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Research Article

After 3D Printing, What's Next: Discovering Scientific Trends of 4D Printing

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ABSTRACT

The field of additive manufacturing has seen the rise of 3D Printing and 4D Printing as noteworthy subjects of research. This study highlights the advancements in advanced Printing techniques. To identify, evaluate, and analyze the existing literature on this subject, the research followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, focusing on documents indexed in the Elsevier Scopus database. Through bibliometric analysis (BA), including co-authorship, keyword co-occurrence, and citations, the research landscape and scientific progress in this area were examined. The analysis revealed that a total of 1,638 documents have been published and indexed on this topic since its inception. The search was conducted on February 17, 2023, at 2:30 AM +8 GMT. The results indicated that articles are the primary form of publication, with a strong emphasis on Materials Science, Engineering, and Chemistry as the favored thematic subjects in the published works. Among the various sources of publications, ACS Applied Materials and Interfaces, published by ACS Publications, emerged as the most influential. On the research leadership front, Gladman A. Sydney, affiliated with Harvard University, was identified as the most influential lead researcher in this domain. Further examination revealed that prolific authors in this field are primarily associated with institutions in China, the United States, India, the United Kingdom, and Singapore. In conclusion, the findings highlight that the trend of 4D Printing within the scientific community is still in a phase of ongoing development.

Keywords*: 3d printing, 4d printing*

Introduction

Technology for 3D Printing has been around for approximately three decades. Yet, another technology is emerging as the additive manufacturing sector identifies new applications, materials, and printers. 4D Printing is an emerging trend in research and interesting topics in additive manufacturing, and the emerging industry is doing a significant amount of research to improve technological advancement in 4D Printing. A 3D-printed object can change into a different structure through the process of

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4D Printing under the impact of external energy inputs such as temperature, light, or other environmental stimuli (Chu et al., 2020).

4D Printing is an emerging technology that has the potential to revolutionize the way we create and interact with objects. It is an advanced form of 3D Printing that allows printed structures to self-assemble or transform over time when exposed to certain environmental stimuli, such as heat, water, or light. This technology is still in its infancy, but the potential applications are vast and varied, from the medical field to construction and aerospace (Ding et al., 2017; Wu et al., 2018). The concept of 4D Printing was first introduced in 2013 by Skylar Tibbits, an architect, and researcher at MIT. Tibbits envisioned a printing technology that could create objects that could change shape, size or even function over time. This technology could revolutionize manufacturing, making it more efficient and less wasteful (Kuang et al., 2019; Momeni et al., 2017; Sydney Gladman et al., 2016).

One of the most promising applications of 4D Printing is in the medical field. Researchers are exploring the potential of 4D Printing to create implants that can adapt and change with the human body. For example, 4D-printed stents could expand and contract as needed, reducing the risk of complications such as blood clots. 4D Printing could also be used to create artificial organs that can grow and adapt to the patient's needs (Javaid & Haleem, 2019; Sahafnejad-Mohammadi et al., 2022; Shakibania et al., 2021; Zhu et al., 2019). In the construction industry, 4D Printing could allow for the creation of buildings that can change and adapt over time. For example, buildings could change shape in response to changes in the environment, such as wind or temperature. This technology could also make construction more efficient and less wasteful, as buildings could be printed on-site using only the materials that are needed. The aerospace industry is another area where 4D Printing could significantly impact (Chu et al., 2020; Joshi et al., 2020; Wu et al., 2018). 4D printed parts could be designed to change shape in response to changes in the environment, such as temperature or pressure. This could lead to more efficient and safer aircraft that are better able to withstand the stresses of flight (Choi et al., 2015; Joshi et al., 2020; Kuang et al., 2019; Tibbits, 2014). As been observed by the researcher in the emerging trends in education and industry, it can be suggested that 4D Printing outputs may be economical and have environmental implications, outputs can be utilized during classroom discussion in replacement with other traditional methods (Mobo, 2021; Siman, 2023).

Despite the many potential benefits of 4D Printing, there are still many challenges that need to be overcome. One of the biggest challenges is the development of new materials that can self-assemble or transform in the way that is needed. Researchers are also working on improving the speed and accuracy of 4D Printing, as well as finding ways to integrate the technology with other manufacturing processes.

The Elsevier Scopus database's study of the literature on 4D Printing finds many published documents, including articles, reviews, and conference papers. The publications that have been published offer important insights into the ideas, concepts, tools/methods, opportunities, and difficulties in the additive manufacturing sector. On the other side, the books, conference papers, and reviews that have been published offering an overview or synopsis of the research on the subject.

There is an urgent need to critically examine the research landscape and scientific advancement of the topic, which is currently absent in the literature, given the extensive literature, theoretical concepts, and empirical discoveries on it. This paper aims to present and emphasize the scientific advancements and research advances in 4D Printing. It was hoped that the results would help bridge the gap between the vast amount of published material on the subject and a critical appreciation of the present state and potential future directions of the area.

