Emerging Trends and Future Directions in Fused Deposition Modeling: A Bibliometric Analysis (2013-2023)

Fatiha Rabbaje[1*], *Abdelmajid* Ait Taleb[1], and *Larbi* Lasri [1]

[1]jm Mechanical and Structural Engineering Department, ENSAM, University of Moulay Ismail,Meknes, Morocco,

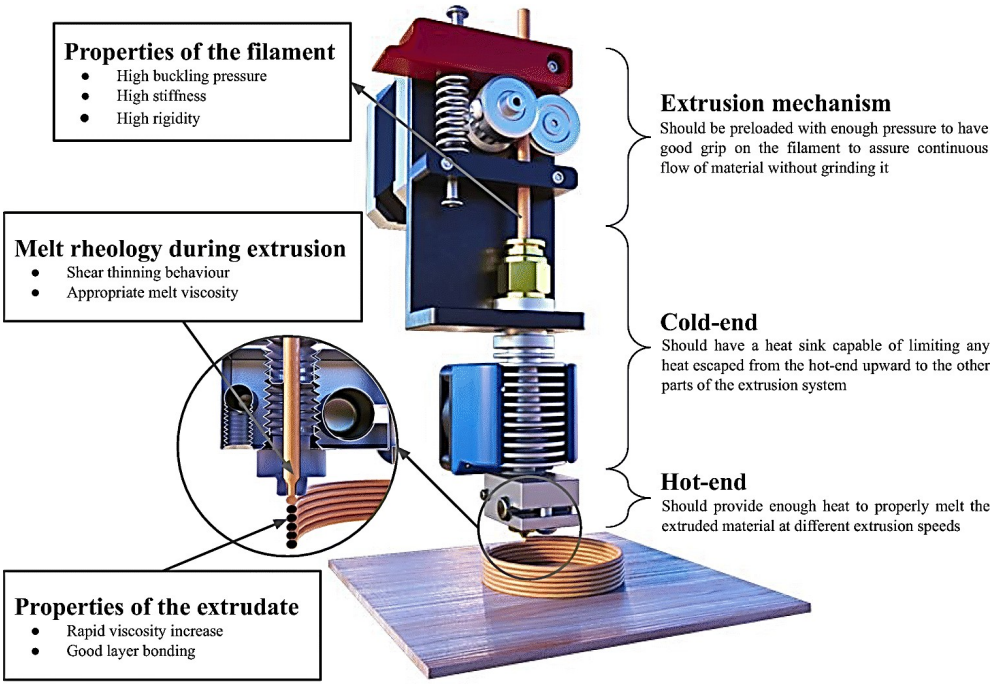
Abstract. This bibliometric overview provides a detailed and comprehensive analysis of the research conducted on Fused Deposition Modeling (FDM) technology from 2013 to 2023. The analysis includes a thorough examination of publications, conference papers, and patents related to FDM technology. The overview offers valuable insights into the evolution, current state, and prospective trajectories of FDM technology. The analysis covers a wide range of topics related to FDM technology, including its applications, advancements, limitations, and prospects. This bibliometric overview aims to help researchers gain a deeper understanding of the FDM technology and its potential applications. It offers a comprehensive overview of the current state of research in the field and identifies new areas of research that could lead to significant advancements in FDM technology. The study utilized bibliometric indicators and network analysis methodologies, encompassing keyword analysis, citation metrics, journal productivity, associated publications, and author-related metrics. To conduct this analysis, two freely available software tools, VOSviewer and Bibliometrix [1], were employed.

Keywords: Fused Deposition Modeling; 3D printing; Bibliometric Analysis; VOSviewer; Bibliometrix.

