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4D Printing: Research Focuses and Prospects

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Abstract: As an emerging technology in the field of additive manufacturing, 4D printing is highly disruptive to traditional manufacturing processes. Therefore, it is necessary to systematically summarize the research on 4D printing to promote the development of related industries and academic research. However, there is still an obvious gap in the visual connection between 4D printing theory and application research. We collected 2070 studies from 2013 on 4D printing from the core collection of Web of Science. We used VOSviewer 1.6.20 and CiteSpace software 6.3.3 to visualize the references and keywords to explore focuses and trends in 4D printing using scientometrics. In addition, real-world applications of 4D printing were analyzed based on the literature. The results showed that "tissue engineering applications" is the most prominent focus. In addition, "shape recovery", "liquid crystal elastomer", "future trends", "bone tissue engineering", "laser powder bed fusion", "cervical spine", "4D food printing", "aesthetic planning" are also major focuses. From 2013 to 2015, focuses such as "shape memory polymers" and "composites" evolved into "fabrication". From 2015 to 2018, the focus was on "technology" and "tissue engineering". After 2018, "polylactic acid", "cellulose", and "regenerative medicine" became emerging focuses. Second, emerging focuses, such as polylactic acid and smart polymers, have begun to erupt and have become key research trends since 2022. "5D printing", "stability" and "implants" may become emerging trends in the future. "4D + Food", "4D + Cultural and Creative", "4D + Life" and "4D + Clothing" may become future research trends. Third, 4D printing has been widely used in engineering manufacturing, biomedicine, food printing, cultural and creative life, and other fields. Strengthening basic research will greatly expand its applications in these fields and continuously increase the number of applicable fields.

Keywords: 4D printing; CiteSpace; VOSviewer; scientometrics; visualization

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1. Introduction

Additive manufacturing technology is based on designed three-dimensional CAD model data and transforms various forms of materials, such as powders, wires, liquids, and sheets, into three-dimensional entities through digitally-driven layer-by-layer accumulation [1–3]. Since the 1980s, additive manufacturing technology, particularly 3D printing technology, has developed rapidly [4,5]. With Professor Tibbits of the Massachusetts Institute of Technology proposing the concept of 4D printing in 2013, the "3D + time" manufacturing method entered people's vision, and then there was a craze for research on 4D printing [6–8]. Currently, the main 4D printing process technologies used by researchers are fused deposition molding (FDM), stereolithography (SLA), selective laser sintering (SLS)\laser melting (SLM), directed energy deposition (DED), and other process technologies, such as photosensitive polymer jetting (PolyJet) and direct ink writing (DIW) [7,9–12]. 4D printing is an emerging, intelligent additive manufacturing technology developed based on 3D printing technology. Its intelligent characteristics are reflected in the fact that printed products have automatic stress response characteristics that can achieve a corresponding evolution in form and nature under different incentive conditions. This is a "dynamic" product [13,14]. There are at least two stable states in a 4D printed structure, and under the stimulation of the corresponding medium, the structure can transition from one state to another [9]. By combining it with ordinary materials, the structure can undergo dynamic changes under the excitation of certain media [15]. Many scholars have explored dynamic changes in 4D printing under different conditions from multiple perspectives, such as shape memory [16], residual stresses [17], phase transformations [18], and springback [19]. Dynamic changes in structures include changes in shape and material properties or functions [20]. The self-responsive stress characteristics of 4D-printed products have great development potential and have attracted the interest of many scholars worldwide [7,20–22]. Cerbe et al. [17] investigate the relationship between stress and strain during 4D printing, proposing that printing parameters affect structures' heating and cooling process. Fu et al. [23] reviewed important 4D printing technologies in conjunction with basic polymer science and engineering and discussed the challenges and future opportunities faced by 4D printing. Chen et al. [24] proposed that 4D bioprinting will become the next generation of bone repair technology, providing more inspiration for clinical medicine of bone regeneration. At present, scholars have carried out extensive research on 4D printing technology and initially formed a theoretical system of "smart materials" + "smart structures" + "3D printing" [25]. With the continuous deepening of scientific research, 4D-printed smart products have broad application prospects in many fields, such as future robot development, intelligent equipment manufacturing, aerospace, and biomedicine [26].

