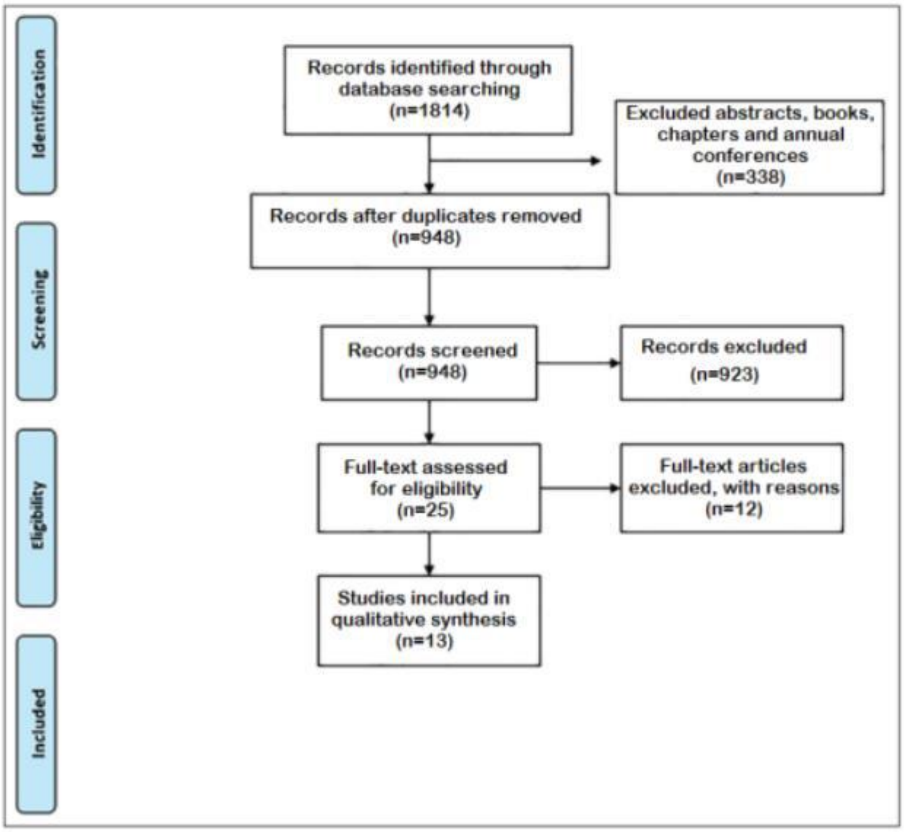
The Risk of Bias

The risk of bias was assessed according to the JBI quasi-experimental checklist so that a careful and rigorous assessment of the quality of the articles included in this review was ensured with regard to a more reliable conclusion. In total, questions were analyzed according to the risk of bias presented, which can be classified as low, uncertain and high risk of bias (Figure 2). The issues mentioned were:

1. Is it clear in the study what is the “cause” and what is the “effect”?
2. Were the participants included in any similar comparisons?
3. Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?
4. Was the follow-up complete, and if not, were differences between groups in terms of their follow-up adequately described and analyzed?
5. Were the outcomes of participants included in any comparisons measured in the same way?
6. Were the outcomes measured reliably?
7. Was an appropriate statistical analysis used?

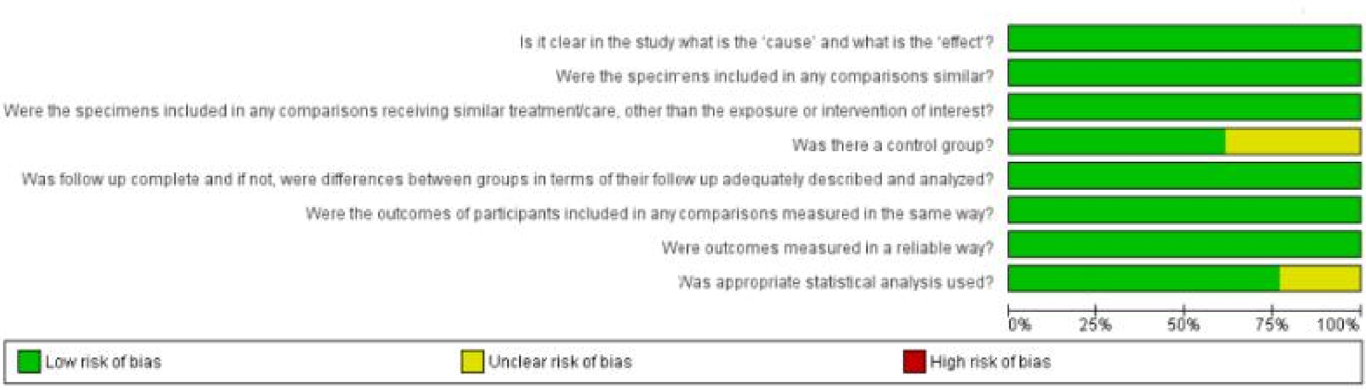
From the results of the risk of bias, represented in figures II and III, we can infer that the studies present, in the majority, with a low risk of bias, and of all the articles included in the present systematic review, 4 presented only one question each with an unclear risk of bias (Boyes et al., 2018; Chrasseangpaisam Wiwatwarrapan Srimaneepong 2022; Nagata et al., 2022; Russo et al., 2021) and 2 presented two questions each with unclear risk of bias (Riva et al ., 2022 and Ye et a., 2021). Regarding question number four, there was no clarity regarding the description of the control group in the studies cited. Now, regarding question number seven, it can be said that the articles in question did not show which statistical analysis was used to arrive at the obtained result.

Figure 1 - Organization Chart of the Select of Articles in the Databases.