* Corresponding author: f.rabbaje@edu.umi.ac.ma

1 Introduction

The Fused Deposition Modeling (FDM) process is a type of additive manufacturing [2] or 3D printing technology that involves creating objects layer by layer by extruding melted material through a nozzle. These technologies can simplify the entire fabrication process into a single step, produce complex designs, reduce production cycle time and cost, and increase reproducibility. As a result, they have found wide applications in various industries, including pharmaceuticals, biomedicine, soft robotics, flexible electronics, aerospace, automotive, and architecture. Fused deposition modeling (FDM) has become increasingly popular due to its cost-effectiveness in terms of both the printer and materials used, as well as its user-friendly and compact equipment features.
The FDM process initiates with a digital model, typically created using computer-aided design (CAD) software [3]. This digital blueprint guides the FDM printer, dictating the precise dimensions and structure of the intended object.
In this process, the filaments are extruded in layers parallel to the X-Y plane and the layers are built in a successive manner in the Z-direction to create a layer-by-layer 3D part. The extrusion system within FDM 3D printer plays a critical role in the printing process. This component of the printer comprises several distinct sections:.
1. A motor responsible for pushing the filament forward.
2. A barrel through which the filament passes without undergoing melting.
3. A heating block where the filament is heated until it melts.
4. A nozzle that facilitates the transition of the material's cross-sectional area from the filament to the desired size for the printed road .
These individual sections are visually represented in Figure 1.
This layering process enables the creation of complex geometries and intricate designs with relative ease. Moreover,



FDM offers versatility in material choices, allowing for the use of various thermoplastics with different properties, colors, and even composite materials [4].

The technology's adaptability, relatively low cost, and accessibility have popularized FDM across industries, including prototyping, structural electronics [5], automotive, aerospace, healthcare, construction [6] and education [7]. Its capability to swiftly produce custom, functional prototypes or end-use parts has established FDM as a valuable tool in modern manufacturing and rapid product development workflows [8].

The objective of this work is to comprehend the research status and development trends in the FDM field and identify its potential applications in different branches of industry. Since its invention in 1984, numerous studies have been conducted, which have formed an important and valuable foundation. Therefore, it is crucial to carry out a bibliometric study that maps out the current guidelines in this domain. The bibliometric analysis conducted provides insight into the most influential authors, highest cited papers, journal publications, and collaboration countries in FDM-related research. This information can inspire researchers in their future research. The analysis was combined with knowledge domain mapping methods to examine trends in the current state of research and development in FDM-related researchs.

This document is structured into two primary sections: the initial section details the methodology adopted, while the second section presents the findings, organized into four subsections. The first subsection delineates the progression of scientific publications, while the second subsection Examining the occurrence of keywords provides insights into the predominant FDM processes and their significance, derived from the terminology employed in the reviewed papers. The third subsection focuses on citation analysis, elucidating the fundamentals. The fourth and concluding section delves into supplementary indicators, encompassing significant aspects such as the most prolific author, influential publication, impactful journal, and collaborative efforts among countries engaged in research related to FDM.

2 Methodology

Bibliometric analysis is a rigorous method to explore scientific data. It helps to understand the evolution and emerging areas of a specific field [9]. Bibliometric analysis involves analyzing vast amounts of data, including citations, publications, and keywords. Bibliometric analysis is a useful tool for understanding the collective scientific knowledge and development of literature [10]. It can help researchers to gain a comprehensive understanding of a field, identify gaps in knowledge, generate new research ideas, and position their contributions to the field. Bibliometric studies can provide a solid foundation for advancing a field in meaningful and innovative ways. In essence, it allows scholars to make sense of large volumes of unstructured data and map out the evolutionary nuances of literature fields.
The field of bibliometrics relies on various indicators such as citation counts, H-index, Journal Impact Factor, and keyword occurrence. In recent years, bibliometric studies have gained interest across multiple research disciplines [11].
Performing a bibliometric analysis involves four basic steps: defining the search criteria, keywords, and periods; selecting the database, processing data, and analyzing results and discussions. When conducting a bibliometric analysis, it is important to choose the appropriate database to collect items. Web of Science (WoS) and Scopus are the most commonly used databases to extract published articles in a particular field. Figure 1 shows a sequence process flow of the four stages of bibliometric analysis.
We conducted a bibliometric study to understand the trends in the Fused Deposition Modeling (FDM) research domain. The study involved examining scientific documents related to FDM retrieved from the Scopus Core Collection database over the last decade (2013 to 2023). To collect data, we used "Fused Deposition Modeling" and "Fused Filament Fabrication" and "Material Extrusion» as search terms. These terms were selected because they are frequently used to refer to this technology. We considered all forms of expression writing, such as used "Fused Deposition Modeling" and 'FDM'. The collected items belong to different manuscript types, like articles and conference proceedings. We obtained 6968 documents found from the SCOPUS Core Collection database from 2013 to 2023.
The first step in our process is to clean the database to ensure that the data is correct and usable. We filtered the collected data by language, keeping only English manuscripts, and then removed duplicate items, to achieve this, we used the Excel filter tool on the title and keyword fields, resulting in 4002 articles. Next, Figure 2 illustrates the main steps of the methodology followed.