Although academic research on 4D printing technology has been greatly enriched, in the process of reviewing existing research results, we found three obvious gaps in 4D printing technology. First, owing to the numerous research results on 4D printing, there has been an obvious lack of systematic research since the advent of 4D printing technology and a more comprehensive review is required to reveal the research focuses and application prospects of 4D printing technology. Second, most existing studies have explored the development of 4D printing technology from a technical perspective. In general, overall research on 4D printing technology is insufficient. Third, single-disciplinary research on 4D printing has been dominant. Comprehensive research must be conducted from a multidisciplinary perspective to help understand the focuses and trends of 4D printing and further popularize the application of 4D printing technology. Therefore, in terms of content, we consider 4D printing as a research object and discuss its research focuses and application prospects so that readers can better understand the key points and development directions of 4D printing technology. In terms of methods, we are based on scientific metrology and use visualization technology to better display the research focuses and trends of 4D printing technology to readers quantitatively and intuitively. Finally, by analyzing the visual information of 4D printing technology, we discover the future application prospects of 4D printing technology, help readers quickly understand the development direction and application prospects of 4D printing technology, and find key entry points for future research. Specifically, our research focuses on the research and application prospects of 4D printing technology to solve the following problems:

- RQ1: What research hotspots have existed in 4D printing since its inception?
- RQ2: What have been the research trends in 4D printing in the last decade?
- RQ3: What is the current status of 4D printing applications?
- RQ4: How should 4D printing be developed further in the future?

The remainder of this paper is organized as follows. In Section 2, described the sources of the literature and briefly analyzed the collected literature to explicitly visualize and analyze it using scientometrics. In Section 3, based on the collected literature, VOSviewer and CiteSpace are used to visualize and analyze references and keywords and explore their research focuses and emerging trends. In Section 4, combined with the previous research focus on 4D printing, the application prospects of 4D printing technology in four fields—engineering manufacturing, biomedicine, food printing, and cultural and creative life—are analyzed. Section 5 summarizes the paper, presents new findings of the research, highlights the theoretical and practical significance, and explains the limitations of the future outlook.

2. Data Collection and Methods

2.1. Data Sources

We selected SCI, SSCI, AHCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, and IC from the core collection of Web of Science and screened the literature related to 4D printing. To obtain comprehensive data and guarantee the validity of the literature screening, we chose to combine "all fields", "topics" and "title" searches. First, considering that the concept of 4D printing was proposed by Prof. Tibbits of MIT in 2013, we delineated the time range from 1 January 2013 to 30 June 2024 as the time to collect literature, which is consistent with the formal proposal of the concept of 4D printing and in line with the need to collect comprehensive and up-to-date literature. Secondly, we used "all fields" to collect references from the time range from January 2013 to June 2024 and then used the combination of "subject" and "title" search methods to remove duplicate references. Considering that 4D printing remains within the scope of additive manufacturing and is a rapid prototyping technology, a variety of expressive keywords for 4D printing are listed in the search. The advanced search format created was Ts1 = (4D (all fields) and (additive manufacturing (subject) or 4D printing (subject))). Ts2 = (4D (all fields) and (additive manufacturing (title) or 4D printing (title))). Ts1 obtained a total of 2054 references, Ts2 obtained a total of 1064 references, and after the deduplication process, a total of 2070 references were obtained (search time was 10 July 2024); the publication types and search results are shown in Table 1.

Table 1. Publication types and search results.

Search Field	Sum.	Research Papers	Review Paper	Conference Papers	Editorial Material	Book Reviews	Other
TS_1	2054	1393	463	146	28	3	21
TS_2	1064	771	180	69	19	3	22