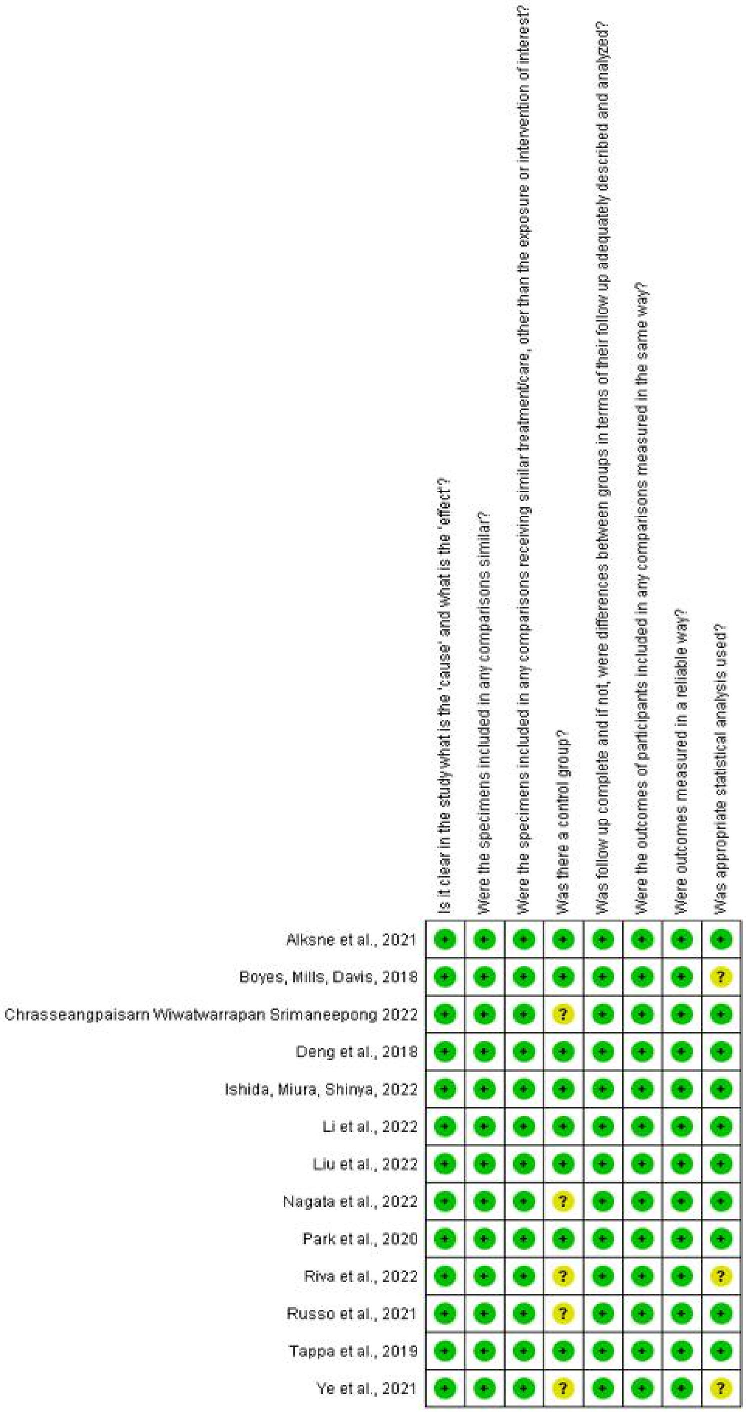
Source: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

Figure 2 - Risk of Bias Graph.



Source: Authors (2023).

Figure 3 - Risk-of-bias summary of included studies.



Source: Authors (2023).

Table 1 - Table with data from the included studies, presenting as data the author and year, objective, polymers used, analysis performed, and outcomes.

Author and year	Objective	Polymer	Analysis	Outcomes
Alksne et al., 2021	To evaluate whether scaffolds coated with ‘’cell derived extracellular matrix’’ (ECM), which are secreted by ‘’dental pulp stem cells (DPSCs)’’, facilitate ‘’artificial bone construction integration	Polylactic Acid (PLA) coated by ECM and PLA not coated by ECM	Proteomic, Flow cytometry and Immunohistochemical	DPSC-specific ECM protein network ornamenting surface-enhanced MSC attachment, migration and proliferation and even promoted spontaneous stem cell osteogenesis
Boyes, Mills, Davis, 2018	Three-dimensionally (3D) print accurate artificial teeth using scans from X-ray microtomography (XMT)	Polylactic Acid (PLA) and Thermoplastic Elastomer (TPE)	Toughness and resistance	PLA has greater hardness and resistance and was therefore used for printing enamel, while TPE was used for dentin and pulp cavity.
Charasseangpaisarn, Wiwatwarrapan, Srimaneepong, 2022	Compare 3D printing PLA to traditional poly (methyl methacrylate) (PMMA) as a denture basis	PolyMethyl Methacrylate (PMMA) and PLA	Flexural Thermic	PLA had lower flexural strength than PMMA in all temperature conditions, while the PMMA 25°C (M25) and PMMA 37°C (M37) obtained the highest mean values. PLA 25°C (L25) and PLA 37°C (L37) had significant higher flexural modulus than the other groups. However, the flexural properties of L55 could not be observed, which may be explained by Tg and HDT of PLA
Deng et al., 2018	To quantitatively evaluate maxillary complete denturs fabricated from polylacticacid (PLA) using fused deposition modelling(FDM) technology	PLA	3D desviation	The overall mean value and standard deviation of space between PLA denture patterns and plaster model was 0.277 ± 0.021 mm, while that of the wax denture patterns was 0.279 ± 0.045 mm, which showed a good fit overall. No statistically significant ($P > 0.05$) difference was observed between the PLA patterns and wax patterns
Ishida, Miura, Shinya, 2022	Clarify the application possibility of the fused deposition modeling (FDM) technology on the fabrication of jigs for a flexural test of dental composite resins (CRs)	PLA	Beldin elasticity and flexural strength	Flexural strength and flexural elastic modulus of packable CR were significantly larger than those of flowable. However, there were no significant differences among the jigs in both results
Li et al., 2022	Explore the effects of the impression gap and base thickness of FDM-printed PLA custom trays on the accuracy of maxillary and mandibular definitive casts with Kennedy class II, modification I partial edentulism and to optimize these 2 design parameters	PLA	Layer Hight, Fill Density, Printing Speed, Temperature, Support Type, Fillament Diameter and Filament Flow	The accuracy of definitive casts from custom trays with a 2.0-mm or 3.0-mm impression gap and 1.5-mm or 2.0-mm base thickness was significantly better than that of definitive casts from custom trays with a 1.0-mm impression gap or 1.0-mm base thickness and was not significantly different from that of definitive casts from stock metal trays
Nagata et al., 2022	Verify the accuracy of models fabricated using a fused deposition odeling (FDM) and PLA	PLA, Resin and Plaster	Measure the marginal fit	At the buccal center, the marginal gaps were 118 ± 21.7, 62 ± 16.4, and 50 ± 26.5 μm for the PLA, resin, and plaster models, respectively, with a significant difference between the PLA model and the other two. However, the marginal gap at all other measurement points was not significantly different between the models ($P > 0.05$)

