



# The state of additive manufacturing in dental research – A systematic scoping review of 2012–2022

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## ABSTRACT

**Background/purpose:** Additive manufacturing (AM), also known as 3D printing, has the potential to transform the industry. While there have been advancements in using AM for dental restorations, there is still a need for further research to develop functional biomedical and dental materials. It's crucial to understand the current status of AM technology and research trends to advance dental research in this field. The aim of this study is to reveal the current status of international scientific publications in the field of dental research related to AM technologies.

**Materials and methods:** In this study, a systematic scoping review was conducted using appropriate keywords within the scope of international scientific publishing databases (PubMed and Web of Science). The review included related clinical and laboratory research, including both human and animal studies, case reports, review articles, and questionnaire studies. A total of 187 research studies were evaluated for quantitative synthesis in this review.

**Results:** The findings highlighted a rising trend in research numbers over the years (From 2012 to 2022). The most publications were produced in 2020 and 2021, with annual percentage increases of 25.7% and 26.2%, respectively. The majority of AM-related publications in dentistry research originate from Korea. The pioneer dental sub-fields with the most publications in its category are prosthodontics and implantology, respectively.

**Conclusion:** The final review result clearly stated an expectation for the future that the research in dentistry would concentrate on AM technologies in order to increase the new product and process development in dental materials, tools, implants and new generation modelling strategy related to AM. The results of this work can be used as indicators of trends related to AM research in dentistry and/or as prospects for future publication expectations in this field.

## 1. Introduction

Design and production of a final form or a prototype for new concept/re-designed products through conventional methods might not be effective in the manner of design flexibility, manufacturability and production cost and it could be time-consuming most

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especially for complex forms. As an alternative solution, additive manufacturing (AM) has gained increasing attention from related users and decision-makers, consequently it has been actively utilised in many fields such as art, architecture, fashion design, machinery manufacturing, medical, aerospace, automotive, defence and food industries because of its advantages such as flexible design and manufacturing, shorter prototyping time, ease of manufacturing of complex formed products, lower design and manufacturing cost [1, 2]. Companies now incorporate AM technologies into the overall manufacturing process. Research for Wohlers Report 2022 shows AM industry growth of 19.5% in 2021. This is up from 7.5% growth in 2020 [3]. Rapid prototyping, three-dimensional (3D) printing, and digital manufacturing are some of the nomenclatures that have been used to refer to this technique over time. The "ISO/ASTM 52900-21" standard defines its present name as 'additive manufacturing' [4]. AM technology is a potent manufacturing process that has been increasingly used in biomedical engineering since the late 1980s. The ability to fabricate improved complex and customized biomedical products enables this technology to rapidly diffuse all healthcare areas, including dentistry [5].

### 1.1. Fundamental principle of additive manufacturing

There are different AM technologies, with each having its own advantages, challenges, material types, and printing procedures, although the basis of them all is layer-by-layer production [6]. Today, available methods of production of the physical models through AM technologies can be categorised into seven groups according to the international standard of ISO/ASTM52900-21 (Additive manufacturing-general principles-fundamentals and vocabulary). These processes fall into the following categories: directed energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL) and vat photopolymerization (VPP) [4]. Specific to the biomedical field, different materials with varying degrees of precision are available within these AM methods.

The first step of the typical process for three-dimensional (3D) printing of biomedical products is creating 3D models which is provided by obtaining the images from conventional computer-aided design (CAD) modelling of a patient through medical data capture methods such as magnetic resonance imaging (MRI), and computed tomography (CT). The second step is converting the data obtained from the patient into a 3D virtual model using CAD software. Then, the model is exported as a digital file, usually in the stereolithography (STL) file format. The STL file data is then sliced to create a series of two-dimensional (2D) layers, where each layer represents a cross-section of the 3D virtual model. Using the resulting 2D sliced data, the AM machine repositions materials, biomolecules, and even living cells layer-by-layer with extreme precision to produce 3D objects. These objects may require post-processing to remove support materials or improve structural properties in some cases [7]. The development of biocompatible and printable materials makes AM technologies increasingly useful in different clinical applications.