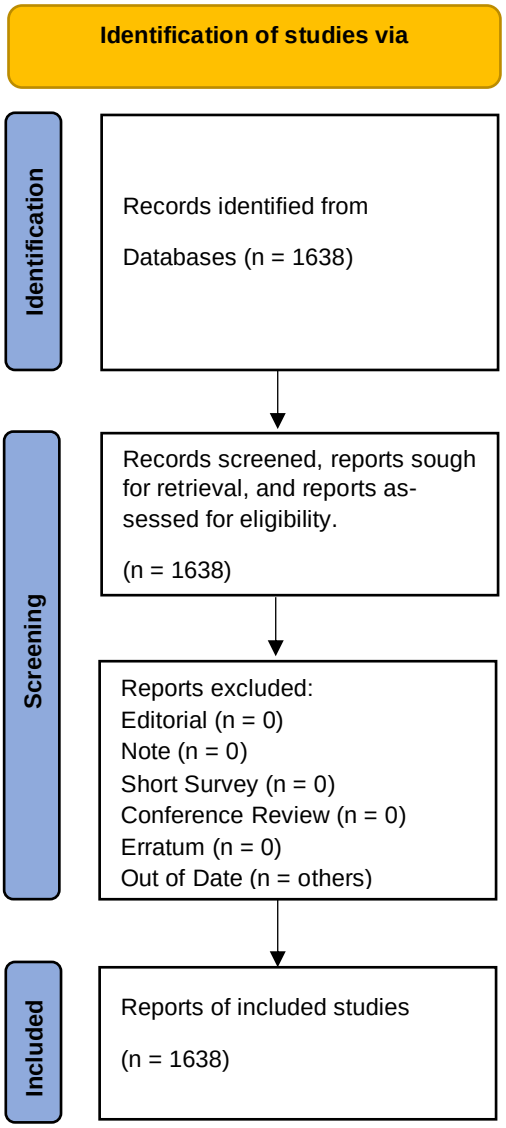


Figure 1. Simplified PRISMA Process adopted in this Bibliographic Analysis

Methodologies

In this study, the research trends within the domain of Industry 4.0 were investigated through a comprehensive bibliometric analysis spanning the years from 2011 to 2021. This specific timeframe was chosen due to its capacity to amass a substantial and dependable dataset, ideal for meticulous data analysis employing the VOSViewer software. Consequently, the research methodology adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach, serving as a framework for the identification, selection, and subsequent analysis of pertinent documents obtained from the Scopus database, a component of Elsevier's resources (Moher et al., 2009; Page & Moher, 2017; Sarkis-Onofre et al., 2021). The process of identifying and selecting relevant materials related to Industry 4.0 involved formulating search queries structured around relevant keywords. The search encompassed the period from the inception of the concept up until February 16, 2023. To capture an updated understanding of the subject, a search query labeled as "TITLE-ABS-KEY (4d AND Printing)" was executed in the Scopus database, ultimately yielding a compilation of documents pertaining to the topic. The results of this comprehensive search revealed a total of 1,638 documents that have been published and indexed since the initiation of the research. The actual search process was conducted on

February 17, 2023, at 2:30 AM, accounting for +8 GMT.

The assortment of documents procured was diverse, encompassing various formats such as articles, conference papers, reviews, book chapters, books, short surveys, as well as retractions, errata, and notes. These materials were further processed and consolidated into a CSV (comma-separated values) format for ease of handling and analysis. This collection was subsequently imported into the VOSViewer software, specifically version 16.6, to facilitate analyses involving co-authorship, co-occurrence of keywords, and citation patterns. This enabled a comprehensive assessment of the research landscape pertaining to the subject. Within the VOSViewer platform, intricate analyses were conducted to discern the key figures in the research landscape, including influential researchers, affiliated organizations, and countries actively engaged in the study of 4D Printing. By employing network visualization maps, the relationships and connections between authors, affiliations, organizations, and nations were meticulously explored and evaluated (van Eck & Waltman, 2009, 2011).

Results

Based on the papers recovered from the Scopus database and published from the beginning up to the recent date, the publication trends on 4D Printing were evaluated. The number of publications has significantly increased from the year 2019 to the present, according to the data under "publication counts." It demonstrates that between 2018 to the present, the number of publications doubled. Due to the growing demand for 4D Printing and its technical advantage, more publications have been on the subject throughout time. The distribution of documents on the subject according to the PRISMA screening process is also depicted in the picture. According to what was seen, 1638 documents, including articles, conference papers, reviews, conference reviews, book chapters, and books, were returned by the topic's filtered and identified publications.