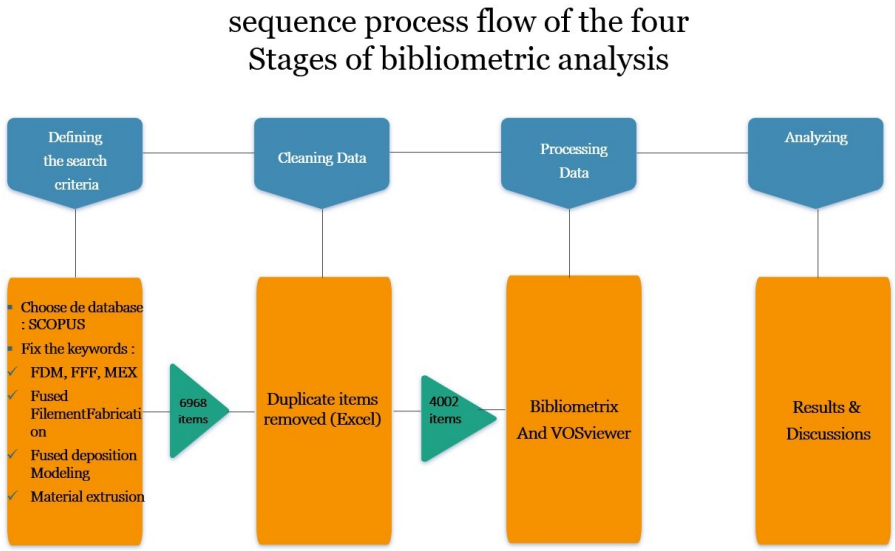


Figure 2

We used the freely available bibliometric analysis software VOSviewer [12] and Bibliometrix [13] to analyze and visualize the publications. VOSviewer is a computer program that enables the graphical visualization of bibliometric network mapping. Its functionality facilitates the interpretation of maps and data.
Bibliometrix is a package for the R statistical programming language for quantitative research in scientometrics and bibliometrics. Bibliometrix is the application of quantitative analysis and statistics to publications such as journal articles and their accompanying citation counts.

3 Results and discussion

3.1 Scientific publications

The analysis of bibliometric results begins by examining the chronological progression of scientific productivity within the FDM field from 1990 to 2023. The annual quantity of scientific output is used as a metric for assessing the academic influence of this technology. It is noteworthy that scientific research has consistently grown year by year, steadily ascending. Figure 2 displays the annual count of FDM-related documents. The number of publications on FDM has significantly increased rising from 126 in 1990 to 4145 in 2023 across various research areas, including management and materials, medicine, fashion, construction, and other topics. The results indicate that in 2023, there was a significant increase of 14.8% in total publications (28025 publications). This exponential [14] growth justifies FDM's current strong position and suggests a promising future for the company, unexpected developments and innovations. Therefore, we consider it interesting to limit our systematic study to the period from 2013 to 2023, summarize the research hotspots during this period and explore new research areas and breakthroughs associated with development trends in related fields.