2.2. Literature Analysis

To better study the research hotspots and application prospects of 4D printing, we classified the publication years and citations of the collected references. The results are shown in Figure 1. Judging from the publication year, since the concept of 4D printing was first proposed in 2013, relevant research results have increased annually until 2023 (from 2024 to 30 June 2024, it is impossible to infer the trend in 2024), reaching 467 articles by 2023. The year-on-year growth of 4D printing technology is due to the gradual establishment of a complete theoretical framework by 4D printing technology and an interdisciplinary cooperation model, which promotes the rapid iteration and innovation of new technologies [25]. Simultaneously, 4D printing technology has attracted great attention from the public, and 4D printing has great potential [27]. From 2013 to 2023, the number of citations of 4D printed references has increased rapidly, indicating that 4D printing has received increasing attention from academics. From the perspective of the Web of Science, materials science is the main research category of 4D printing, with a total of 873 references. This is mainly because the implementation of 4D printing technology is highly dependent on the special properties and the responsiveness of materials. The core of 4D printing technology is to enable a printed object to change its shape or structure under external stimulation [28]. The autonomous deformation ability of 4D printing is mainly owing to the special properties of the materials, such as temperature, humidity, and electromagnetic responses [6]. Therefore, the research and development of materials are key to realizing 4D printing technology [14,29,30]. At the same time, it can also be seen from the top ten categories of Web of Science that current research on 4D printing technology mainly focuses on materials, technologies, and applications. From the perspective of research direction, materials science is also the main research direction of 4D printing, with the total number of references reaching 1104, accounting for more than half of the total references. Research on smart materials plays a central role in the development of 4D printing [28]. The smart materials required for 4D printing not only provide the basic physical form but also give printed products the ability to change dynamically, giving them the "fourth dimension"—the changing characteristics of time. Currently, these are the main themes in 4D printing research direction.

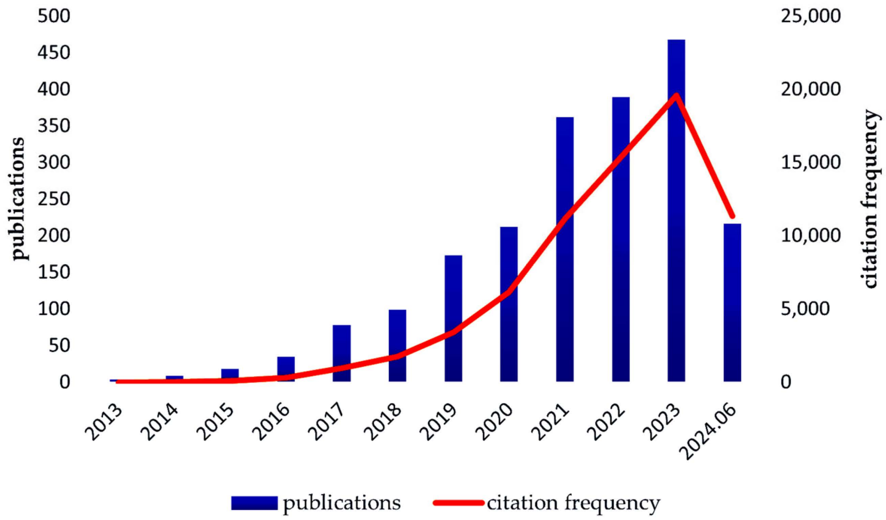


Figure 1. The number of times publications related to 4D printing are cited.

2.3. Visualization Analysis Using Scientific Metrology

Scientometrics is a discipline in which quantitative research on scientific activities is conducted. It focuses on the relationship between the investment of scientific researchers and research funds and the number of papers, citations, and other outputs, as well as the dissemination and formation of scientific information exchange networks process [31]. Scientometrics was initiated by D. Price and others in the early 1960s and adopted quantitative research methods to study the nature of science itself. Garfield laid the foundation for the development of scientometrics by creating a large SCI database [32]. After years of development, scientific metrology has expanded from simple literature measurements to analyzing scientists' research activities, scientific and technological innovation models, and scientific communication networks [33]. As the latest research direction of additive manufacturing, 4D printing technology has attracted widespread attention from scholars worldwide since its inception [6,22,34]. Since it was proposed in 2013, 4D printing technology has produced rich research results in the past ten years, providing us with a solid foundation for conducting visual analysis using scientific metrology [35]. As effective software for scientific metrology, VOSviewer can visualize and analyze large-scale, high-dimensional datasets [36]. In addition, VOSviewer provides various technologies, such as rotation, scaling, and filtering, for research on browsing and manipulating datasets in real-time, and the appearance and behavior of VOSviewer can be customized to suit specific needs and preferences [37]. CiteSpace is a citation visualization analysis software that focuses on the analysis of underlying knowledge in the scientific literature [38]. CiteSpace helps researchers sort past research trajectories and predict the prospects of future research by visualizing the relationships between references in a scientific knowledge map [39]. CiteSpace can reveal the structural changes and evolution laws of scientific knowledge and uses a network diagram composed of nodes and connections to show the co-occurrence relationships between different references, authors, or keywords [40]. CiteSpace can also identify hot themes and development trends in the research field and help users track cutting-edge issues [41]. CiteSpace can generate keyword co-occurrence maps, which visualize the frequency and co-occurrence of keywords in the literature, thus intuitively showing past and present hotspots in the field [40]. Keywords with a high frequency of occurrence typically represent core themes in the field [42]. The change in the keyword co-occurrence graph in the timeline is a concentrated reflection of the development trend. Newly appearing keywords or keyword combinations indicate emerging research directions [41]. Simultaneously, the keyword co-occurrence diagram can also determine the overall pulse of this field [38]. By analyzing the connection between different keywords, the relationship and evolution process between various themes can be understood [39]. CiteSpace provides a variety of parameter setting options, such as time slicing, selection criteria, and clipping methods, which allow users to conduct flexible analyses based on their research requirements [42]. CiteSpace is widely used for writing reviews. We can use the knowledge maps generated to comprehensively outline theoretical views and evolutionary paths in specific fields [41]. Therefore, we chose VOSviewer 1.6.20 and CiteSpace 6.3.3.

