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The use of 3D Printing Technologies in Education: A Bibliometrics Review of the Literature between 2004 and 2023

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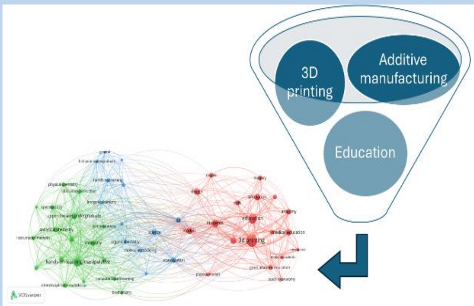
Abstract: 3D printing technologies is showing a great potential in many fields. A rapidly growing one is the educational field. The ability to realize structures and models with low cost, low effort and relatively fast manner are examples of this technology strengths. In this work, we report a bibliometric analysis of the literature published between 2004 and 2023 related to the use of 3D printing technology in education. WebofScience library was utilized to extract the related literature. This paper offers a comprehensive look at how 3D printing is used in education, highlighting its evolution and emerging trends. It emphasizes the need for a bibliometric review due to the growing volume of related research. The findings pinpoint recent advancements, identify research gaps, and suggest future avenues for exploration, including broader research collaborations and innovative teaching methods. Results from this review indicate an increase in publication in the years between 2020 and 2023. Moreover, the number of publications from the USA was the highest among other countries included in this survey. Publications in the medical field predominant other topics as well as Medical focused journals. Main key words use by authors were such as “3D printing”, “Hands-on learning/manipulatives” and “Medical education”.



Keywords: 3D printing, Bibliometric analysis, Education, Teaching, Learning, Educational aids

Introduction

3D printing technologies have emerged as a transformative force, reshaping industries, and redefining the possibilities of manufacturing [1]. This revolutionary approach involves the layer-by-layer construction of three-dimensional objects from digital models, offering unparalleled flexibility and customization. Initially conceived for rapid prototyping in manufacturing processes, 3D printing has swiftly evolved, infiltrating diverse fields with its innovative applications.

The most commonly used 3D printing technologies encompass various methodologies, each with its unique approach to creating three-dimensional objects. As an example of such technologies, fused deposition modeling (FDM) relies on the extrusion of heated thermoplastic filament layer by layer, following a predetermined pattern to construct the final object. Another example is stereolithography (SLA) employs a liquid resin cured by ultraviolet light, with a build platform incrementally moving downward as each layer solidifies. Additionally, selective laser sintering (SLS) utilizes a powdered material, typically a polymer or metal, which is selectively fused by a laser to form successive layers and achieve the desired shape. These technologies have revolutionized manufacturing by offering versatile solutions for prototyping, customization, and the production of intricate designs across various industries [2]. **Figure (1** shows examples of the previously mentioned technologies.

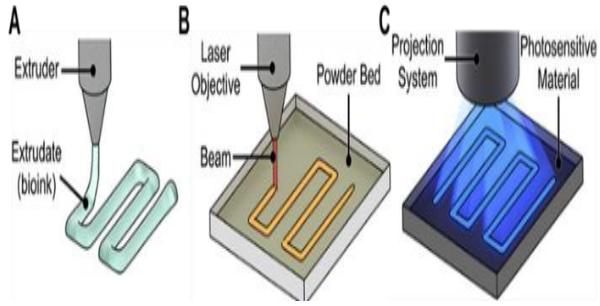


Figure (1): Different 3D printing technologies, (A) Fused Deposition Modeling, (B) Selective Laser Sintering and (C) Stereolithography. Adapted with permission from [3]. Copyright (2016) American Chemical Society.

In recent times, 3D printing technologies have captured the imagination of researchers, engineers, and designers across various domains, sparking a surge in interest and exploration. Industries ranging from healthcare [4] to architecture [5], and aerospace [6] to consumer goods [7], are witnessing a paradigm shift as 3D printing continues to redefine traditional production methods. This surge in interest is not merely confined to large corporations but extends to a global community of innovators, contributing to a dynamic and ever-expanding landscape of 3D printing applications.