Park et al., 2020	Compare the flexural strength of 3D printing resin materials to Temporary Fixed Dental Prosthesis	PMMA and PLA	Flexural Strength	DLP and SLA groups had significantly higher flexural strength than the conventional group (p < 0.001). No significant difference was observed in flexural strength between DLP and SLA groups. The FDM group showed only dents but no fracture
Riva et al., 2022	Analyse the ability of Additive manufacturing of PLA to mimic the thrust force of mandibular bone during drilling	PLA	Drilling properties and Peak Force	With respect to the shell drilling force, corresponding to the cortical bone, the values are in line with those found in the literature. In fact, the means settle in the range of 11-13 N. Regarding the plateau force, corresponding to the drilling of the trabecular bone, it was not possible to measure it due to the chosen filling strategy that left holes too wide for the tip used
Russo et al., 2021	Evaluate the trueness of trial dentures fabricated by using 3D-printing fused deposition modeling (FDM)	PLA	Intaglio Distane and Global Distance	Mean values of the intaglio distance were not significantly different from zero (P=.223). The manufacturing accuracy of the intaglio surface was higher than that measured for the entire denture (P<.001), confirmed both by the averaged signed (0 mm and -0.028 mm, respectively) and the absolute mean deviations (0.06 mm and 0.08 mm, respectively). No significant differences were found between maxillary and mandibular trial dentures
Tappa et al., 2019	Demonstrate 3D printing methods for the fabrication of patient-specific fixation implants that allow for localized drug delivery	PLA	Compressive and flexural strength mechanical testing	Bland PLA constructs showed significantly higher flexural strength when printed in a Y axis at 100% infill compared to other axes and infill ratios; however, there was no significant difference in flexural strength between other axes and infill ratios. GS and MTX-impregnated constructs had significantly lower flexural and compressive strength as compared to the bland PLA constructs. GS-impregnated implants demonstrated bacterial inhibition in plate cultures. Similarly, MTX-impregnated implants demonstrated a cytotoxic effect in osteosarcoma assays
Yee et al., 2021	Study the fully digital workflow for the design and manufacture of prostheses for maxillectomy defects	PLA and PEEK	Density,biocompatibility, elastic módulos and suitable strenght	The chosen material, PEEK, has suitable strength, low density, good biocompatibility, and a similar elastic modulus to cortical bone, making it suitable for fabricating a reduced weight obturator prosthesis
Liu et al., 2022	To assess the 3D accuracy of multi-implant impressions for complete arches obtained using 3D printing technology, ando to determine the clinical feassibilty	PLA and Poly (methylmethacrylate)	Flexural strength and tensile bond strenght	There was less implant-position deviation for the 3D-printed group (mean ± SD: 56.37 ± 12.52 μm) than for the conventional group (71.94 ± 18.86 μm) (P = .014). No significant differences were found in angular deviation between the two groups (P > .05). Flexural strength results suggested that polylactic acid(112.7 ± 1.62 MPa) was stronger than poly(methyl methacrylate) (104.0 ± 2.17 MPa; P < .0001). The tensile bond strength of polylactic acid (0.07 ± 0.005 MPa) was higher than that of poly(methyl methacrylate) (0.03 ± 0.004 MPa; P < .0001).

Source: Authors (2023).

4. Discussion

The articles present in this systematic review sought to analyze whether dental biomaterials, obtained through the 3D printing method of PLA, presents favorable mechanical, chemical and biological properties for their clinical use.

These articles used printing methods named as Fused Filament Fabrication (FFF) (Ye et a., 2021; Lo Russo et al., 2021; Nagata et al., 2022; Charasseangpaisarn, Wiwatwarrapan, Srimaneepong, 2022; Deng et al., 2018; Ishida, Miura, Shinya, 2022; Leonardo et al., 2022) Digital Light Processing (DLP) and Stereolithography (SLA) (Park et al., 2020).

FFF extrudes the molten material in layers, in order to obtain the geometry of the desired object (Thompson et al., 2016). It can be used in biomedical, automotive, pharmaceutical, aerospace, textile and sports areas (Rebong et al., 2016). al., 2018; Singh et al., 2020). Its prominence in dentistry is due to the accessibility guaranteed by its low cost and the possibility of manufacturing various complex structures (Reverte et al.,2020).