3. Results

3.1. Focuses and Trends Based on References

To explore the knowledge network structure of the 4D printing technical literature, we used VOSviewer 1.6.20 and CiteSpace 6.3.3 to conduct cocitation literature analysis on the collected references.

We used VOSviewer software to date the literature from January 2013 to June 2024, selected a map based on bibliographic data, then read the data from bibliographic database files and imported the data from the Web of Science core collection. References in citations were selected for the type of analysis, and 10, 50, 100, and 200 were selected for the minimum number of citations of a document. Finally, we found that it is more realistic to select 50 to produce the VOSviewer-created density, network, and overlay visualizations of the cited literature map. The final landscape map is shown in Figure 2, and the 19 most-cited references are listed in Table 2. In the cited literature map created by VOSviewer, 389 items were included, generating 24 clusters and 4316 links. In Figure 2, the difference in the number of reference citations is represented by the size of the node, and the different clustering is distinguished by color. We observed the visual landscape map in Figure 2 and found that in 2016, 4D printing technology produced many references with high influence and a high citation rate. In particular, the bionic 4D printing coding method put forward by [43] has obvious advantages compared to other cited literature. As 4D printing technology raw material research continues to deepen, coding and manufacturing methods have gradually become the focus of scholarly research. Among the 19 most-cited references created by VOSviewer, all were related to the manufacturing methods and applications of 4D printing. Therefore, external stimulation, modeling simulation design, and application areas of 4D printing technology have greater potential for development in the future and may become a research hotspot for 4D printing technology.

We utilized CiteSpace software with a time slice set from January 2013 to June 2024 and selected cited literature on node type and g-index coefficients at K = 25, K = 5, K = 50, and K = 100. The CiteSpace results were the most realistic when K = 25, and the final landscape is shown in Figure 3, where the 25 most cited references are shown in Figure 3. Figure 3 shows a 4D printout of the overall network landscape of co-cited literature, which contains 1006 nodes and 4869 connectors. The color bar at the top of the figure indicates when the literature was co-cited, with each color representing one year. The node with the large outline indicates that it is a landmark paper, and the black text indicates the name of the generated cluster, which is preceded by a smaller sequence number, indicating the greater importance of the cluster. Red indicates the outbreak degree of the cluster node. The brighter red the color and the larger the node outline, the higher the cited intensity of the literature. According to the size of the serial numbers of the clusters in the figure, "emerging applications", "4D-printed shape memory polymers" and "4D-printed active composite structures" are the three largest clusters, reflecting that they are the greatest research focuses of 4D printing technology. Moreover, such as "3D printing", "liquid crystal elastomers", "geometry-driven finite elements", "biomedical applications", etc., are also hot research areas for 4D printing.