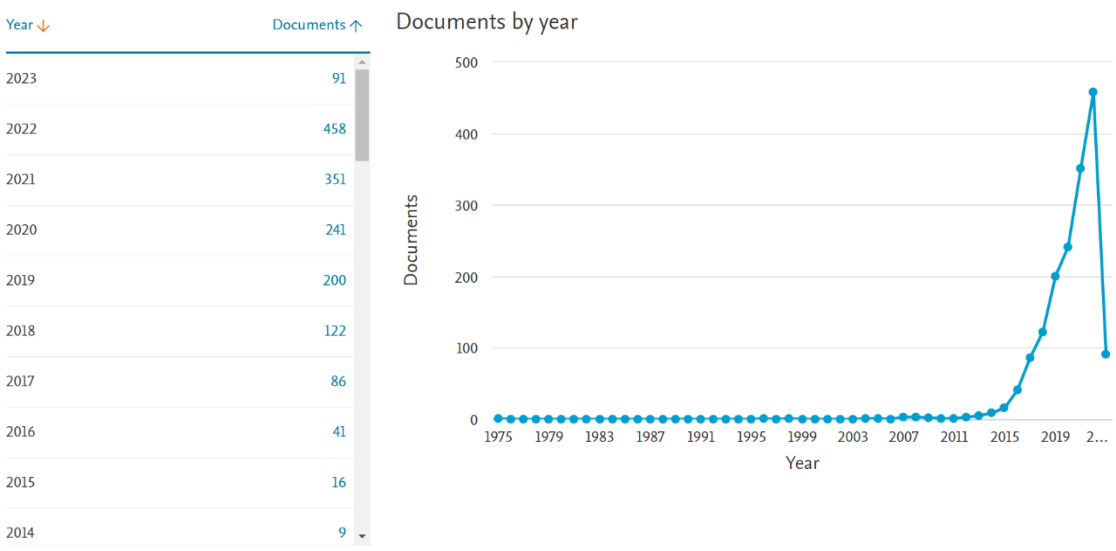


Figure 2. Publication Counts

ACS Applied Materials and Interfaces exhibits the highest distribution of publication sources or academic journals chosen by the researcher, as seen in the figure. As can be seen, ACS Publications generates about 52 documents on the subject. The investigation also reveals that Smart Materials and Structures is the world's second-largest paper producer in 4D Printing.

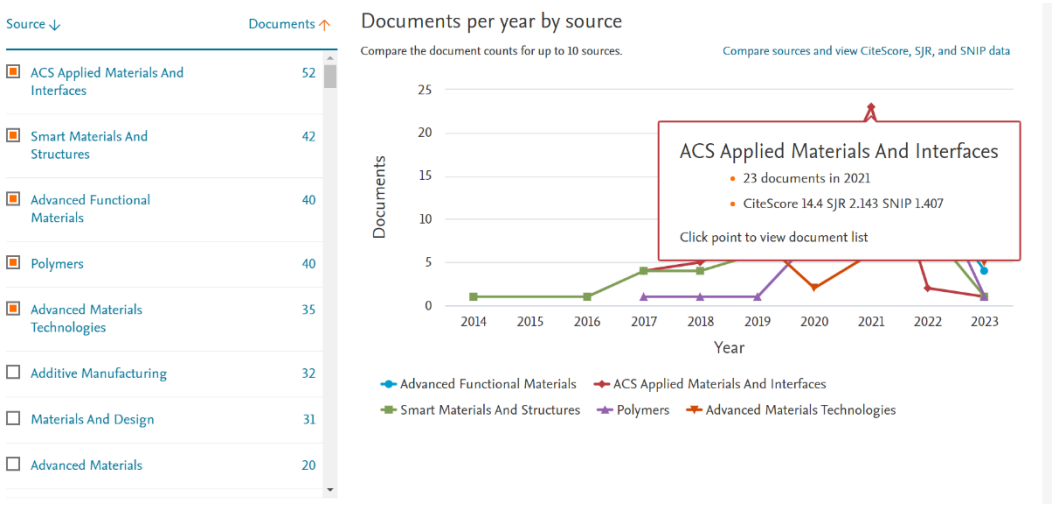


Figure 3. Document per year by source

Citations based on sources show that ACS Applied Materials and Interfaces, Smart Materials and Structures, and Advanced Functional Materials are the most cited sources. Most of the sources cited are from journals to journals.