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One of the noteworthy aspects of this technological revolution is its profound impact on education. Beyond its industrial applications, 3D printing has emerged as an invaluable tool for enhancing the learning experience [8–10]. In educational settings, 3D printing provides a tangible and interactive dimension to theoretical concepts, allowing students to materialize their ideas and gain hands-on experience in a wide array of subjects. From physics and biology to design and engineering, educators are increasingly incorporating 3D printing into curricula to foster creativity, problem-solving skills, and a deeper understanding of complex concepts.

Bibliometrics analysis is key for following up current trends in research and anticipating future interest. There have been several bibliometrics reviews published related to 3D printing in the past years. However, their main focus was on the industrial applications of this technology or the research and development to mitigate its limitation. Few other reviews focused on more specific topics of using 3D printing. Pernaa et al. [11] Published a systematic literature analysis aimed at comprehensively review prior research on the incorporation of 3D printers in chemistry education. Findings suggest that while 3D printing has been primarily employed for producing research instruments, there is a notable gap in understanding its impact on learning and students' perceptions, highlighting the need for comprehensive student-centered pedagogical models in this context. Ford and Minshall [12] published a review article on where and how 3D printing is used in teaching and education. As a result of their review, the utilization of 3D printing in educational environments such as schools, universities, libraries, and special education settings, six distinct use categories have been identified and delineated. These categories include using 3D printing: (1) as an instructional tool for students; (2) to educate educators about 3D printing; (3) as a supplementary technology during teaching sessions; (4) to fabricate artifacts that enhance the learning experience; (5) to develop assistive technologies; and (6) to support outreach activities. Despite finding instances of 3D printing-based teaching practices within these categories, the implementation remains in its early stages, prompting recommendations for future research and educational policy enhancements.

We have conducted this bibliometrics analysis to better understand the current interest in 3D printing technology as a tool to support educational practice from a general perspective. Currently, there is a scarcity of similar bibliometric reviews that look at the subject from a broader perspective. We aim to fill this gap by offering a comprehensive overview of the research landscape surrounding the utilization of 3D printing in education. Through its broad perspective, this review seeks to provide valuable insights into the trends, patterns, and research directions within this rapidly evolving field. In the current work, we have analyzed the included publications and highlighted different aspects such as topics, countries, number of citations among others. This was done with the aim of overlaying where this technology is better acting and what will be its future. This bibliometric review focused on the following research questions:

- What is the current state of using 3D printing in education, this includes different educational aspects, key publications and collaboration patterns?
- What is the main used terminology related to 3D printing in the context of education.
- What are the trends and future perspectives of using 3D printing technology as a facilitating tool for education?

Materials and Methods

Methods

The objective of this research is to uncover the patterns and trends within studies that explore the use of 3D printing technologies in education. This is achieved through a bibliographic analysis of pertinent publications. Bibliometric analysis, a well-established method for examining published articles, is employed to discern research developments in a given field [13]. This approach illuminates the scientific landscape by emphasizing the publication patterns of scholarly work. The study encompasses the examination of authors, collaborations, keywords, and citations in publications, aspects that have been extensively addressed in previous bibliometric analyses [14,15].

Data Collection

Included publications regarding the application of 3D printing in education were gathered from the WebofScience, a database chosen for its extensive coverage of the literature [16] and its widespread use in related bibliometric studies. A variety of keyword combinations were employed in the search process [17]. This was implemented via the following code: “TI=(((3d) or (three ADJ dimension*) or (3 ADJ dimension*)) adj (print* or manufact*)) OR AB=(((3d) or (three ADJ dimension*) or (3 ADJ dimension*)) adj (print* or manufact*)) OR TI=((Rapid ADJ protyp*) or (Rapid ADJ manufacturing) or (Addictive ADJ manufacturing) or Stereolithograph* or (Fused ADJ Deposition ADJ Model*) or (Layered ADJ Object ADJ Manufact*)) OR AB=((Rapid ADJ protyp*) or (Rapid ADJ manufacturing) or (Addictive ADJ manufacturing) or Stereolithograph* or (Fused ADJ Deposition ADJ Model*) or (Laser ADJ Sinter*) or (Layered ADJ Object ADJ Manufact*))”

The publication period spanned from 2004 to 2023, with a focus only on English-language articles published in scientific journals excluding literature reviews. To ensure relevance, a filter provided by Web of Science, termed "Web of Science Categories" was applied, allowing only articles within the categories of "Education Scientific Disciplines" or "Education Educational Research" to be included. This refined search yielded 503 articles that were incorporated into this review. Subsequently, the bibliometric data pertaining to the search results was extracted from the databases for further analysis.