DLP polymerizes layers of resin by ultraviolet curing, in order to increase printing efficiency and reduce production costs, quickens the process (He et al., 2021; Coppola et al., 2022). Furthermore, it has precision and can generate porous structures, such as membranes used in bone regeneration and the application of antimicrobial agents (Chen et al., 2022).

SLA, in turn, is highly accurate and fast, which guarantees uniform print quality (Deshmane et al., 2021). It generates objects of high resolution and precision, with excellent surface finishes and complex geometries and details (Bona et al., 2021; Khorsandi et al., 2021), through ultraviolet photopolymerization through layers of a liquid (Zhang et al., 2021).

Different polymers have been used as dental materials in these printing methods, such as polylactic acid (PLA) (Park et al., 2020; Ye et a., 2021;Tappa et al., 2019; Cresswell-Boyes et al., 2018;Liu et al., 2022; Nagata et al., 2022; Alksne et al., 2022; Charasseangpaisarn, Wiwatwarrapan, Srimaneepong, 2022; Deng et al., 2018; Ishida, Miura, Shinya, 2022), thermoplastic elastomer (TPE) (Cresswell-Boyes et al., 2018), polymethyl methacrylate (PMMA) (Park et al., 2020; Liu et al., 2022; Charasseangpaisarn, Wiwatwarrapan, Srimaneepong, 2022) and poly(ether-ether -ketone) (PEEK) (Ye et a., 2021).

TPE is a class of polymers that acquires a plastic state in the presence of heat, which makes it easier to mold. The mixture of these polymers can improve the mechanical properties of the materials, in order to provide less brittleness and greater ductility (Dang et al., 2018). As it presents lower hardness and resistance than PLA, Boyes et al., 2018, when obtaining a material for studying dental structures through X-ray microtomography (XMT) scanning, used in the manufacturing of dentin and cavity pulp, while PLA became the enamel. It is noted, therefore, that the clinical use of PLA, in terms of favorable characteristics such as resistance and hardness, is viable. Nagata et al, 2022, also analyzed dental models based on PLA, but using different types of impressions: FDM, SLA and conventional methods. When determining the marginal adjustment of temporary crowns, it was possible to conclude that the combination of PLA filaments made with FDM and SLA was not significantly different from other conventional models, except at a point in the center of the mouth, which presented the greatest marginal adjustment. This occurred due to the surface roughness generated after molding using the FDM method and justifies a possible usefulness of this combination for dental treatments, given that it creates the possibility for the dental surgeon to improve his work technique on manufactured models.

PMMA can be used in dentures (Charasseangpaisarn, Wiwatwarrapan, Srimaneepong, 2022) and prosthetic abutments, with properties modified by the materials to be incorporated in different printing methods (Park et al., 2020). It has good performance, good aesthetics and surface hardness, resistance to ultraviolet light, chemical stability, resistance to fracture and corrosion, biocompatibility, low cost and weight and minimal inflammatory reactions when in contact with tissues, making it a viable material for clinical use. (Mouro-Fraguas et al., 2020; Peters, 2010; Marin et al., 2021). Studies by Charasseangpaisarn et al., 2022 reveal that although PMMA, when compared to PLA in FDM for making denture bases, has greater flexural resistance in all temperature ranges stipulated for testing (25°C, 37°C and 55°C), PLA has a higher flexural modulus at temperatures of 25°C and 37°C. In this way, 3D PLA printing can be an alternative to conventional PMMA methods already on the market for making denture bases, as it has favorable mechanical and chemical properties, such as a higher flexural modulus. Liu et al., 2022, also analyzed Charasseangpaisarn et al., 2022, the flexural resistance of PMMA and PLA for the production of multi-implants. However, contrary to this author, PLA presented greater flexural resistance than PMMA, proving to be viable for clinical use. Another promising feature of PLA is that it showed greater tensile strength when compared to PMMA (Liu et al., 2022).

Park et al., 2020 also compared the flexural strength of PMMA and PLA in the manufacture of fixed dental prostheses, which were printed in SLA, DLP and FDM. PMMA was printed by SLA and DLP, while PLA by FDM, so this group had dented but not fractured specimens and that one had fractures and/or cracks in several pieces. Thus, it is understood that the manufacture of fixed prostheses based on PLA is possible and more advantageous when compared to PMMA.

PEEK has low density, good biocompatibility and an elastic modulus similar to cortical bone (Ye et al., 2021). It stands out for being chemically inert, having good resistance to wearing, being insoluble in most conventional solvents at room temperature and having a low affinity for biofilm adhesion (Panayotov et al., 2016; Papathanasiou et al., 2020). It is therefore used in the manufacture of removable partial dentures, obturators, fixed crowns and implants (Ye et al., 2021; Najeeb et al., 2016; da Silva et al., 2022). Ye et al., 2021 manufactured prostheses for patients with maxillectomy defects based on PLA and PEEK and when analyzing density, biocompatibility, modulus of elasticity and resistance, they observed that PEEK is the material of best choice as it has lower density, good biocompatibility, modulus of elasticity similar to cortical bone, adequate resistance, such that PEEL was characterized as a suitable material for the manufacture of weight-bearing obturator prostheses, for example.

PLA is a low-cost biodegradable material (Nagata et al., 2022), derived from plants and, therefore, produces less CO2 when decomposed compared to petroleum derivatives (D'Anna et al., 2019; Farah et al., 2016). It has good mechanical properties and a good modulus of elasticity. It provides excellent reproductions and accuracies (Deng et al., 2018). It is used in dentistry to create temporary fixed prostheses (Brounstein et al., 2021), total (Lo Russo et al., 2021) and obturators(Ye et a., 2021), surgical screws, pins and bone plates (Tappa et al., 2019), printing of dental structures such as enamel(Cresswell-Boyes et al., 2018), implants (Liu et al., 2022), dental models(Nagata et al., 2022), composition of scaffolds for guided bone regeneration (Alksne et al., 2022), denture making (Charasseangpaisarn et al., 2022; Deng et al., 2018) and JIGs (Ishida et al., 2022).