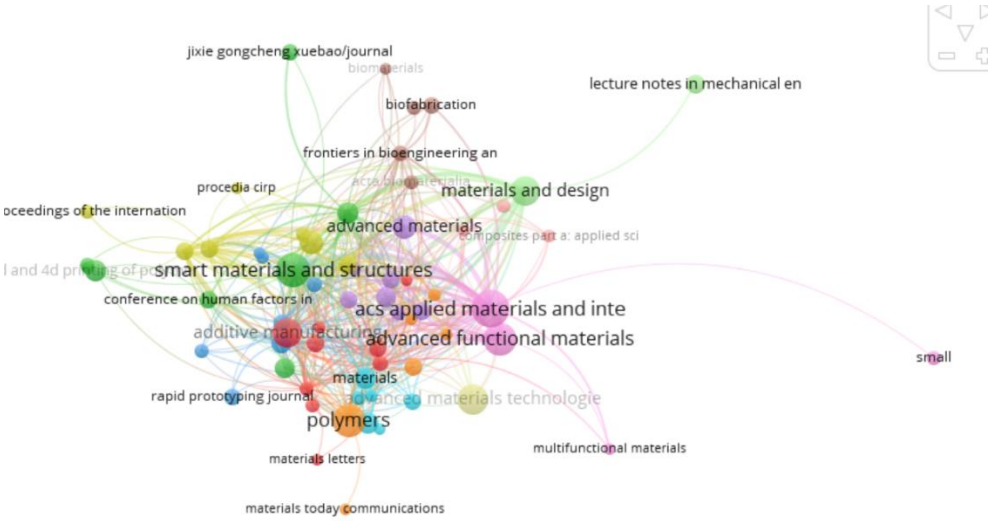


Figure 4. Citations based on Sources

The most influential author is Bodaghi, M, known as Innovator in Smart Materials and 4D Printing and 4DMP Lab Director from Nottingham Trent University. According to the Google Scholar profile of the author, he produces numerous publications in 4d Printing, with a total of 179 publications indexed in google scholar with a total of 4069 citations (Mahdi Bodaghi | Nottingham Trent University, n.d.; Mahdi BODAGHI - Google Scholar, n.d.). Dr. Mahdi Bodaghi is a senior lecturer (assistant professor) in mechanical engineering at Nottingham Trent University's School of Science and Technology. The 4D Materials & Printing Lab (4DMPL), which has a large portfolio of research focusing on the electro-thermo-mechanical multi-scale behaviors of smart materials and 3D/4D printing technologies, was founded and is run by him as well. He co-founded the 4D Printing Society and co-edited the book series Smart Materials in Additive Manufacturing (Vol. 1 & 2), published by Elsevier. He is known for his extensive experience and research in smart materials and additive manufacturing.(*Mahdi Bodaghi | Nottingham Trent University*, n.d.).

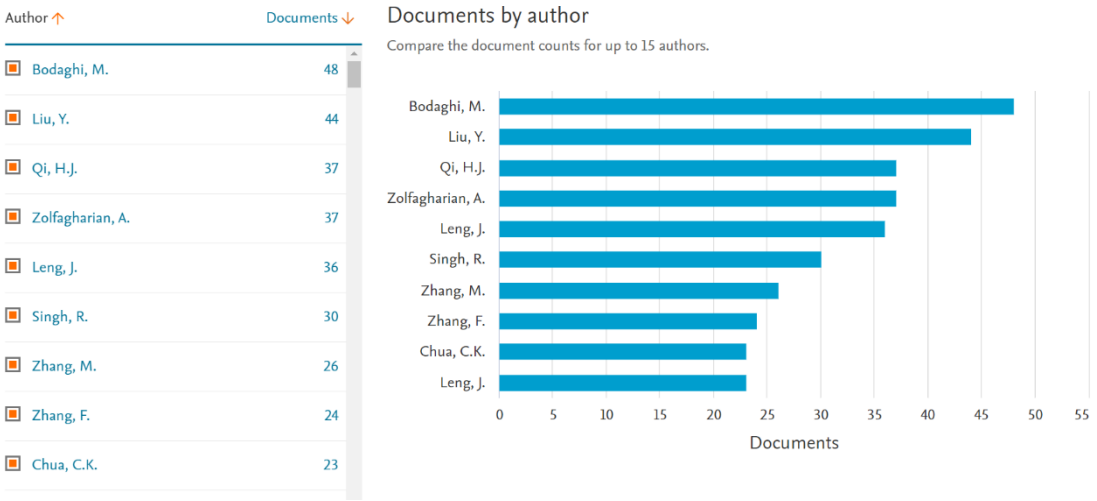


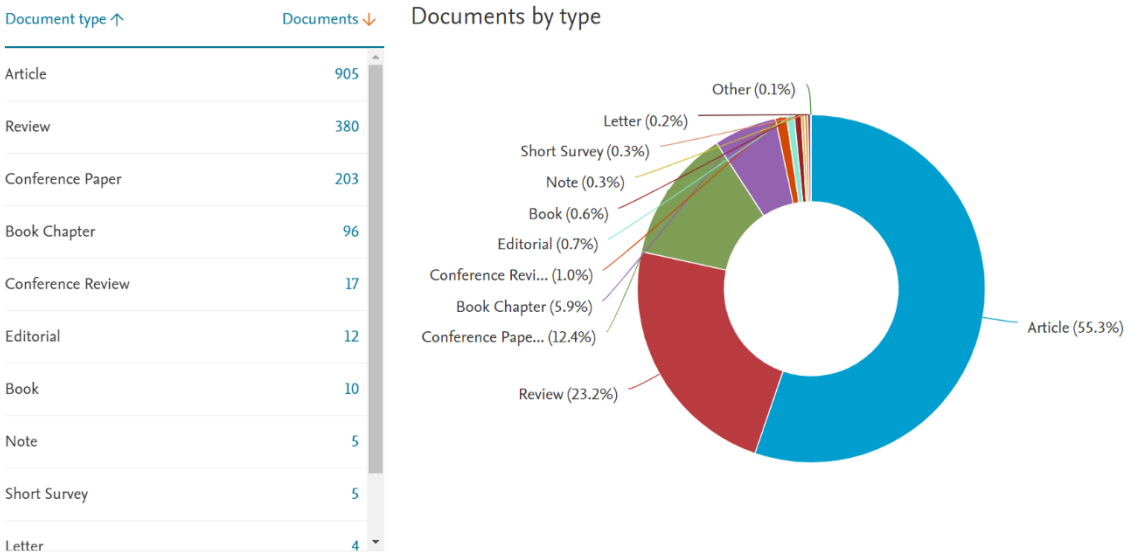
Figure 5. Documents by Author

The most cited article was published last 2016 with the title "Biomimetic 4D printing" under Nature Materials (Sydney Gladman et al., 2016)with more than 1850 citations from different articles. "Self-Healing Hydrogels" by Taylor DL et al. is also the most cited review article (Taylor & in het Panhuis, 2016).