### 1.2. Historical progress of AM technologies

The patent of the first 3D printer for stereolithography, which used ultra violet (UV) light to produce 3D solid objects from photocurable liquid polymer, was obtained by Hull in 1986 [8]. The selective laser sintering (SLS), which sinters solid powders layer-by-layer by using a laser beam, is also unveiled in 1986 by Deckard [9]. In the same period, Sachs et al. [10] proposed a novel powder bed-based method named 3D powder binding (3DPB). In 1989, Crump invented fused deposition modelling (FDM) which fabricates a 3D object by depositing layers of a heat-softened polymer onto a build platform [11]. Subsequently, a laminated object manufacturing technique was developed for making 3D objects, which uses a laser and adhesive system [12]. More recently, four-dimensional (4D) printing was announced by Tibbitts in 2013 [13]. 4D printing appears based on the 3D printing facility and smart material and design [14]. In 4D printing, time is used as the fourth dimension, aside from/in addition to the conventional 3D space, allowing the production of smart objects, which can change their shape, function, or properties over time in response to available stimuli such as temperature, wind, water, and light [15–20].

### 1.3. Research fields related to AM in dentistry

AM technologies have been utilised in many areas of dentistry for the last 20 years [1]. The main applications in dentistry vary from prototype models for anatomy teaching guidance to implants and personalized orthodontic brackets. When the use of AM technologies is reviewed in relation to the field of dentistry, it is seen that reconstruction (restoring the normal anatomy of the maxillofacial region) and orthognathic surgery (3D-printed surgical guiding templates to treat skeletal malocclusion) are the most significant current applications in Maxillofacial Surgery. Therefore, denture implantation (customized dental implants), auto-transplantation and allogenic tooth transplantation with a custom-made implant drill using AM systems have completely transformed approaches for Implantology [21]. Fixed partial dentures, removable partial or complete dentures, and facial prostheses are the prosthetic restorations commonly used with AM technology in Prosthodontics [21]. Additionally, CAD and computer-aided manufacturing (CAM) techniques have become increasingly popular in both dental laboratory and clinical dentistry over the past three decades. CAD-CAM technology offers several advantages to patients, including a decrease in the number of clinical visits, reduction in manufacturing costs, and time. Complete removable dental prostheses (CRDPs) manufactured using CAD-CAM technology are a prime example of this [22]. As knowledge on this subject continues to increase and materials and techniques continue to advance, it is anticipated that the importance of additive manufacturing, particularly in the production of prostheses, will also increase in the coming years [23] Furthermore, the study showed that methylmethacrylate concentrations were significantly lower in 3D-printed CRDPs than in milled CRDPs when using the resins mentioned in the study [24]. However, a recent study has shown that the shear bond strength of conventionally reprimed 3D-printed resins, which are used to fabricate CRDPs, is lower than that of the resins used in CAD-CAM milling and conventional heat

polymerization techniques [25].

Resin models, which are not affected by humidity as traditional plaster models, personalized brackets, which are fitted better to the tooth surface with good aesthetic properties, and clear aligners are key application areas in Orthodontics [26,27]. In Endodontics, 3D-printed templates to access obliterated root canals, surgical guides for osteotomy, and apical resection procedures are examples of successful uses of AM Technologies [28,29]. To support tissue regeneration of gum and other supporting tissues of the teeth in patients with periodontitis, additive biomanufacturing can be used to produce different types of scaffolds which can mimic a type of peri-odontal tissue [30].

#### 1.4. Process algorithm of AM applied in dentistry

The main workflow of AM technology follows these steps: Data collection, data processing, material selection, and the final fabrication procedure [21].

1. *Data collection*: Currently, there are four common methods for data collection: software design, optical scanning, mechanical scanning, and radiological scanning. The most common methods for mechanical scanning are CT and MRI.
2. *Data processing*: The scanned data (usually DICOM format) is imported into the software to rebuild a 3D model. The volumetric data are converted into 3D triangular mesh surfaces, after the segmentation process. The reconstructed data is saved as an STL file which can be identified and processed by AM machines.
3. *Material selection*: Various types of metals, ceramics, polymers, and hydrogels are used in dentistry. Dental implants made from titanium material manufactured using SLM are effective, personalized, and have great mechanical qualities and dimensional correctness. Current dental materials utilised in AM are largely composed of bio-ceramics, notably Zirconia ( $ZrO_2$ ), Alumina ( $Al_2O_3$ ), Leucite ( $KAlSi_2O_6$ ), Lithium disilicate ( $Li_2Si_2O_5$ ) and Tricalcium phosphate [26,27].
4. *Printing procedure*: The printing procedure used in all fields of dentistry commonly comprises the categories described in the ISO/ASTM52900-21.