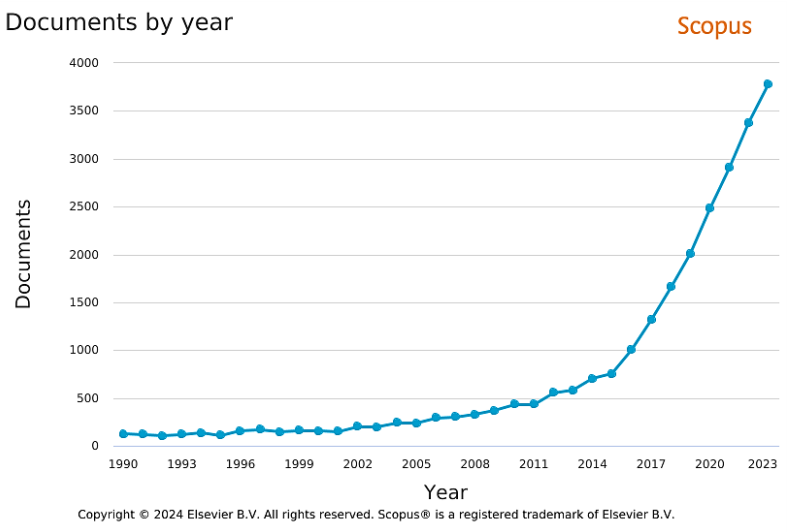


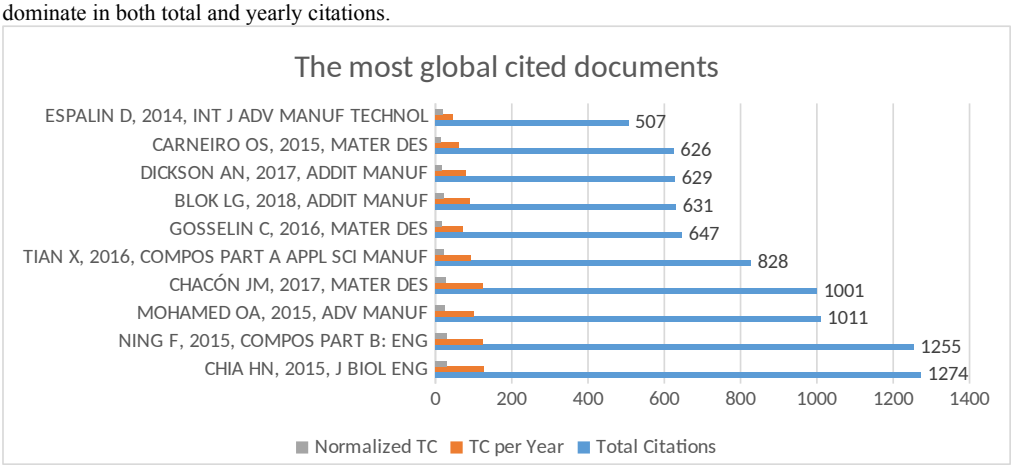
Figure 3 Scientific publications related to the FDM field.

3.2 Publications, authors, and country analysis

3.2.1 Most influential publications

Numerous academic papers published and cited by global researchers have greatly influenced the development of fused deposition modeling (FDM). A study analyzing 4,607 documents in the field of FDM from 2013 to 2023 presented the 10 most influential academic papers in the graph.

This graph highlights the most globally cited documents in the field, showing both total citations and citations per year. The paper by CHIA HN (2015) [15]in the Journal of Biological Engineering is the most cited, with 1274 citations, followed closely by NING F (2015) [16]in Composites Part B: Engineering with 1255 citations. Other notable papers, like MOHAMED OA (2015) and CHACÓN JM (2017), each exceed 1000 citations, indicating their high impact. On the lower end, ESPALIN D (2014) has 507 citations. The orange bars show the average citations per year, reflecting ongoing relevance, while the blue bars indicate the cumulative impact. Overall, the graph underscores the lasting influence of key research papers in this domain, particularly those published in 2015, which dominate in both total and yearly citations.



3.2.2 Most influential authors

Quantifying scientific output has gained significant importance within the scientific community. A range of indicators are employed to achieve this, including the h-index. In 2005, Hirsch suggested a measure that considers the quantity and impact of a researcher's publications, making it a powerful and simple indicator to calculate. The h-index quantifies the number of papers published by an author that have been cited h times. This section employs Bibliometrix to identify the top ten FDM publications and their most influential authors, based on 12125 papers retrieved from the SCOPUS database over the last decade.

Table 1 Most relevant authors 2013–2023

Authors	**TP**	**TNC**	**TNC/TP**	**h-index**
Singh, Rupinder K.R.	126	3051	24,214	35
Vidakis, Nectarios	50	1546	30,920	26
Petousis, A. Markos	48	1485	30,938	25
Kumar, Ranvijay Ranjith	37	631	17,054	15
Jain, Prashant Kumar	32	734	22,938	14
Mountakis, Nikolaos	29	702	24,207	18
Masood, S. H.	28	2468	88,143	21
Percoco, Gianluca	28	353	12,607	11
Singh, Sunpreet	28	950	33,929	16
Kechagias, John D.	27	815	30,185	20

Note: **TNC** = Total numbers of citations; **TP** =Total paper

Table 2 presents the top ten authors who have demonstrated significant productivity in Fused Deposition Modeling (FDM) research over the past decade, along with their respective h-index. The table features detailed information including the authors' full names, the number of full papers (TP) in the FDM field, total numbers of citations (TNC) from 2013 to 2023 average citations per paper (TNC/TP), and the h-index. Notably, the top three authors based on the h-index are:

- **Singh, Rupinder K.R**. with an h-index of 35, specializing in Feedstock; Reinforced Plastic; Fused Filament Fabrication.
- **Vidakis, Nectarios** with an h-index of 26 and a TNC/TP of 30,920, covering various aspects of Additive Manufacturing; 3D Printing; Fused Filament Fabrication.
- **Petousis, A. Markos** with an h-index of 25 and a TNC/TP of 30,938, focusing on Reinforced Plastic; Friction Stir Welding; Ultimate Tensile Strength.