Table 1. Most Cited articles

Authors	Titles	Year	Source Title	Cited by	Document Type
Sydney Gladman A.; Matsumoto E.A.; Nuzzo R.G.; Mahadevan L.; Lewis J.A.	Biomimetic 4D printing	2016	Nature Materials	1850	Article
Taylor D.L.; in het Panhuis M.	Self-Healing Hydrogels	2016	Advanced Materials	785	Review
Tibbits S.	4D Printing: Multi-material shape change	2014	Architectural Design	751	Article
Parandoush P.; Lin D.	A review on additive manufacturing of polymer-fiber composites	2017	Composite Structures	651	Review
Ge Q.; Sakhaei A.H.; Lee H.; Dunn C.K.; Fang N.X.; Dunn M.L.	Multimaterial 4D Printing with Tailorable Shape Memory Polymers	2016	Scientific Reports	649	Article
Khoo Z.X.; Teoh J.E.M.; Liu Y.; Chua C.K.; Yang S.; An J.; Leong K.F.; Yeong W.Y.	3D Printing of smart materials: A review on recent progresses in 4D Printing	2015	Virtual and Physical Prototyping	583	Article
Momeni F.; M.Mehdi Hassani.N S.; Liu X.; Ni J.	A review of 4D Printing	2017	Materials and Design	563	Article
Ge Q.; Qi H.J.; Dunn M.L.	Active materials by four-dimension Printing	2013	Applied Physics Letters	517	Article
Ge Q.; Dunn C.K.; Qi H.J.; Dunn M.L.	Active origami by 4D Printing	2014	Smart Materials and Structures	506	Article
Kuang X.; Roach D.J.; Wu J.; Hamel C.M.; Ding Z.; Wang T.; Dunn M.L.; Qi HJ.	Advances in 4D Printing: Materials and Applications	2019	Advanced Functional Materials	447	Review

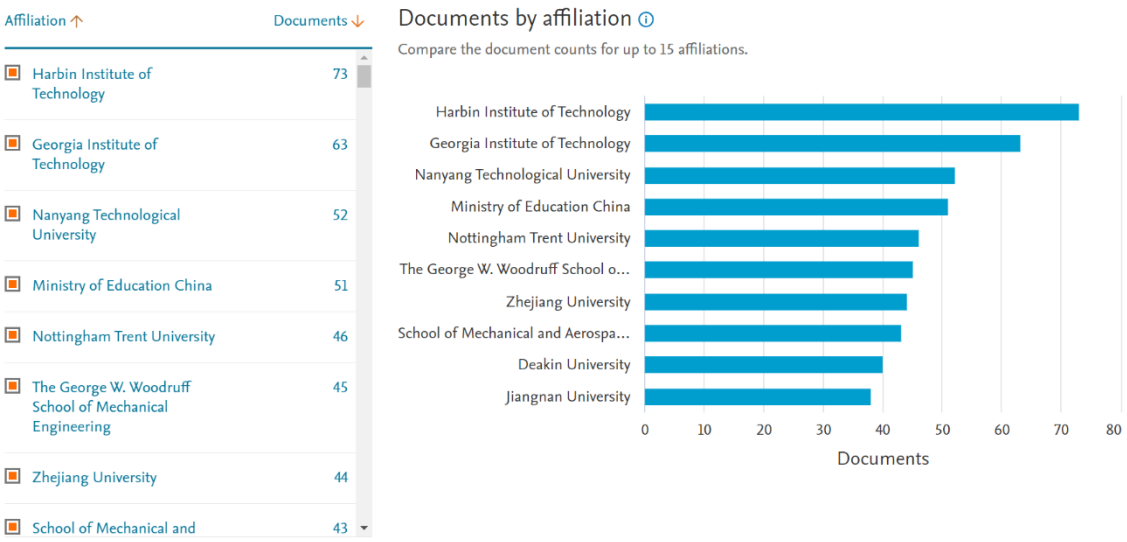
The most preferred type of document among researchers is research articles (905), followed by review articles (380) and Conference papers (203).



Document type	Documents
Article	905
Review	380
Conference Paper	203
Book Chapter	96
Conference Review	17
Editorial	12
Book	10
Note	5
Short Survey	5
Letter	4

Figure 6. Documents by type

The Harbin Institute of Technology emerges as the primary hub for researchers, boasting a substantial count of 73 authors. This esteemed institution is a public university situated in Harbin, China.