Data analysis

The generated file from Web of Science was then processed using VOSviewer (v1.6.20) to produce visual representation of the data. Moreover, a custom Python code was developed to perform quantitative data analysis.

Results

This study aims to analyze articles published from 2004 to 2023. The subsequent sections delve into various facets, providing readers with insights into the recent trends within the articles covered in this review. Furthermore, the presentation encompasses significant elements such as key publications, prolific authors, and the primary countries contributing to the majority of the published works.

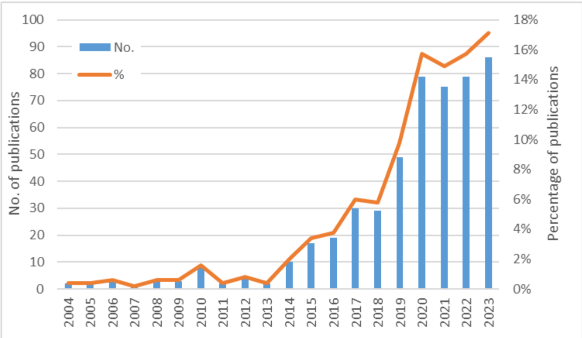

Figure (2): No. of articles published vs. year of publication.

Table (1): Overview of top 10 journals in which most articles were published.

Journal	No. of publication	%	Impact factor
Journal Of Chemical Education	99	19.7	3.0
Anatomical Sciences Education	29	5.8	7.3
European Journal of Dental Education	25	5.0	2.4
International Journal of Engineering Education	21	4.2	-
Bmc Medical Education	20	4.0	3.6
Journal Of Surgical Education	19	3.8	2.9
American Journal of Physics	15	3.0	0.9
Journal Of Veterinary Medical Education	14	2.8	-
Computer Applications in Engineering Education	14	2.8	2.9
European Journal of Physics	13	2.6	0.7

Overview of publications

The published work in the field of 3D printing related to education began with a small interest starting from 2004. The ending of the patent owned by Stratasys 2009 opened the door for much cheaper 3D printers to be available in the market [18]. Moreover, the growing of the RepRap society was obvious, who introduced the first do it yourself (DIY) fused filament fabrication 3D printer. This paved the way for the experimentation of using 3D printing technologies in many fields. Therefore, the year 2014 witnessed the start of an increase in interest with around 10 publications. Afterwards, the published work in this field increased rapidly reaching around 80 publications per year in the year from 2020 to 2023 (Figure (**2**). Around 63.5% of publications retrieved were published in those years. The total number of publications included in this analysis is 503 which were published in 127 sources. Around 54% of the included publications were published in about 8% of the included journals. The Journal of Chemical Education included the highest number of publications having 19.7%. The Anatomical Sciences Education journal was the second in the list shown in Table (**1** (5.8%) and with the highest impact factor, 7.3, among the top 10.

Authors working in this field spread all over the world. However, most of the published work came from the USA with around (36.4%). China, Germany and Australia came after with a total number of publications of 10.5%, 6.8% and 6.2%, respectively (Figure (**3**). The University of Pennsylvania was the highest university in terms of number of publications (7.5%) followed by the University of California and the University of Nebraska (5.8%). The University of Toronto in Canada was among the top ten universities in term of number of publications (4.6%). In Singapore and the UK, Nanyang Technological Univesity and the University of Bristol were among the top ten universities as shown in Table (**2** with 3.2% and 2.4% of the total number of publications included in this review. Figure (**4** illustrates the collaboration among countries for the articles included in this review. The size of the circle represents the number of published articles for the specific country and the color of represents clusters with strong co-authorship.