Alksne et al., 2022, revealed that additive manufacturing of PLA, in the form of scaffolds surrounded by extracellular matrix (ECM), produced by dental pulp (DPSCs), contributes to bone regeneration in vivo when compared to unwrapped PLA scaffolds by ECM. It was then found that PLA with ECM is capable of improving bone fixation, migration and proliferation, as well as spontaneous osteogenesis of stem cells, due to the “proteomic, flow cytometry and immunohistochemical” results.

PLA was also analyzed by Deng et al., 2018 and Russo et al., 2021 in the FDM manufacture of upper complete dentures. This printing was able to satisfy the precision requirements already existing in other printing methods, such as those made by the wax printer. Therefore, for financial reasons, PLA printed by FDM can be a good low-cost substitute for the manufacture of complete dentures.

In the manufacture of PLA JIGS, Ishida, Miura, Shinya, (2022), revealed that PLA obtained by FDM can be used for the resistance analysis of dental composite resins (CRs). Fluid CR and compactable CR were compared and the latter showed higher values of elasticity and compressive strength than the former, with no significant differences between the JIGs* in both results. It was then found that mechanical properties of PLA JIGs can be evaluated with the same precision as JIGs made with other materials and become potential low-cost substitutes, as previously evidenced by Deng et al. (2018).

Riva et al. (2022), revealed that PLA in FFF can be used in an attempt to emulate the different jaw bones in patients with tooth loss who require the use of a dental prosthesis anchored to the bone using threaded structures. The manufacture of

PLA-based mannequins, as it has properties similar to the jaw bone, may be a promising reality for its clinical use. The dentist can also try a simulation of the procedure to improve the technique, since the bone drilling process requires care regarding the stability of the temperature of the environment so that there is no tissue necrosis in the stimulated area.

Impression gaps and base thickness of customized PLA-based FDM trays for patients with partial edentulism were analyzed by Li et al. (2022). The choice of these trays is due to selective pressure impressions, which have advantages when shaping the partially edentulous edges due to the roughness obtained in the PLA material in FDM. There was then an improvement in impression retention and a reduction in impression gaps in relation to conventional metal trays, which guaranteed further clinical use of PLA.

Finally, Tappa et al. (2019) showed that 3D PLA implants, such as pins, surgical screws and bone plates, when impregnated with drugs, such as Gentamicin(GS) and Methotrexane(MTX), have antibacterial and chemotherapeutic effects because the drugs can be successfully loaded into the biopolymer.

The results were found in the analysis of articles and studies by Tappa et al., 2019, Lo Russo et al., 2021, Boyes et al., 2021, Boyes et al. 2018, Liu et al., 2022, Nagata et al., 2022, Alksne et al., 2021, Charasseangpaisarn et al., 2022, Deng et al., 2018, Ishida et al., 2022, Riva et al., 2022; Li et al., 2022, thus pointing to the possible viable clinical use of printed PLA.

Limitations of the review include the heterogeneity of the results, as the selected articles used PLA in different printing methods and in different quantitative analyses, because few used the DLP (Park et al., 2020) and SLA (Park et al., 2020) compared to FFF (Lo Russo et al., 2021; Cresswell-Boyes et al., 2018; Nagata et al., 2022; Charasseangpaisarn et al., 2022; Deng et al. 2018; Ishida, Miura, Shinya, 2022; Riva et al., 2022), so that the results may tend towards a conclusion that PLA presents better properties when associated with a printing method than another. Another limitation is that there are in vitro studies (Park et al., 2020; Ye et a., 2021; Lo Russo et al., 2021; Liu et al., 2022; Park, Shin, 2018; Hong et al., 2021) and that two articles selected (Deng et al., 2018; Peng et al., 2018) by the database could not be included in the present review due to the inability to access the full reading of the texts in full. Furthermore, the selection bias of the different types of objects used in the studies shows the difficulty in comparing certain properties in different objects analyzed, so that direct comparison between the methods used is not possible.

It can be said that there are improvements in the properties of materials obtained by additive manufacturing and incorporated with PLA, but there are not many studies developed on this topic yet because they are still considered relatively new. Therefore, it is important that more research and studies are carried out and a greater number of articles are written so that future projects can clarify and highlight the importance of the clinical use of PLA and its advantageous properties in the various selected printing methods, in order to enable your job. It is also necessary to develop more in vivo studies on the topic of this systematic review, since the oral cavity cannot be fully simulated in in vitro studies as carried out in some articles included here (Park et al., 2020; Ye et al., 2021; Lo Russo et al., 2021; Liu et al., 2022; Park, Shin, 2018; Hong et al., 2021).

5. Conclusion

Even with the above limitations of this research, it is possible to conclude that:

- PLA, as a dental material and as a biomaterial, 3D printed, presents mechanical, chemical and biological properties favorable for its clinical incorporation.
- The techniques used in the manufacture of clinical materials based on PLA, in the field of dentistry, currently include Fused FilamentFabrication (FFF), Digital Light Processing (DLP) and Stereolithography (SLA), with FFF being the most used.
- PLA-based 3D printing generates personalized products for each case and works at high levels of precision and speed.

- The need for more studies on the PLA-based 3D printer is necessary so that between the different means of obtaining it (FFF, DLP or SLA) there can be a more detailed and equal comparison of the chemical, mechanical and biological properties of the compounds clinical results obtained.

In the future, aiming to improve and expand the articles in the literature containing 3D printed PLA used clinically as a biopolymer for dental material, it would be interesting to invest in in vivo scientific research, ensuring benefits and effectiveness of dental materials incorporated by PLA beyond those that can already be perceived in the interpretation of current literature.