#### 1.5. Limitations of AM technologies in dentistry

Reduction of material waste, less production time, ease of manufacturing, customized production, and variability of materials are the advantages of AM technologies [31]. However, despite these advantages, there are some limitations to employing this technology in many fields of production including dentistry. For example, in patient-specific models to be fabricated, MRI technology cannot be used to collect the data for AM procedures in patients with metallic implants. Another limitation is that some materials are not compatible and cannot be processed by AM [31]. Fabrication and replacement of these materials may not be straightforward and/or economical to develop.

Some of studies reported aesthetic problems with the mandibular AM dentures shape. Most especially obtaining adequate quality of the product surface and post-processing needs can be underlined as the important points to be improved. Depending on the geometries being replicated, the manufacturing process, and the materials being used, the accuracy of the structures produced varies. Variations of each of the existing fabricating processes are being researched and show potential for producing nanoscale structures [32]. The bonding of printed denture teeth can be considered another limitation as it's crucial to take the bond strength into consideration. It is reported that the bond strength of printed teeth to a printed denture base is lower than the bond strength obtained through conventional processing [23].

The other challenge is the standardization problem for AM-fabricated surgical models used in real clinical procedures. International standardization of AM models in terms of size, materials, machine types, and disease types also provides better communication among the operators in different hospitals and countries [7]. Additionally, FDA-approved synthetic polymers and metals are used for AM in these surgical applications. Nevertheless, immune rejection and/or inflammation can still be revealed after the surgery, which leads patients to need a second surgery [7]. Therefore, in the current literature, some studies should be considered with caution due to high standard deviations [33].

#### 1.6. Raw materials utilised in AM processes in dental applications

Metals, ceramics, and polymers are the most commonly utilised materials in AM. Metals and ceramics are usually preferred in applications for implants, which should be inert. On the other hand, polymers are used in applications when the material is required to be degradable to provide tissue growth. Application of composite implants comprised of a mixture of materials may be necessary, when a single material alone fails to provide function. A wide range of materials (from metals to cells) can be produced by one of the AM processes [31]. To optimize the fabrication process, each procedure has its own specific dental applications and raw materials [6].

Recent studies have reported a growing interest in the use of additive manufacturing (AM) in dentistry. For instance, AM technology can provide highly accurate and aesthetic dental prostheses, and AM can be a valuable tool for the fabrication of dental implants with improved biomechanical properties. However, despite the increasing attention paid to AM in dentistry, there is limited comprehensive reviews that summarize the current state of research in this field. To address this gap, the present study conducts a systematic scoping review of the literature on AM in dental research between 2012 and 2022, focusing on the trends, gaps, and future prospects of AM applications in dentistry. This study aims to provide insights into the current state of research on AM in dentistry, as well as to identify potential directions for future research [1,21,33–42].

## 2. Methodology

This systematic review of the literature was led by PRISMA-ScR guidelines (preferred reporting items for systematic reviews and meta-analyses) [43] and consisted of 187 selected studies. The research question was described according to PICO (P: Population/Patient/Problem; I: Intervention; C: Comparison; O: Outcome): Publications about additive manufacturing in dental research, conducted in different fields of dentistry: What is the current status, focus and distribution of international scientific publications by selected items (i.e. years, countries, institutions, research fields, research type etc.)?

### 2.1. Literature search strategy

An electronic search was limited to publications in the English language and performed in Web of Science (WOS) and PubMed databases using a combination of search terms applied with the Boolean Operators “AND” and “OR”, between the dates of 2012-03-01 and 2022-03-31. The keywords used in the electronic search were ‘additive manufacturing’, ‘rapid manufacturing’, ‘rapid prototyping’, ‘rapid tooling’, ‘3D-printing’, ‘dentistry’, and ‘dental’. The string search term created from the combination of relevant keywords was (TI = (additive manufacturing or rapid manufacturing or rapid prototyping or rapid tooling or 3D-printing)) AND TI = (dentistry or dental) and searched in title and abstract sections.