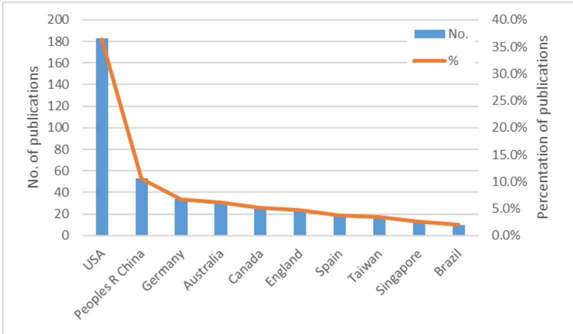

Figure (3): Top 10 countries in terms of publication.

Table (2): Top 10 Universities in terms of publications.

University name	Country	Count	%
University of Pennsylvania	USA	36	7.2
University of California	USA	29	5.8
University of Nebraska	USA	26	5.2
University of Florida	USA	24	4.8
University of Toronto	Canada	23	4.6
University of North Carolina	USA	21	4.2
University of Indiana	USA	20	4.0
University of Georgia	USA	16	3.2
Nanyang Technological University	Singapore	16	3.2
University of Bristol	UK	12	2.4

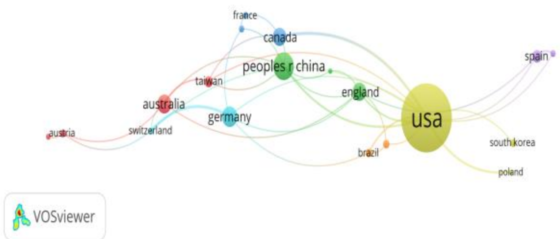

Figure (4): Co-authorship based on countries.

Table (3): Top 5 highly cited authors.

Author name	Research field	Affiliation	Number of Publications	Number of citations
Justin W. Adams	Medical	Monash University	4	730
Sreenivasulu R. Mogali	Medical	Nanyang Technological University	6	126
Wai Y. Yeong	Engineering	Nanyang Technological University	5	123
Garry Falloon	Education	Macquarie University	5	87
Paul G. Stevenson	Medical	Telethon Kids Institute	5	87

Highly cited work

Justin W. Adams, who was the most cited author, came from Monash University in the USA. Within the included publications in this survey, he produced four articles. As shown in Table (**1** and Table (**3**, researchers and journals with a medical background predominant production of the published work included in this study. McMenai et al. [19] produced the mostly cited article with 421 citations. This work was published in the Journal of Anatomical Sciences Education. Lim et al. [20] produced the second highly cited publication with 279 citations which was published in the same journal. As shown in Table (**4**, most of the top 10 highly cited articles were published in the Anatomical Sciences Education journal. Follows, brief description of the top 10 highly cited articles.

Table (4): Top 10 highly cited articles.

Article Title	Authors and years	Source of publication	Times Cited
The Production of Anatomical Teaching Resources Using Three-Dimensional (3D) Printing Technology	McMenamin et al., 2014, [19]	Anatomical Sciences Education	421
Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy	Lim et al., 2016, [20]	Anatomical Sciences Education	279
Usage of 3D models of tetralogy of Fallot for medical education: impact on learning congenital heart disease	Loke et al., 2017, [21]	BMC Medical Education	123
Teaching UV Vis Spectroscopy with a 3D-Printable Smartphone Spectrophotometer	Grasse et al., 2016, [22]	Journal of Chemical Education	121
Use of 3-Dimensional Printing Technology and Silicone Modeling in Surgical Simulation: Development and Face Validation in Pediatric Laparoscopic Pyeloplasty	Cheung et al., 2014, [23]	Journal of Surgical Education	118
Take away body parts! An investigation into the use of 3D-printed anatomical models in undergraduate anatomy education	Smith et al., 2018, [10]	Anatomical Sciences Education	114
3D Printed Molecules and Extended Solid Models for Teaching Symmetry and Point Groups	Scalfani & Vaid, 2014, [24]	Journal of Chemical Education	112
Evaluation by medical students of the educational value of multi-material and multi-colored three-dimensional printed models of the upper limb for anatomical education	Mogali et al., 2018, [25]	Anatomical Sciences Education	86
Injecting Realism in Surgical Training-Initial Simulation Experience with Custom 3D Models	Waran et al., 2014, [26]	Journal of Surgical Education	84
3D Printout Models vs. 3D-Rendered Images: Which Is Better for Preoperative Planning?	Zheng et al., 2016, [9]	Journal of Surgical Education	82