Affiliation	Documents
Harbin Institute of Technology	73
Georgia Institute of Technology	63
Nanyang Technological University	52
Ministry of Education China	51
Nottingham Trent University	46
The George W. Woodruff School of Mechanical Engineering	45
Zhejiang University	44
School of Mechanical and	43

Figure 7. Documents by Affiliation

Materials Science and Engineering stands out as the dominant contributor in terms of article count within the field, with each subject area containing slightly fewer than a thousand articles. Following closely are Chemistry, Physics, and Astronomy, and Computer Science, in that order.

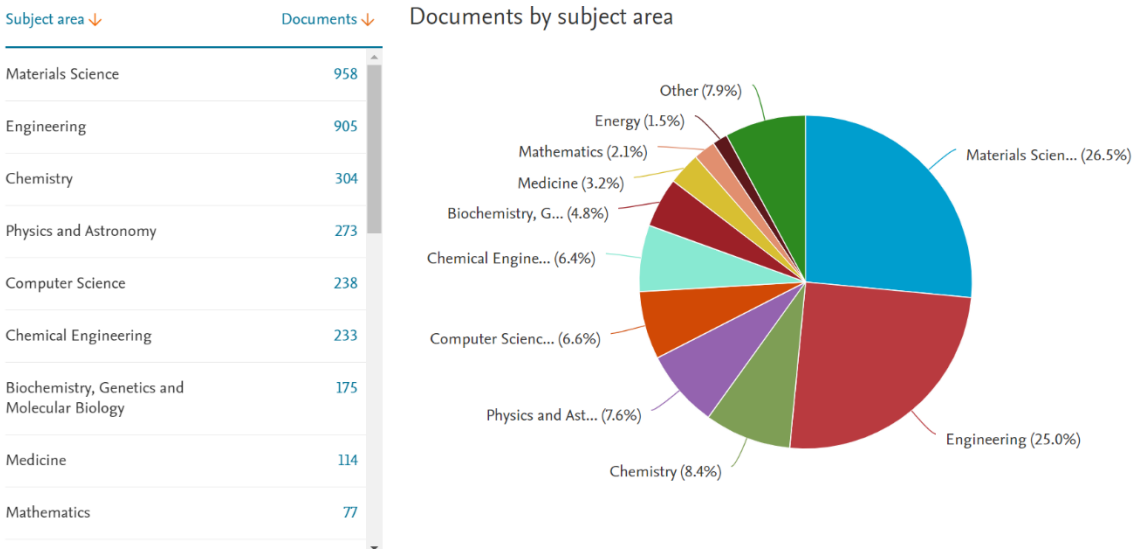


Figure 8. Documents by Subject Area

Analyzing the documents on a country basis reveals that China takes the lead in terms of the highest number of published documents. This is followed by the United States, India, the United Kingdom, and Singapore, in descending order of publication frequency.

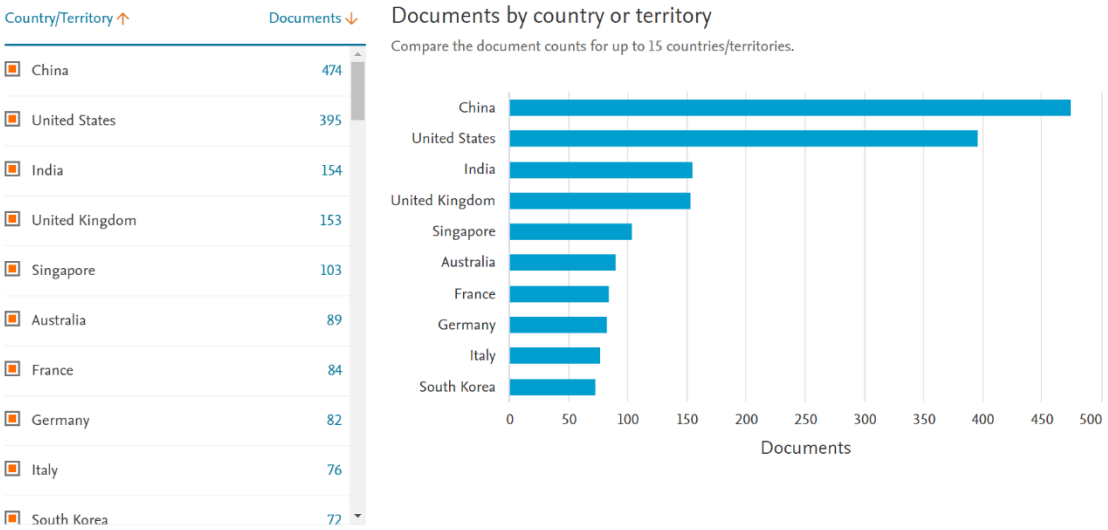


Figure 9. Documents by Country

Collaboration stands as a vital cornerstone of research culture, offering a multifaceted lens through which scientific research and technological advancement are viewed. The figure presented illustrates a network visualization depicting the analysis of country-based co-authorship in the realm of 4D Printing.