### 2.2. Inclusion and exclusion criteria

The studies matching with the following inclusion criteria were included in this systematic review: Additive manufacturing and 3D printing studies conducted in at least one field of dentistry such as maxillofacial surgery, implantology, restorative dentistry, prosthodontics, orthodontics, endodontics, and traumatology. The aim of this study was to identify the current state of additive manufacturing in dental research. To achieve this aim, studies that were written in languages other than English, studies that had no direct clinical relevance in dentistry, book chapters, letters, and opinion articles were excluded. Conversely, related clinical and laboratory research, including both human and animal studies, case reports, review articles, and questionnaire studies that were indexed in Web of Science (WOS) and PubMed databases, were included.

### 2.3. Evaluation of selected studies

After the careful assessment of both title and abstract sections during the review of related publications, the evaluation of full-texts was completed and the publications which did not match the inclusion criteria were excluded from this study. Disagreements concerning the inclusion and exclusion of a study were discussed by the authors until a decision was obtained by consensus. The data extraction form consisted of the following information identified for each study: Authors, year, country, name of the journal, name of the institution, department, the field of dentistry, type of article, and topic of study. For studies conducted in more than one centre,

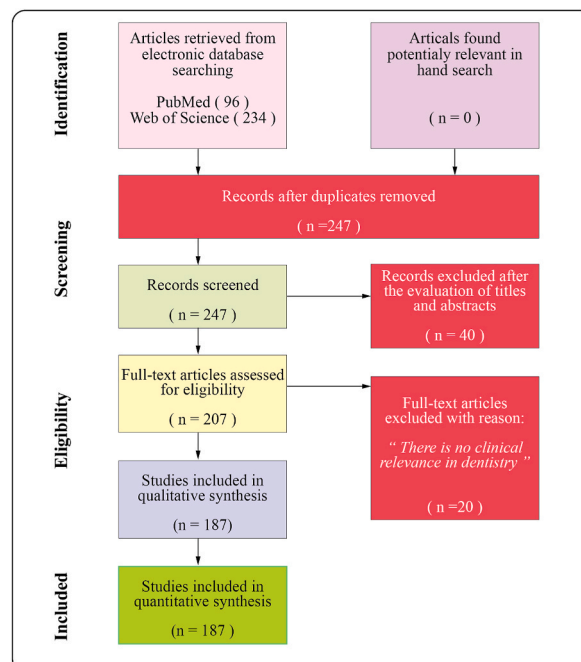


Fig. 1. The systematic flow chart of the study selection process).

information belonging to the first author of the article was recorded in the data extraction form.

### 3. Results and discussion

#### 3.1. Study selection

A total of 330 records were returned using the present electronic search strategy from the WoS and PubMed databases. After the removal of duplicates, 247 records remained for assessment of title and abstract. 207 eligible studies were involved in the full-text assessment and 187 studies were considered in-criteria (suitable) for this review work. The systematic flow chart of the study selection process is shown in detail in Fig. 1. The data of the included publications was listed in the supplementary document. This supplementary document provides publication records and the research content summary of the included studies in this review work [21,31,35,44–227].

#### 3.2. Scoping synthesis of the parameters

The quantitative results extracted from the review were represented through the graphs given in the following sections. Major publication numbers by items were priorate placed in the graphs. In the graphs, the column of “Others” indicates collection of the publications which have less than 2% of included publication number (187) in the review work.

##### 3.2.1. Distribution of publications by year

According to the results of the examination of the distribution of the studies included in this review by publication years, it was indicated that three of these studies were published in 2013, three in 2014, five in 2015, five in 2016, 13 in 2017, 18 in 2018, 29 in 2019, 48 in 2020, 49 in 2021 and 14 in 2022 (Fig. 2a). The highest number of publications was in 2020 and 2021 with increasing percentages of 25.7% and 26.2%, respectively.

These results clearly indicate that there is an increasing trend up to 2021 in studies related to AM in dentistry in the previous years. This also indicates that research on AM technology in dentistry is gaining increased attention and advancements would be better adopted by the dental research field with a future perspective. It may be said that the technology and equipment is becoming both commercially viable and widely accepted in the dental industry as a consequence of the activity undertaken in the research arena.