McMenamin et al. [7] reported how additive manufacturing, specifically three-dimensional (3D) printing, facilitates the generation of replicas of dissected human cadavers and other anatomical specimens, addressing various challenges. These 3D prints are precise, high-resolution reproductions in accurate colors, utilizing data from surface scanning or CT imaging. The report illustrates the application of 3D printing in creating models that depict negative spaces and incorporate contrast CT radiographic data through segmentation software. The accuracy of these printed specimens is then compared to that of the original ones. This innovative method offers numerous advantages over plastination, allowing for swift, scalable production of multiple copies of dissected specimens at any size, making it suitable for teaching facilities globally while mitigating cultural and ethical concerns associated with cadaver specimens, whether embalmed or plastinated.

Lim et al. [20] evaluated the efficacy of 3D prints in comparison to cadaveric materials for acquiring knowledge in external cardiac anatomy. The results from this preliminary investigation indicate that the use of 3D prints does not put students at a disadvantage when compared to cadaveric materials. Moreover, the findings suggest that, to the fullest extent, 3D prints may provide specific advantages in learning anatomy. This supports their incorporation and continual assessment as supplementary tools in curriculums based on cadaveric materials.

Loke et al. [21] study aimed to assess the impact of 3D models on the understanding and learning of tetralogy of Fallot among pediatric residents after a teaching session. Thirty-five pediatric residents were included in the study, showing no significant differences in background characteristics, including previous clinical exposure to tetralogy of Fallot. In the group presented with 2D images and the group presented with 3D models, similar levels of knowledge acquisition were observed based on post-test scores. However, residents taught with 3D models reported higher composite learner satisfaction scores ($P = 0.03$). Although the 3D model group also demonstrated higher self-efficacy aggregate scores, the difference was not statistically significant ($P = 0.39$).

Grasse et al. [22] presented a cost-effective 3D-printable smartphone spectrophotometer designed to maintain the required functionality and analytical accuracy for instructing principles such as the Beer−Lambert Law. The optical components are organized intuitively, providing accessibility for students to observe and experiment with relevant parts and parameters. In this context, they detailed the device and offer exercises aimed at imparting various concepts in analytical spectrophotometry.

Cheung et al. [23] detailed the creation and face validation of a simulator for pediatric pyeloplasty, constructed using a cost-effective laparoscopic dry laboratory model developed through 3D printing and silicone modeling. The model exhibits favorable characteristics in terms of usability, realism, and tactile sensation. Additionally, it is compatible with imaging under common modalities, showcasing its potential as an effective educational tool.

Smith et al. [10] presented in a comprehensive four-stage mixed-methods study assessing the educational efficacy of 3D-printed anatomical models in a medical program, various approaches were employed. The study included a quantitative pre/post-test to measure knowledge change, student focus groups, qualitative student questionnaires on individual model usage, and teaching faculty evaluations. The utilization of 3D-printed models in small-group anatomy sessions led to a significant knowledge increase compared to traditional 2D-image teaching methods ($P < 0.0001$). Student feedback identified key themes such as model properties, teaching integration, resource utilization, assessment, clinical imaging, and pathology. Questionnaire responses highlighted diverse ways students incorporated the models into their home study environment, integrating them with anatomy resources. In conclusion, 3D-printed anatomical models, derived from CT data of a deceased donor, prove successful as standalone teaching tools and valuable supplements to established learning methods like dissection-based teaching in anatomy education.

Scalfani & Vaid [24] generated a set of digital 3D design files representing molecular structures, designed for teaching chemical education topics like symmetry and point groups. This article discusses two main methods for preparing 3D printable chemical structures, both initiated with either a crystallographic information file (cif.) or a protein databank (pdb.) file and ultimately converted into a 3D stereolithography (stl.) file using commercially and freely available software. From this series, 18 molecules and 7 extended solids were successfully 3D printed. Their findings affirm that the discussed file preparation methods are effective for creating 3D printable digital files of chemical structures, and 3D printing stands as an excellent means for producing accurate models of molecules and extended solids.