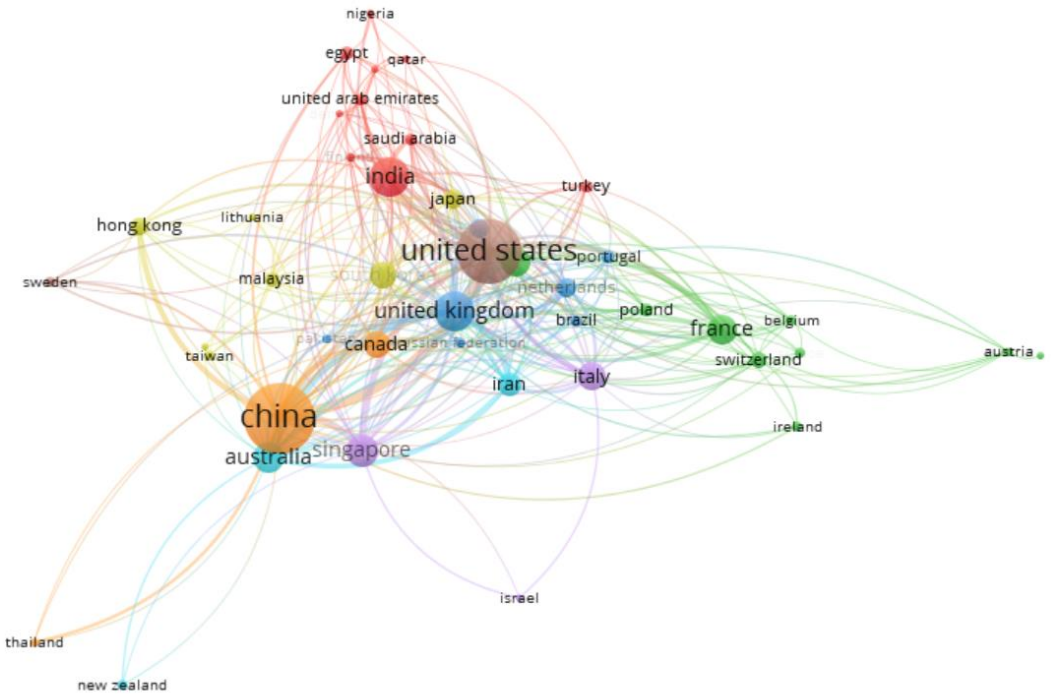


Figure 10. Co-authorship by country

Leading the roster of funding support is the National Natural Science Foundation of China, backing 256 documents, trailed by the National Science Foundation with 103 documents, and the National Key Research and Development Program of China with 49 documents. Notably, China emerges as the most prolific contributor in terms of funding for research endeavors in the domain of 4D Printing.

Figure 11. Funding Sponsor

The co-occurrence analysis offers invaluable insights into the frequency with which interconnected and chosen keywords within a specific research topic are referenced in the scientific literature. Among the keywords examined in the context of 4D Printing, the most recurrent co-occurring terms include "smart materials," "fused deposition modeling," "biomaterials," and various others.