It can also be seen in the graph that number of publications in 2020 (48) and 2021 (49) is close each other (Fig. 2a). When considering the volume of publications in previous years and their annual increase, there is an expectation that 2021 should look

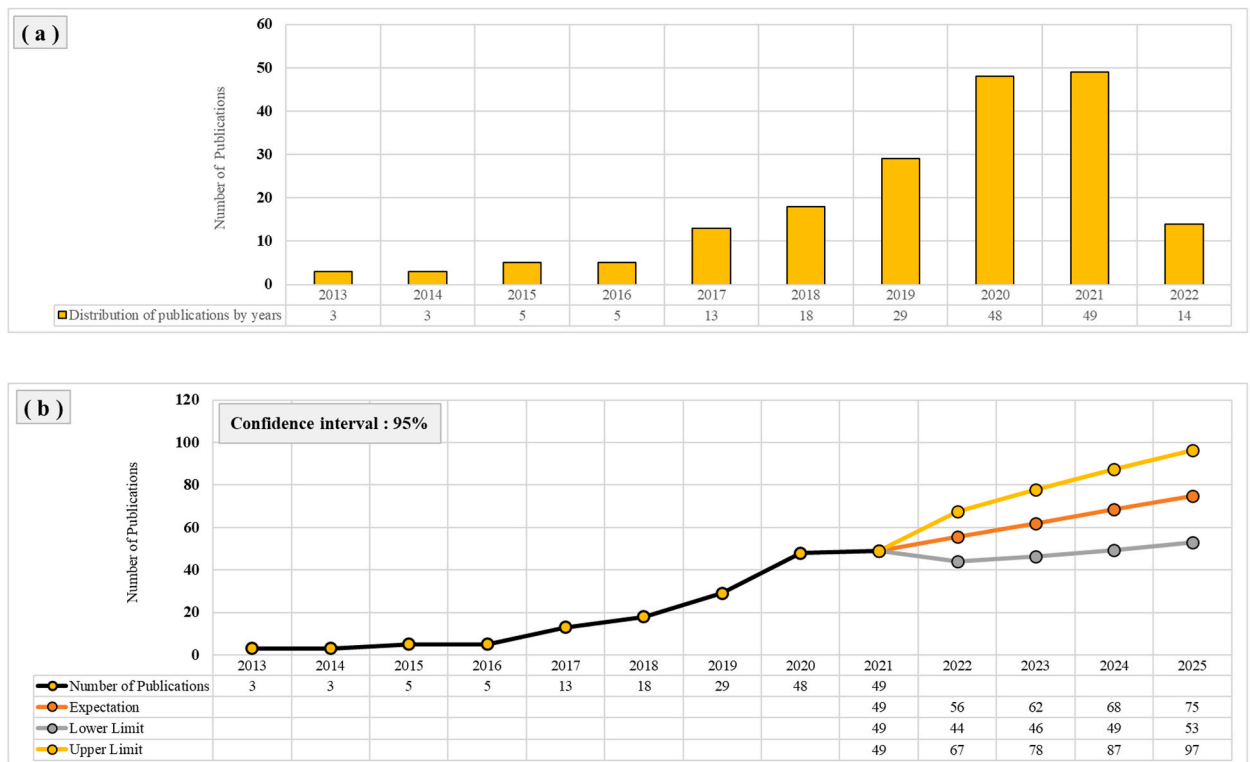


Fig. 2. Distribution of publications (a) and the forecast (b) by years.

greater than it does. This may be as a consequence of a limitation on research outputs published due to the Covid-19 pandemic. Like in many research fields, research studies on AM in dentistry were possibly negatively affected during the pandemic. However, this would be better interpreted at the end of the year 2022 and so on.

Additionally, the number of publications in 2022 given in this review is less than the previous year of 2021, as this only covers the first three months of publications which are available in indexing databases. On the other hand, nominal expectation was calculated through a linear expectation forecast (exponential smoothing forecast) for the forthcoming years including 2025 which indicates that there will be an increase in the number of publications (approximately 53% in 2025) in AM related studies in dentistry (Fig. 2b).

### 3.2.2. Distribution of publications by countries

The publications included in this study originated from 39 different countries. The graph was created for countries with at least four publications (greater than 2%) (Fig. 3). According to the results of the examination of the distribution of the studies included in this review by Countries: 30 publications were from Korea, 23 from the USA, 20 from China, 16 from Germany, 12 from India, 10 from Brazil, six from Romania, six from Switzerland, six from Taiwan, four from Italy, four from The Netherlands, and four from Spain. The greatest number of publications originated from Korea and USA (16% and 12.3%, respectively) (please see supplementary document for more details).