Mogali et al. [25] proposed that 3D printed models have the potential to either substitute or enhance current resources in anatomical education. A novel multi-colored, multi-material 3D printed model of the upper limb, with a spatial resolution of 1 mm, was developed based on a plastinated upper limb prosection, encompassing muscles, nerves, arteries, and bones. This study investigates the educational value of the 3D printed model from the learner's perspective. Fifteen students compared the 3D printed models with plastinated prosections, sharing their views through a survey and focus group discussion. The 3D printed models received positive feedback for accurate anatomical features, color-coded tissue representation, flexibility, and ease of handling, providing a valuable addition to anatomical education alongside wet cadaveric or plastinated prosections.

Waran et al. [26] study aimed to evaluate the efficacy of employing models for training surgeons in performing standard procedures involving intricate techniques and equipment. All participating surgical candidates successfully acquired the foundational knowledge of the surgical procedure introduced in the workshop. The number of attempts and time invested in the learning process were indicative of each candidate's seniority and prior experience. Considering the need for surgical trainees to undergo multiple attempts when learning crucial procedures, the utilization of these models in surgical training simulation offers a safe environment for repetitive practice until proficiency is achieved. Theoretically, this approach could expedite the learning curve while standardizing the teaching and assessment methods for these trainees.

Zheng et al. [9] study presented three distinct cases of pancreatic cancer to surgical residents using 3D-rendered images and 3D-printed models to determine the most effective modality for devising preoperative plans. Thirty first-year surgical residents were randomly assigned to two groups. In addition to traditional 2D computed tomography images, Group A examined 3D computer models, while Group B reviewed 3D-printed models. Residents in group B exhibited notably higher scores in the quality of surgical plans compared to those in group A. This discrepancy primarily stemmed from a significant variation in understanding key surgical steps between the two groups. Participants universally expressed a high level of satisfaction with the exercise. The findings from this study substantiate the hypothesis that 3D-printed models enhance the quality of preoperative plans for surgical trainees.

Keywords analysis

Based on the articles included in this review, 3D printing was used as a keyword in 25.4% of the articles. "Hands-on learning/manipulatives" and "Medical education" were mentioned 11.9% and 6.7%. This indicates that the research in the medical sector predominant the production of publication using 3D printing technologies for educational purposes. **Figure** (**5** shows frequency of the top 20 keywords. "Additive manufacturing" was 3.4% which indicates that "3D printing" is the most adopted term among researchers in the education sector. **Figure (**6 shows an illustration of the co-occurrence based on Author keywords. The greater the number of connections between the two bubbles, the higher the frequency of their co-appearance in publications, indicating a more robust correlation. Bubbles within the same cluster share a common color, signifying a stronger correlation among them.

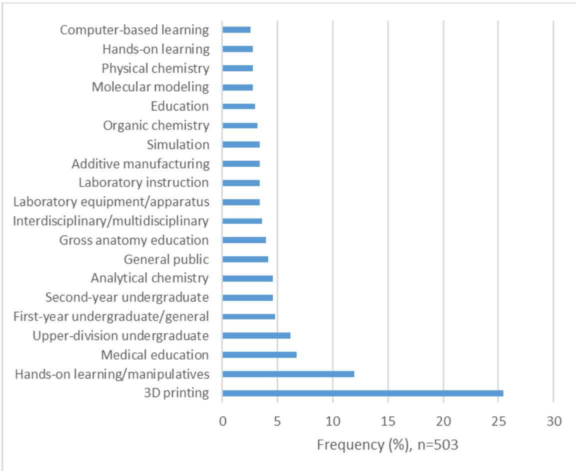

Figure (5): Frequency of Top 20 keywords mentioned.