3.2.3 Most influential countries

We used VOSviewer software to analyze the bibliographic coupling of countries in FDM publications. Our analysis uncovered that academic papers on FDM originate from a wide range of countries, with a total of 149 countries represented. Table 3 presents the top 20 most productive countries, ranked according to the total number of papers that contain additional information: **Total papers (**country's production**)**, **citations** (The number of times these documents have been cited in other research), **total link strength** (A measure of the collaborative or influential network strength between these documents and others). A higher total link strength suggests stronger research connections or collaborations.

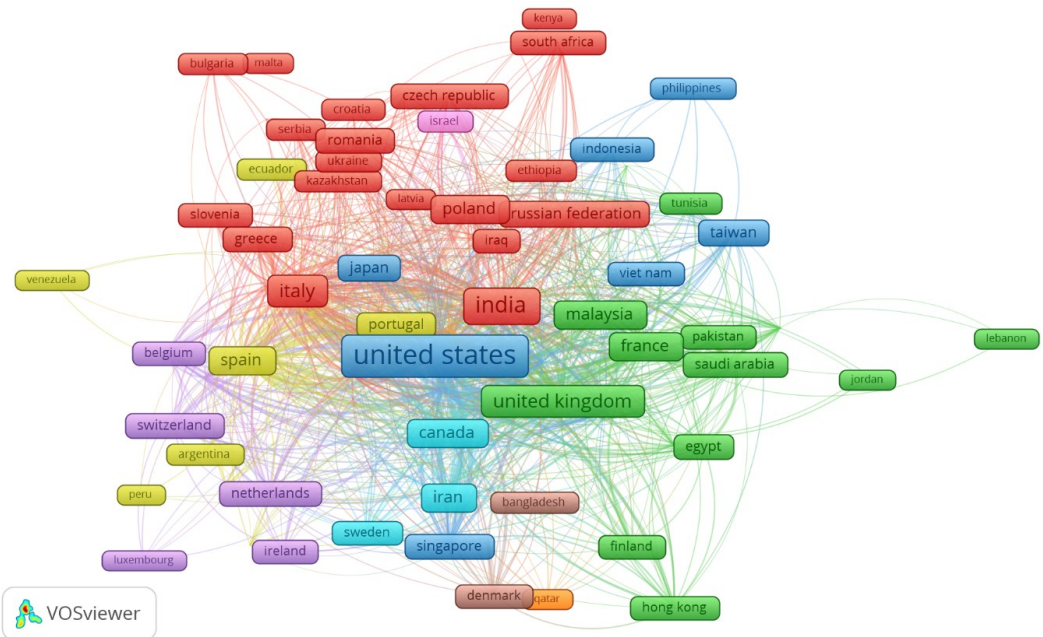
Table 4: The Ten Leading Countries in FDM Research Output from 2013 to 2023

country	Total papers	citations	total link strength
United States	2022	51870	123567
China	1548	33191	76266
India	1150	16328	59097
United Kingdom	556	14271	54543
Italy	617	13227	41240
France	304	7078	31435
Germany	562	9018	29950
Canada	326	7255	28573
Spain	325	8568	28317
Australia	276	8375	24918

- The **United States** stands out as the clear leader in research output, with **2 022 papers**, the highest number of 51 870 citations, and an impressive total link strength of 123 567. This signifies the country's dominance in both producing research and its collaborative strength within the academic community.
- Following the U.S., **China** ranks second with **1 548 papers**, 33 191 citations, and a strong total link strength of 76 266, establishing it as a major contributor to global research and collaborations.
- In third place, **India** demonstrates significant productivity with 1 150 papers, 16 328 citations, and a total link strength of 59 097. Despite producing fewer documents than China, India maintains a substantial presence in citations and collaboration strength.

Figure 4 represents a VOSviewer graph, it highlights the global collaboration network in the FDM field, showcasing the United States as the leading hub, with strong contributions from countries like India, the United Kingdom, and China. Different clusters reveal collaborative communities, either geographically based or thematically oriented, which form the backbone of global scientific production in this research domain. The network visualizes not only which countries produce the most research but also how interconnected they are within the global scientific community.