### 3.2.3. Distribution of publications by journals

The publications included in this study were published in 89 different journals reviewed on WoS and Pubmed databases. The graph created for journals with at least four publications (greater than 2%) is shown in Fig. 4. According to the results of the examination of the distribution of the studies included in this review by Journals: there were 18 studies published in J Prosthet Dent., 16 studies published in Materials, five studies each published in Polymers, Appl. Sci. and J Prosthodont., four studies each published in J. Mech. Behav. Biomed Mater., Biomed Res. Int, Dent. Mater., Eur J Dent Educ., Int J Prosthodont., J. Clin. Med., and Rapid Prototyp. J. The greatest number of publications was published in J Prosthet Dent. and Materials (9.6% and 8.6%, respectively) (please see supplementary document for more details). In short, the journals included in this review can be grouped under engineering, material science and dental research fields.

### 3.2.4. Distribution of publications by institutions

The research that led to the publications included in this study were conducted at 137 different institutions, three of them were private clinics, two of them were research centres and the others were universities or university hospitals. The graph was plotted for institutions with at least four publications (greater than 2%) as shown in Fig. 5. According to the results of the examination of the distribution of the studies included in this review by institutions: Ludwig Maximilians University (Munich-Germany), and Seoul National University (Seoul-Korea) have four publications; Korea University (Seoul-Korea) and Yonsei University (Seoul-Korea) have six publications; Kyungpook National University (Daegu-Korea), and Texas A&M University (Dallas-USA) have eight publications. The highest number of publications originated in Kyungpook National University (Daegu-Korea), and Texas A&M University (Dallas-USA) with percentage of 4.3% (8 publications for each).

### 3.2.5. Distribution of publications by field of dentistry

The studies were categorised into 10 different groups and the distribution of the number of studies according to the fields of dentistry is as follows: one for paediatric dentistry, two for traumatology, three for endodontics and periodontology, 10 for orthodontics, 11 for restorative dentistry, 14 for maxillofacial surgery, 27 for general dentistry, 30 for implantology and 86 for prosthodontics (Fig. 6). The review studies evaluating the dental applications of additive manufacturing were accepted as general dentistry; studies including implant treatments were accepted as implantology, and the remaining surgical treatments were accepted as maxillofacial surgery. The highest number of publications were from prosthodontics and implantology with percentages of 46% and 16%, respectively.

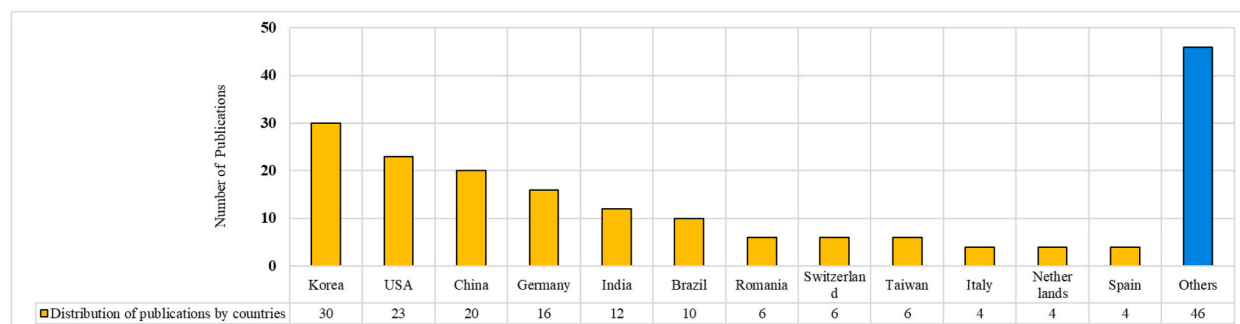


Fig. 3. Distribution of publications by countries.