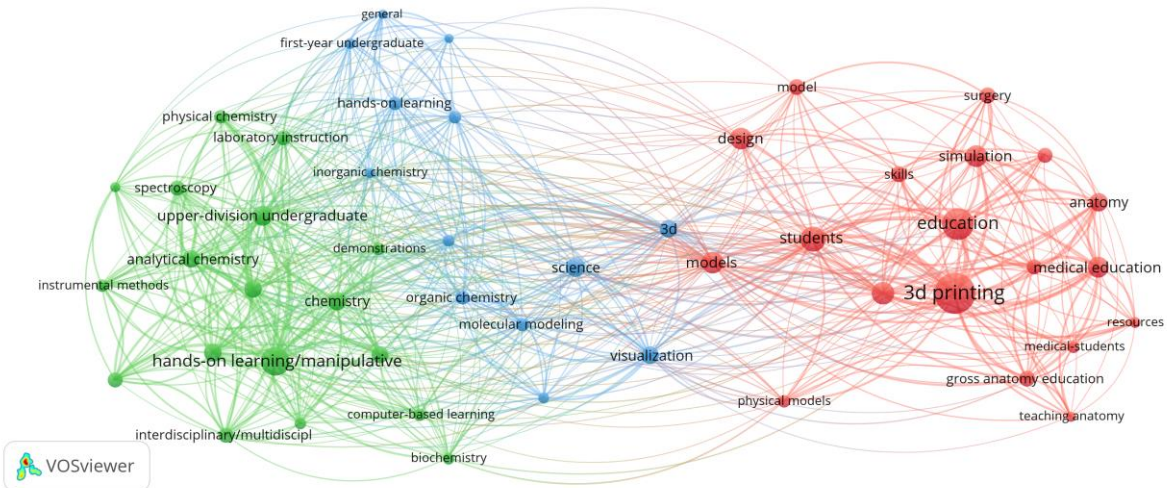

Figure (6): Co-occurrence of top 50 keywords based on All keywords.

Discussion and future perspectives

The application of 3D printing in education has closely mirrored technological advancements in the field, making it more accessible, affordable, and capable over time [27]. User-friendly software interfaces and educational resources have lowered barriers to entry for educators. Moreover, advancements in materials science have broadened the range of printable objects, enhancing hands-on learning experiences across various disciplines. For example, FDM printers, known for their affordability and ease of use, are versatile tools suitable for a wide range of educational applications, from science, technology, engineering and mathematics (STEM) subjects to arts and design, owing to their ability for easy experimentation and iteration with different materials with various properties [28]. SLA printers, characterized by high precision and intricate detail capabilities. This technology has relatively fast printing performance. However, it is based on ultraviolet curing of liquid resin, thus it requires more capable operators compared to FDM. Conversely, SLS printers excel in producing durable, functional parts with complex geometries and superior mechanical properties, despite their higher cost and specialized operational requirements. This technology can be used in producing training models for the purpose of medical training for example [29]. In educational settings, the choice among these technologies hinges on factors such as cost, ease of use, material options, and specific application needs, guiding educators to select the most suitable option to enhance learning experiences and achieve educational objectives.

Integrating 3D printing into pedagogical models enhances hands-on learning across diverse subjects, including humanities and arts education. For example, in history classes, 3D-printed models of ancient structures facilitate discussions on architectural styles. In literature studies, tangible representations of fictional settings foster deeper engagement. Pikkarainen and Piili [30], developed a technical pedagogy in which they introduced a methodology for integrating 3D printing in educational curricula. Moreover, Brumpt et al. [31] ran a systematic review to investigate the applicability of using 3D printing to produce anatomical models for medical training. They found that the use of 3D printing is an effective tool for teaching. Additionally, interdisciplinary projects combining history, literature, and art promote critical thinking and creativity. Bower et al. [32] discussed the concept of Makerspaces pedagogy. They found that the use of tools such as 3D printing among others for low-cost fabrication is to be effective for enhancing STEM education. Moreover, Tanabshi [33] showed how barriers may be overcome between different disciplines using 3D printing technology. Moreover, it promotes hands-on-experience, collaboration, and in-depth understanding of the taught topic.