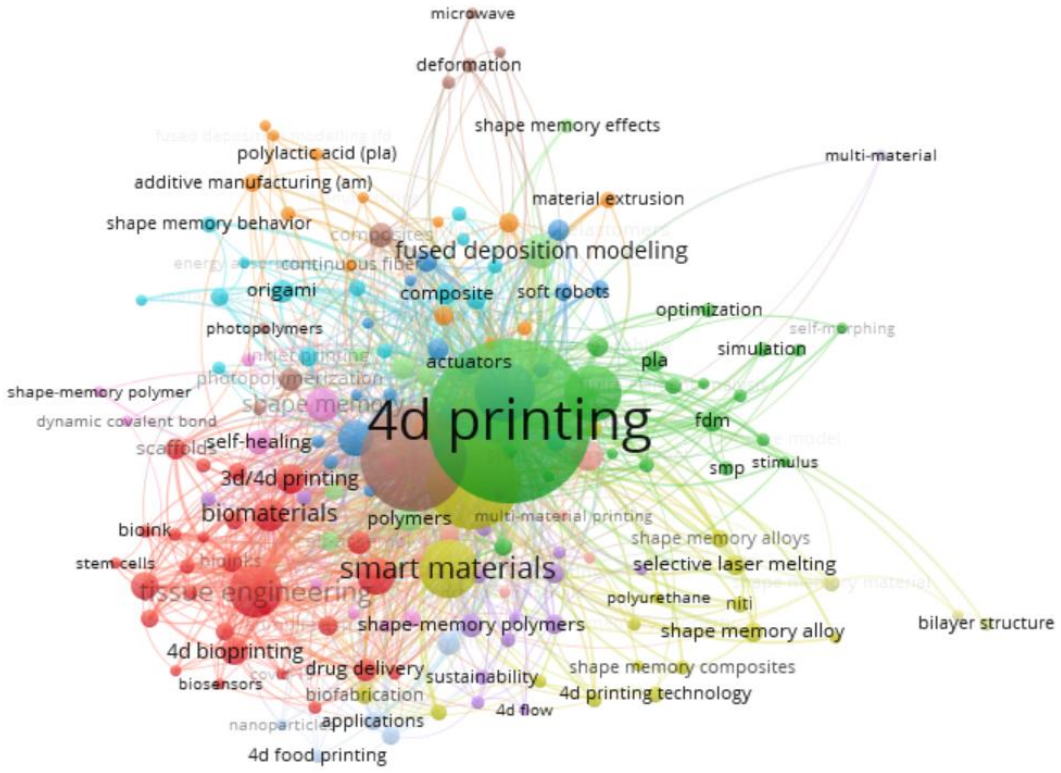


Figure 12. Co-occurrence of author keywords

Bibliometric analysis stands as a pivotal technique for assessing the progression and maturation of research domains, enabling a grasp of both present trajectories and prospective pathways. This mathematical and statistical tool is extensively employed to discern, structure, and scrutinize the research terrain, as well as the scientific tendencies associated with any designated subject of scientific significance. Across time, this method has been harnessed to investigate a diverse array of subjects and fields, encompassing topics spanning from energy and climate change to matters of waste management (Leonidou et al., 2010).

The field of 4D Printing has rapidly evolved into a captivating arena of research and innovation, as evidenced by the comprehensive bibliometric analysis presented. The results paint a vivid picture of the current landscape, providing valuable insights into research preferences, collaboration patterns, funding dynamics, and emerging trends. These findings open up discussions that hold implications for researchers, institutions, policymakers, and industries invested in additive manufacturing and its potential applications (Choi et al., 2015; Momeni et al., 2017; Sydney Gladman et al., 2016).

The apparent preference for research articles among scholars underscores a dedication to in-depth exploration and intellectual contributions within the 4D Printing domain. This inclination towards research articles signals a commitment to advancing the field's foundational understanding and technical capabilities. Concurrently, the prominence of review articles signals a need for synthesizing and organizing existing knowledge, bridging the gap between newcomers and experts. The prevalence of conference papers, indicative of academic engagement and knowledge dissemination, showcases the vibrant nature of scholarly discussions and collaboration, fostering an environment of shared learning and exploration. The emergence of the Harbin Institute of Technology as a research powerhouse showcases the pivotal role of institutions in shaping the trajectory of 4D Printing. Its notable presence, bolstered by 73 contributing authors, not only

highlights its research leadership but also underscores the potential for institutions to foster interdisciplinary collaboration and innovation. The institute's impact reverberates beyond its campus, inspiring collaborations that transcend geographical boundaries. This institutional influence sparks discussions about the strategies that enable such excellence and how other institutions can similarly contribute to the advancement of 4D Printing research.

The global distribution of research contributions vividly illustrates the worldwide appeal of 4D Printing research. This global engagement extends an invitation to international collaboration, capitalizing on the diverse perspectives and expertise across borders. The inclusivity of this field encourages cross-cultural exchanges, offering the potential to enrich research through collaborative endeavors that tackle global challenges. This global dialogue prompts discussions about the mechanisms and platforms that facilitate effective international collaboration, further accelerating the pace of discovery. The identification of major funding providers emphasizes the significance of strategic investments in driving 4D Printing research forward. The targeted allocation of resources by entities such as the National Natural Science Foundation of China and the National Science Foundation underscores their recognition of the field's transformative potential. These funding patterns spark conversations about the role of funding agencies in fostering innovation, supporting groundbreaking research, and shaping the technology's trajectory. These discussions lay the foundation for informed decisions regarding resource allocation and the alignment of funding with emerging trends.

Lastly, the interdisciplinary nature of 4D Printing, spanning multiple subject areas, underscores the power of collaboration across domains. Interdisciplinary synergy fosters discussions on the transformative potential of merging knowledge from diverse fields. Collaborations that cross disciplinary boundaries have the potential to solve complex challenges, drive innovation, and pioneer holistic solutions. These discussions reflect the need for collaborative platforms, communication bridges, and educational frameworks that facilitate effective interdisciplinary dialogue and action.

Conclusion

The study used bibliometric analysis techniques to evaluate the research trends in 4D Printing. Published papers from various publications indexed in the Scopus database were identified, screened, and evaluated using the PRISMA. The Scopus database's specific search query returned 1638 results, including articles, reviews, conference proceedings, and all others without exclusion. The generated data were further reviewed using the VOSViewer software based on the co-authorship, keyword co-occurrence, and citation analyses to determine the most recent research trends. A bibliometric analysis showed the existence of substantial networks of countries, institutions, and scientific communities that have collaborated on several projects and produced highly cited publications over time. The study's results gave thorough information on the state of science and the research environment, which might be useful to future scientists, businesses, and governments that need an overview of the field or quick data to make choices, locate partners, or even funding for their work. The search was done last February 17, 2023, at 2:30 AM +8 GMT. Upon searching the Scopus database after 12 hours, two additional documents were added in the database. In this regard, the researcher concluded that more research for 2023 is expected to be published and indexed in Scopus. In conclusion related to the trends of the topic, 4D Printing is an exciting new technology that has the potential to revolutionize the way we create and interact with objects. While there are many challenges to overcome, the potential applications are vast and varied. From the medical field to construction and aerospace, 4D Printing could significantly impact many different industries. As research continues, we are likely to see even more exciting developments in this field in the years to come.

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