Figure 4 Top Research Nations and Their Networks in the FDM Field (2013-2023)



4 Conclusion

The bibliometric overview of Fused Deposition Modeling (FDM) research from 2013 to 2023 highlights the growing influence and extensive application of this technology across various industries, including aerospace, healthcare, and construction. The steady increase in publications and citations within this period reflects the expanding interest and advancements in FDM. Through an analysis of 4607 publications, the study identifies key trends, influential authors, major countries involved, and notable research collaborations. The United States, China, and India emerge as the top contributors to FDM research, underscoring their roles in driving global innovations.

The study also identifies the most cited papers, which have laid the foundation for FDM's progression, and highlights key researchers like Rupinder Singh and Nectarios Vidakis for their significant contributions to the field. Additionally, the results reveal new areas of potential research, particularly in the materials used for FDM, the optimization of printing processes, and interdisciplinary applications.

This bibliometric study serves as a valuable tool for researchers and industry experts to gain insights into the current state of FDM research, emerging trends, and areas requiring further investigation. The findings suggest a bright future for FDM, with continuous technological advancements and expanding applications across various domains.

References

[1] M. Aria and C. Cuccurullo, "bibliometrix: An R-tool for comprehensive science mapping analysis," *J Informetr*, vol. 11, pp. 959–975, 2017, doi: 10.1016/j.joi.2017.08.007.
[2] I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, "Development of Additive Manufacturing Technology," in *Additive Manufacturing Technologies*, I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, Eds., Cham: Springer International Publishing, 2021, pp. 23–51. doi: 10.1007/978-3-030-56127-7_2.
[3] R. Knoppers and R. Hague, "CAD for Rapid Manufacturing," in *Rapid Manufacturing*, 2005, pp. 39–54. doi: https://doi.org/10.1002/0470033991.ch4.
[4] C. Tuck and R. Hague, "Management and Implementation of Rapid Manufacturing," in *Rapid Manufacturing*, 2005, pp. 159–173. doi: https://doi.org/10.1002/0470033991.ch10.
[5] "IEEE Xplore Full-Text PDF:" Accessed: Feb. 10, 2024. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6766751
[6] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, "Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders," *Mater Des*, vol. 100, pp. 102–109, Jun. 2016, doi: 10.1016/j.matdes.2016.03.097.
[7] Ian Gibson and David Rosen, *Additive Manufacturing Technologies*. 2021.
[8] T. Gornet, "Materials and Process Control for Rapid Manufacture," in *Rapid Manufacturing*, 2005, pp. 125–146. doi: https://doi.org/10.1002/0470033991.ch8.
[9] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *J Bus Res*, vol. 133, pp. 285–296, 2021, doi: 10.1016/j.jbusres.2021.04.070.
[10] O. Ellegaard, J. A. Wallin, and S. Dk, "The bibliometric analysis of scholarly production: How great is the impact?," *Scientometrics*, vol. 105, pp. 1809–1831, 2015, doi: 10.1007/s11192-015-1645-z.
[11] R. Jemghili, A. Ait Taleb, and M. Khalifa, "A bibliometric indicators analysis of additive manufacturing research trends from 2010 to 2020," 2021, *Emerald Group Holdings Ltd.* doi: 10.1108/RPJ-11-2020-0274.
[12] H. Arruda, E. R. Silva, M. Lessa, D. Proença, and R. Bartholo, "VOSviewer and Bibliometrix," Dec. 08, 2022, *NLM (Medline)*. doi: 10.5195/jmla.2022.1434.
[13] C. Cuccurullo, M. Aria, and F. Sarto, "Foundations and trends in performance management. A twenty-five years bibliometric analysis in business and public administration domains," *Scientometrics*, vol. 108, no. 2, pp. 595–611, 2016, doi: 10.1007/s11192-016-1948-8.
[14] "Industrial 3D Printing Market Size, Share, Industry Report, 2027."
[15] H. N. Chia and B. M. Wu, "Recent advances in 3D printing of biomaterials," *J Biol Eng*, vol. 9, no. 1, p. 4, 2015, doi: 10.1186/s13036-015-0001-4.
[16] F. Ning, W. Cong, J. Qiu, J. Wei, and S. Wang, "Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling," *Compos B Eng*, vol. 80, pp. 369–378, Oct. 2015, doi: 10.1016/j.compositesb.2015.06.013.