The accessibility of 3D printing technology varies globally, prompting efforts to bridge accessibility gaps through initiatives providing affordable solutions and educational programs. Despite variations in accessibility, ongoing efforts strive to ensure inclusivity and innovation in education. One of the main initiatives that led the accessibility of fabricating tools such as 3D printing is the fabrication laboratory (Fablab) initiative led by Prof. Neil Gershenfeld [34]. This initiative included a handbook and recourses for establishing a hub for fabricating and building DIY products in a low-cost manner. They also provide alternatives for outsourcing or building low-cost machines such as DIY 3D printers. This allowed even less developed regions with limited financial resources to join. Additionally, the start of the Maker Movement which aims at encouraging the public to build stuff and experience the DIY concept [35]. Those two movements found their way into educational institutions as an essential asset for teaching students and educators how to teach fabricating stuff either for learning the process or for producing educational aids [36].

The integration of 3D printing technologies across educational levels presents both challenges and opportunities. Soomro et al. [37] conducted a systematic review in which they showed how makerspaces, which usually includes 3D printing machines, contribute in fostering creativity, particularly in the STEM disciplines across different educational levels. Opportunities include hands-on learning experiences, interdisciplinary connections, personalized learning resources, project-based learning, and career preparation. Trust et al. [38] showed in their study that educators are keen on utilizing new technologies in the teaching practice. However, their knowledge and experience are very limited with such technologies. To enable effective incorporation of 3D printing into teaching practices, educators require specific training encompassing technical operation, curriculum design, design thinking, and fostering innovation. Pearson and Dubé [39] provided recommendations for how to approach and implement 3D printing in classroom based on theories such as situated learning, experiential learning, critical making, constructionism and self-directed learning.

Assessing the impact of 3D printing on learning outcomes requires various methodologies, including pre- and post-test assessments, qualitative methods, observational studies, longitudinal studies, and comparative studies. There have been many studies published confirming the positive impact of utilizing 3D printing technologies in education. In medical education, Shi et al. [40] conducted a literature review on the use of this technology in fracture teaching and medical learning. The use of 3D printing improved the effectiveness of teaching and learning in this domain. Additionally, Brunner et al. [41] utilized 3D scanning and printing to better train pediatric cardiologists. Both practical skills and theoretical understanding were significantly improved using this approach.

3D printing facilitates cross-disciplinary collaboration and raises ethical considerations, particularly regarding informed consent, privacy, accuracy, and cultural sensitivity. Policy implications related to 3D printing in education include funding allocations, safety regulations, intellectual property rights, and accessibility. Addressing security concerns requires clear policies, technological solutions, and educational initiatives. Rimmer [42] wrote about intellectual property, higher education and 3D printing in a global context. His conclusion is that the rise of 3D printing presents an opportunity for universities to advance public interests through open access, open data, and open innovation models. Additionally, he added that 3D printing prompts a need to update patent law, practice, and policy to accommodate disruptive technologies like 3D printing. However, since the rise of the maker movement, many websites base on the creative common license come to exist such as Thingiverse [43] and Grabcad [44]. Moreover, many contributors from the 3D printing community fed such online resources with designs and 3D printable files. Therefore, the current workflow of downloading a design, setting up a 3D printable file and clicking the print button on a 3D printer to fabricate this design can be done by a non-trained person. This helps greatly the implementation of this technology within educational systems without the need of heavily training requirements for the educators. However, more effort should be done still to produce handbook and practices on how to use this technology from an educational perspective.

Conclusion

This bibliometric examination sheds light on the literature spanning from 2004 to 2023, focusing on the utilization of 3D printing technology in education. It is evident that interest in this domain has surged, particularly over the past four years, with a predominant emphasis on publications in the medical field. This underscores the technology's wide-ranging benefits, including its utility in constructing educational models, preoperative planning, and training. The accessibility of user-friendly 3D printing machines, requiring minimal expertise, coupled with cost-effectiveness and rapid, labor-efficient production, has significantly contributed to the appeal of integrating 3D printing technology as an educational aid. Research on 3D printing technologies in education explores uncharted areas such as supporting diverse learning styles, interdisciplinary collaboration, and ethical, social, and cultural implications, paving the way for innovative teaching and learning approaches.

Disclosure Statement

- **Availability of data and materials:** All data included in this work can be requested from authors if needed.
- **Author's contribution:** Ali Shaqour & Bahaa Shaqour: Conceptualization, Methodology, Investigation, Supervision, Data collection, Data analysis, Writing – original draft, review & editing. Ataa Shaqour: Investigation, Data collection, Data analysis.
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