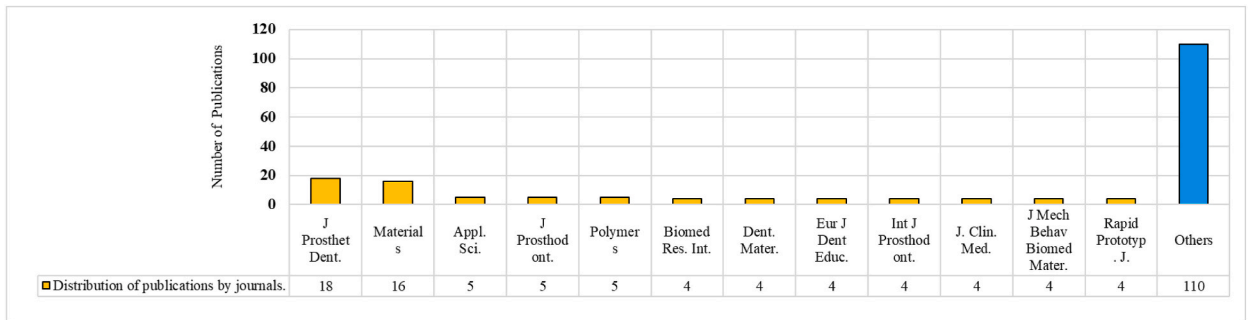


Fig. 4. Distribution of publications by journals.

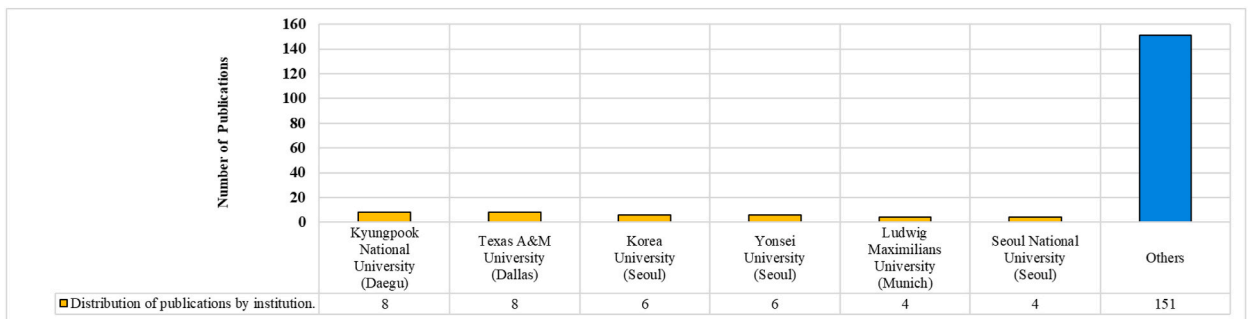


Fig. 5. Distribution of publications by institution.

3.2.6. Distribution of publications by type of publications

The studies were categorised into six different groups and the distribution of the number of studies according to the type of publication is as follows: three of them were Animal Study, four were Technical Notes, five were Questionnaires, 10 were Case Report/Series, 42 were Reviews and 127 were Original Research (Fig. 7), equating to 65.8% overall. These statistics revealed that research studies on AM in dentistry is the major focus, however, Reviews are a considerable number. This may indicate that the researchers wish to follow the advancements in AM technology and its trends as they see its future potential in dental applications.

3.2.7. Future Outlook

Although AM technologies have been widely utilised in many areas, studies are still conducted to shorten the time required for the production process and to provide improved software in order to obtain more accurate outcomes. For this purpose, research continues to develop new materials that can be processed in a shorter time and do not require further processing with AM technologies [6]. Obtaining an improved final product’s surface quality is another important perspective. 3D printed scaffolds to guide the growth of the tissue made from biological materials that are used in tissue engineering for bone grafting, regeneration, or repair of soft and hard tissues are another focal area of AM technologies [31]. It is thought that this field of application will expand further in the future [6]. On the other hand, some of the previous reviews highlighted the limited number of in-vivo studies on the subject of AM technologies, indicating the need for additional studies with sufficient follow-up time [228,229].