Acknowledgments

This review did not receive any specific grant from a funding agency in the public, commercial or non-profit sectors.

Statement of Informed Consent and Ethical approval

Necessary ethical clearances and informed consent were received and obtained, respectively, prior to initiation of studies from all participants.

Declaration of Conflicting Interests

The author declared that there is no potential for conflicts of interest in relation to the research and/or publication of this article.

Funding

The author received no financial support for the research, authorship and/or publication of this article.

References

Alksne, M., Kalvaityte, M., Simoliunas, E., Gendviliene, I., Barasa, P., Rinkunaite, I., Kaupinis, A., Seinin, D., Rutkunas, V., & Bukelskiene, V. (2022). Dental pulp stem cell-derived extracellular matrix: autologous tool boosting bone regeneration. *Cytotherapy*. 24(6):597-607. 10.1016/j.jcyt.2022.02.002.

Ang, H. Y., Chan, J., Toong, D., Venkatraman, S. S., Chia, S. J., & Huang, Y. Y. (2017). Tailoring the mechanical and biodegradable properties of binary blends of biomedical thermoplastic elastomer. *J Mech Behav Biomed Mater.* 79:64-72. 10.1016/j.jmbbm.2017.12.013.

Behzadnasab M., Yousefi A. A, Ebrahimibagha D., & Nasiri F. (2020) Efeitos das condições de processamento nas propriedades mecânicas de peças impressas em PLA. *Protótipo Rápido. J.* 26 :381–389. 10.1108/RPJ-02-2019-0048.

Bona, A. D., Cantelli, V., Britto, V. T., Collares, K. F., & Stansbury, J. W. (2021). 3D printing restorative materials using a stereolithographic technique: a systematic review. *Dent Mater* 37:336–350. https:// doi.org/10.1016/j.dental.2020.11.030.

Brounstein, Z., Yeager, C. M., & Labouriau, A. (2021) Development of Antimicrobial PLA Composites for Fused Filament Fabrication. *Polymers* (Basel). 13(4):580. 10.3390/polym13040580.

Caviezel, C., Grünwald, R., Ehrenberg-Silies, S., Gentil, S., Jetzke, T., Bovenschulte, M. (2017). *Additive Fertigungsverfahren* (3D-Druck)—Innovationsanalyse ; TAB Arbeitsbereicht: Berlim, Alemanha, 2017.

Charasseangpaisarn, T., Wiwatwarrapan, C., & Srimaneepong, V. (2022). Thermal Change Affects Flexural and Thermal Properties of Fused Deposition Modeling Poly (Lactic Acid) and Compression Molding Poly (Methyl Methacrylate). *Eur J Dent*. 10.1055/s-0042-1743148

Chen, T., Wang, D., Chen, X., Qiu, M., & Fan, Y. (2022). Three-dimensional printing of high-fux ceramic membranes with an asymmetric structure via digital light processing. *Ceram Int* 48:304–312. https://doi.org/10.1016/j.ceramint.2021.09.105.

Coppola, B., Schmitt, J., Lacondemine, T., Tardivat, C., Montanaro, L., & Palmero, P. (2022). Digital Light Processing stereolithography of zirconia ceramics: slurry elaboration and orientation-reliant mechanical properties. *J Eur Ceram Soc* 42:2974–2982. https://doi.org/10.1016/j.jeurceramsoc. 2022.01.024.

Cresswell-Boyes, A.J., Barber, A. H., Mills, D., Tatla, A., & Davis, G. R. (2018). Approaches to 3D printing teeth from X-ray microtomography. *J Microsc.* 272(3):207-212. 10.1111/jmi.12725.

Cuan-Urquizo, E., Barocio, E., Tejada-Ortigoza, V., Pipes, R. B., Rodriguez, C. A., & Roman-Flores, A. (2019). Caracterização das propriedades mecânicas de estruturas e materiais FFF: Uma revisão das abordagens experimental, computacional e teórica. *Materiais*. 12 :895.

D'Anna, A., Arrigo, R., & Frache, A. (2019). PLA/PHB blends: biocompatibilizer effects. *Polymers* (Basel).11:1416. https://doi.org/10.3390/polym11091416.

da Silva, G. G., Shimano, M. V. W., Macedo, A. P., da Costa Valente, M. L., & Dos Reis, A. C. (2022). In vitro assessment of polyetheretherketone for an attachment component for an implant-retained overdenture. *J Prosthet Dent* 127(2):319-e1. https://doi.org/10.1016/j.prosdent.2021.07.031.

Dawood, A., Marti, B., Sauret-Jackson, V., & Darwood, A. (2015). 3D printing in dentistry. *Br Dent J*. 219(11):521-9. 10.1038/sj.bdj.2015.914.

Dawood, A., Martí, B., Sauret Jackson, V., & Darwood, A. (2015). Impressão 3D em odontologia. *Br. Dente*. J. 219, 521–529.

de Campos, MR, Kreve, S., da Silva, GG et al. Análise mecânica e microestrutural de um novo modelo de attachments para overdentures retidos por mini-implantes obtidos por impressão 3D com três diferentes polímeros. *Polim. Touro*. (2023). https://doi.org/10.1007/s00289-023-04871-w

Deng, K., Chen, H., Zhao, Y., Zhou, Y., Wang, Y., & Sun, Y. (2018). Evaluation of adaptation of the polylactic acid pattern of maxillary complete dentures fabricated by fused deposition modelling technology: A pilot study. *PLoS One*. 13(8): e0201777. 10.1371/journal.pone.0201777.