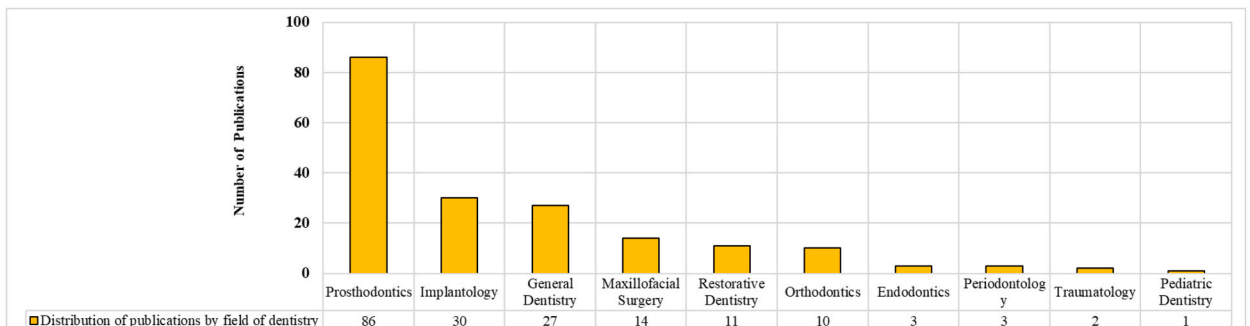


Fig. 6. Distribution of publications by field of dentistry.



Fig. 7. Distribution of publications by type of publication.

The final findings of this review made it apparent that the expectation for the future was that research in dentistry would focus on AM technology development in particular, in order to accelerate the increase in the number of novel dental materials, tools, implants, and next generation modelling strategies.

The detailed methodology employed in this scoping review, including the well-defined inclusion and exclusion criteria, the wide range of time limitation, and the current relevance, are some of its strengths. Moreover, the adherence to the PRISMA guidelines adds to the methodological reliability of this review [230]. However, this scoping review also had some limitations. It is worth noting that the use of AM technology is still not widespread, as it is mostly limited to research centres and universities due to the high cost of the required hardware. Additionally, only articles with clinical relevance were included in this review, which implies that studies conducted in the field of tissue engineering and stem cells, which have not yet entered clinical routine use, were excluded.

#### 4. Conclusion

The systematic scoping review conducted in this paper revealed the current status and the future expectation of scientific publications indexed in the selected databases (WoS and PubMed). The approach of this study is to provide insight to research trends related to the use of AM technology in dentistry and build a foundation for future research, from which new research opportunities could be envisaged. The review results indicated an increasing trend in research in this field over the years. Within the scoped publication number of 187 considered in this study, the most publications were produced in 2020 and 2021, with annual percentage increases of 25.7% and 26.2%, respectively. 49 publications were realised in 2021 and expectation for coming up years is higher. Korea has the highest number of publications related to AM employed in dental research. Prosthodontics and implantology are the sub-fields in dentistry which has the highest number of publications in its category.

With the aid of CAD/CAM technology and 3D imaging, additive manufacturing is at the forefront of, and has a significant impact on, all areas including dentistry. However, there are some difficulties, such as prohibitively expensive materials, lengthy post-processing, and a laborious manual process to fulfil. Although contemporary additive manufacturing machines can produce models in a short amount of time, obtaining digital data and its processing can take more time; as a result, additive manufacturing does not look like it is currently the most appropriate for deployment in emergency situations.

Beside the limitations of this technology, the review of the publications included in this study highlighted in short that future development of digital dentistry would be accelerated through the utilisation of AM technology. AM appears to offer the ability to address a number of issues in dentistry, including customization requirements, denture alignment and retention, and the need to enhance current dental implants. Finally, it can be said that, although the high investment costs and technical limitations of this technology for dental applications create difficulties its adoption in this field, additive manufacturing and technological applications will be increasingly specialised and advanced through future research and development in order to overcome the utilisation limitations of AM applications in dentistry.

Based on this review work, three important future research recommendations can be summarised;

1. Research on new materials: Future research could focus on developing cost-effective, durable, and biocompatible materials for AM technology in dentistry. This includes the exploration of hybrid, nanomaterials, and composite materials with improved properties.
2. Efficient post-processing: Future research could develop new post-processing techniques to improve efficiency and reduce labour and time costs. This includes automated systems and new post-processing materials.
3. New applications: Future research could explore new applications of AM technology in dentistry such as endodontics, orthodontics, and oral surgery. This includes the development of new printing techniques, customization of implants, and the use of AM in emergency situations.

#### Author contribution statement

H. Kursat CELIK: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper. Simay KOC: Performed the experiments; Analysed and interpreted the data; Wrote the paper.



Alper KUSTARCI; Allan E.W. RENNIE: Conceived and designed the experiments; Analysed and interpreted the data.  
Nuri CAGLAYAN: Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data.

### Data availability statement

Data included in article/supplementary material/referenced in article.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.heliyon.2023.e17462>.

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