Deng, K. H., Wang, Y., Chen, H., Zhao, Y. J., Zhou, Y. S., & Sun, Y. C. (2017). Quantitative evaluation of printing accuracy and tissue surface adaptation of mandibular complete denture polylactic acid pattern fabricated by fused deposition modeling technology. Zhonghua Kou Qiang Yi Xue Za Zhi. 52(6):342-345. Chinese. 10.3760/cma.j.issn.1002-0098.2017.06.004.

Deshmane, S., Kendre, P., Mahajan, H., & Jain, S. (2021). Stereolithography 3D printing technology in pharmaceuticals: a review. *Drug Dev Ind Pharm.* 47(9):1362-1372. 10.1080/03639045.2021.1994990.

Doi, Y., & Steinbüchel, A. (2002). Biopolímeros, Aplicações e Produtos Comerciais – Poliésteres III. Wiley-VCH

Farah S, Anderson DG, Langer R. (2016) Physical and mechanical properties of PLA, and their functions in widespread applications - a comprehensive review. *Adv Drug Deliv Rev* 107:367-392. https://doi.org/10.1016/j.addr.2016.06.012.

He, C., Cao, Y., Ma, C., Liu, X., Hou, F., & Yan, L. (2021) Digital light processing of complex-shaped 3D-zircon (ZrSiO4) ceramic components from a photocurable polysiloxane/ZrO2 slurry. *Ceram Int* 47:32905–33291. https://doi.org/10.1016/j.ceramint.2021.08.189.

Hong, Li., Kenan, Ma., Yuchun, Sun., & Hu, Chen. (2021). Design parameters of polylactic acid custom trays manufactured by fused deposition modeling for partial edentulism: Consideration of the accuracy of the definitive cast. *The Journal of Prosthetic Dentistry,* 127(2), 288.e1-288.e11

Horn, T. J., & Harryson, O. L. A. (2012). Visão geral das tecnologias atuais de manufatura aditiva e aplicações selecionadas. *ciência Prog*. 95, 255–282.

Ilyas, RA., Sapuan, S. M., Harussani, M. M., Hakimi, M. Y. A. Y., Haziq, M. Z. M., & Atikah, M. S. N., Asyraf, M. R. M., Ishak, M. R., Razman, M. R., Nurazzi, N. M., Norrrahim, M. N. F., Abral, H., & Asrofi, M. (2021). Polylactic Acid (PLA) Biocomposite: Processing, Additive Manufacturing and Advanced Applications. *Polymers* (Basel). 13(8):1326. 10.3390/polym13081326.

Ishida, Y., Miura, D., & Shinya, A. (2022). Application of fused deposition modeling technology for fabrication jigs of three-point bending test for dental composite resins. *J Mech Behav Biomed Mater.* 130:105172. 10.1016/j.jmbbm.2022.105172.

Hamad, K., Kaseem, M., Yang H. W., Deri, F., & Ko, Y. G. (2015). Propriedades e aplicações médicas do ácido polilático: uma revisão. Expresso Polim. *Deixe*, 9, 435 – 455.

Kessler, A., Hickel, R., & Reymus, M. (2020). Impressão 3D em Odontologia—Estado da Arte. Operador Dente. 45, 30–40.

Khorsandi, D., Fahimipour, A., Abasian, P., Saber, S. S., Seyedi, M., & Ghanavati, S. et al. (2021). 3D and 4D printing in dentistry and maxillofacial surgery: printing techniques, materials, and applications. *Acta Biomater* 122:26–49. https://doi.org/10.1016/j.actbio.2020.12.044.

Kieschnick, A., Schweiger, J., Edelhoff, D., & Güth, J. F. (2020). Status Präsens 2020: Additive CAD/CAM-Gestützte Fertigungstechnologien im Zahntechnischen Labor.

Kristiawan, R. B., Imaduddin, F., Ariawan, D., & Arifin, Z. (2021). Uma revisão da impressão 3D de modelagem por deposição fundida (FDM): Processamento de filamentos, materiais e parâmetros de impressão. *Abra Eng.* 2021; 11 :639–649. 10.1515/eng-2021-0063.

Leonardo, R., Roberto, P., Antonio, F., & Alberto, B. (2022). Additive manufacturing of PLA to mimic the thrust force of mandibular bone during drilling. *Procedia CIRP*, 110, 198-201, https://doi.org/10.1016/j.procir.2022.06.036.

Liu, Y., Di, P., Zhao, Y., Hao, Q., Tian, J., & Cui, H. (2019). Accuracy of multi-implant impressions using 3D-printing custom trays and splinting versus conventional techniques for complete arches. *Int J Oral Maxillofac Implants.* 34(4):1007–1014. 10.11607/jomi.7049.

Lo Russo, L., Lo Muzio, E., Troiano, G., Salamini, A., Zhurakivska, K., & Guida, L. (2021). Accuracy of trial complete dentures fabricated by using fused deposition modeling 3-dimensional printing: An in vitro study. *J Prosthet Dent*. S0022-3913(21)00416-9. 10.1016/j.prosdent.2021.07.021.

Marin, E., Boschetoo, F., Zanocco, M., Honma, T., Ahu, W., & Pezzotti, G. (2021). Explorative study on the antibacterial efects of 3D-printed PMMA/nitrides composites. *Mat Des* 206:109788. https://doi. org/10.1016/j.matdes.2021.109788.

Murariu, M., & Dubois, P. (2016). PLA composites: From production to properties. *Adv Drug Deliv Rev*. 107:17-46. 10.1016/j.addr.2016.04.003.

Muro-Fraguas, I., Sainz-García, A., Gómez, P.F., López, M., Múgica-Vidal, R., & Sainz-García. (2020). Atmospheric pressure cold plasma anti-bioflm coatings for 3D printed food tools. *Innov Food Sci Emerg Technol* 64:102404. https://doi.org/10.1016/j.ifset.2020.102404.

Nagata, K., Muromachi, K., Kouzai, Y., Inaba, K., Inoue, E., Fuchigami, K., Nihei, T., Atsumi, M., Kimoto, K., & Kawana, H. (2022). Fit accuracy of resin crown on a dental model fabricated using fused deposition modeling 3D printing and a polylactic acid filament. *J Prosthodont Res.* 10.2186/jpr.JPR_D_21_00325.

Najeeb, S., Zafar, M. S., Khurshid, Z., & Siddiqui, F. (2016). Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. *J Prosthodont Res* 60:12–19. https://doi.org/10.1016/j.jpor. 2015.10.001.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hofmann, T. C., & Mulrow, C. D. et al (2021) (2020). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372(71). https://doi.org/10.1136/bmj.n71.

Panayotov, I.V., Orti, V., Cuisinier, F., & Yachouh, J. (2016). Polyetheretherketone (PEEK) for medical applications. *J Mater Sci Mater Med*. 27:118.

Papathanasiou, I., Kamposiora, P., Papavasiliou, G., & Ferrari, M. (2020). The use of PEEK in digital prosthodontics: a narrative review. *BMC Oral Health* 20:217. https://doi.org/10.1186/ s12903-020-01202-7.

Park, M. E., & Shin, S. Y. (2018). Three-dimensional comparative study on the accuracy and reproducibility of dental casts fabricated by 3D printers. *J Prosthet Dent* 119(5): 861. e1–861.e7.

Park, S. M., Park, J. M., Kim, S. K., Heo, S. J., & Koak, J. Y. (2020). Flexural Strength of 3D-Printing Resin Materials for Provisional Fixed Dental Prostheses. *Materials* (Basel). 13(18):3970. 10.3390/ma13183970.

Peng, L., Wang, Z. H., Sun, Y. C., Qu, W., Han, Y., & Liang, Y. H. (2018). Computer aided design and three-dimensional printing for apicoectomy guide template. *Beijing Da Xue Xue Bao Yi Xue Ban.;*50(5):905-910.

Peters, K. (2010). Polymer optical fber sensors-a review. *Smart Mater Struct* 20(1):013002.

Rebong, R. E., Stewart, K. T., Utreja, A., Ghoneima, A. A. (2018). Accuracy of three-dimensional dental resin models created by fused deposition modeling, stereolithography, and Polyjet prototype technologies: a comparative study. *Angle Orthod* 88:363–369. https://doi.org/10.2319/ 071117-460.1 53.

Reverte, J. M., Caminero, M. Á., Chacón, J. M., García-Plaza, E., Núñez, P. J., Becar, J. P. (2020). Mechanical and Geometric Performance of PLA-Based Polymer Composites Processed by the Fused Filament Fabrication Additive Manufacturing Technique. *Materia*ls (Basel).13(8):1924. 10.3390/ma13081924.

Singh, S., Singh, G., Prakash, C., Ramakrishna, S. (2020). Current status and future directions of fused flament fabrication. *J Manuf Process* 55:288–306. https://doi.org/10.1016/j.jmapro.2020.04.049.

Singhvi, M. S., Zinjarde, S. S., Gokhale, D. V. (2019). Polylactic acid: synthesis and biomedical applications. *J Appl Microbiol.* 127(6):1612-1626. 10.1111/jam.14290.

Su, S., Kopitzky, R., Tolga, S., Kabasci, S. (2019). *Polylactide (PLA) and Its Blends with Poly(butylene succinate) (PBS): A Brief Review. Polymers* (Basel). 11(7):1193. 10.3390/polym11071193

Tappa, K., Jammalamadaka, U., Weisman, J. A., Ballard, D. H., Wolford, D. D., Pascual-Garrido, C., Wolford, L. M., Woodard, P. K., & Mills, D. K. (2019). 3D Printing Custom Bioactive and Absorbable Surgical Screws, Pins, and Bone Plates for Localized Drug Delivery. *J Funct Biomater*. 10(2):17. 10.3390/jfb10020017.

Thompson, M. K., Morôni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernardo, A., Schulz, J., Graf, P., & Ahuja, B. (2016). Design para Manufatura Aditiva: Tendências, oportunidades, considerações e restrições. *CIRP Ana.* 2016, 65, 737-760.

Valerga, A. P., Batista, M., Puyana, R., Sambruno, A., Wendt, C., & Marcos, M. (2017). Estudo preliminar dos efeitos da cor do fio PLA nas características geométricas de peças fabricadas por FDM. *Procedia Manuf.* 2017; 13 :924–931. 10.1016/j.promfg.2017.09.161.

Van Noort, R. (2012). O futuro dos aparelhos odontológicos é digital. Dente. *Mate*. 28, 3–12.

Wach, R. A., Wolszczak, P., & Adamus-Wlodarczyk, A. (2018). Melhoria das propriedades mecânicas de peças FDM-PLA via recozimento térmico. *Macromol. Mate. Eng.* 303(9). 10.1002/mame.201800169.

Ye, H., Wang, Z., Sun, Y., Zhou, & Y. (2020). Fully digital workflow for the design and manufacture of prostheses for maxillectomy defects. *J Prosthet Dent.* 126(2):257-261. 10.1016/j.prosdent.2020.05.026.

Zhang, Y., Kumar, P., Lv, S., Xiong, D., Zao, H., & Cai, Z. et al. (2021). Recent advances in 3D bioprinting of vascularized tissues. *Mater Des* 199:109398. https://doi.org/10.1016/j.matdes.2020.109398.

Zimmermann, M., Ender, A., Attin, T., & Mehl, A. (2020). Fracture load of three-unit full-contour fixed dental prostheses fabricated with subtractive and additive CAD/CAM technology. *Clin Oral Investig*. 24(2): 1035–1042.