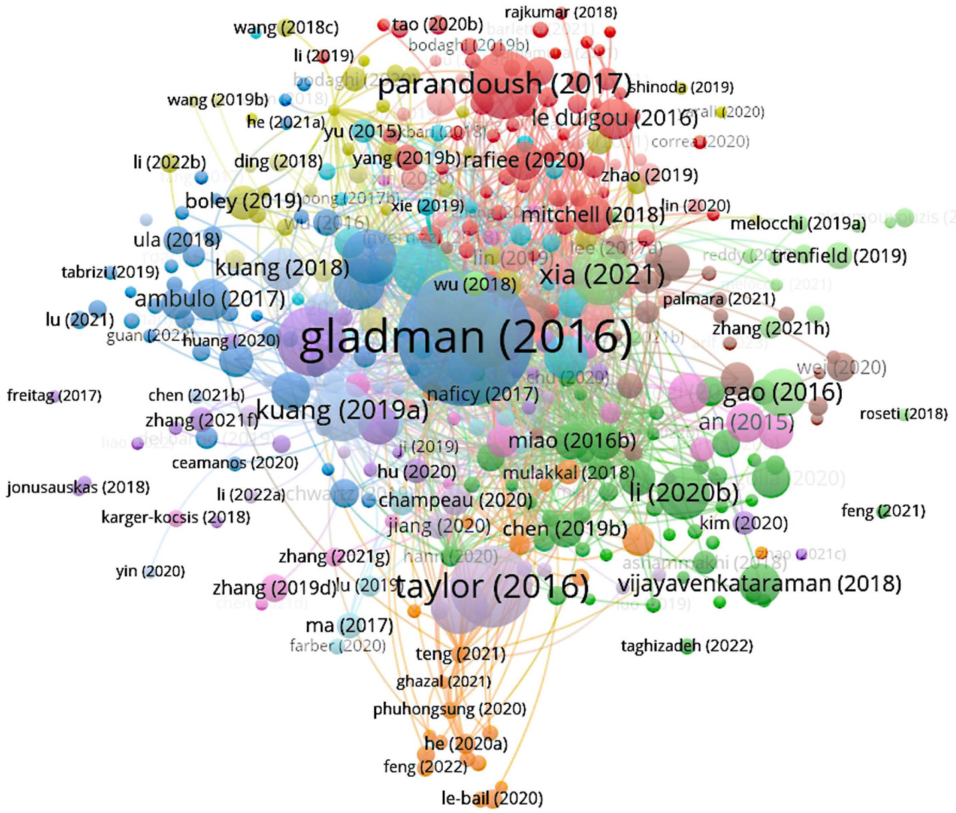


Figure 2. The visual landscape map of co-cited references of 4D printing.

Table 2. The 19 most cited studies.

Document	Theme	Citations	Links
Gladman et al. [43]	Biomimetic printing	2088	176
Taylor [44]	Self-Healing hydrogels	968	10
Tibbits [45]	Programmable materials	814	141
Ge et al. [46]	Tailorable features	742	113
Parandoush et al. [47]	Review: methods	723	14
Momeni et al. [48]	Review: concepts and tools	663	122
Xia et al. [49]	Review: emerging directions	611	27
Kuang et al. [50]	Shape-shifting materials	588	109
Luo et al. [51]	Polyion Complex	552	7
Ge et al. [52]	Programmed action	550	116
Ge et al. [53]	Origami	524	99
Li et al. [54]	Review: biomedical	479	29
Ding et al. [55]	Active composite materials	477	94
Gao et al. [56]	Bioprinting	421	50
Bakarich et al. [57]	Thermally Actuating Hydrogels	367	82
Pan et al. [58]	Artificial intelligence	360	1
Kuang et al. [59]	novel ink	353	50
Vijayavenkataraman et al. [60]	Organ transplantation	350	3
Ambulo et al. [61]	Liquid Crystal Elastomers	340	45

To further explore the focuses and trends in the above three largest clusters, we used CiteSpace to specifically cluster the following three themes. "Emerging applications", "4D-printed shape memory polymers" and "4D-printed active composite structures". The results are shown in Table 3. It can be seen that "comparative review", "critical review" and "typical application" are the main research directions of "emerging applications". Other themes, such as "Biological interface" and "Emerging direction" also occupy an important position in the future research of "emerging applications". "Polymeric material", "smart polymeric composite" and "tissue engineering" are the main research themes of "4D-printed shape memory polymers" and account for a high proportion in the overall research results. Together with "controlled sequential shape" "advanced properties", "comprehensive review", "biomedical application" and "democratic 4D printing" they form the main body of the "4D-printed shape memory polymers" research network. The number of cluster themes formed by "4D-printed active composite structures" is smaller than that of "emerging applications" and "4D-printed shape memory polymers". Cluster "robotics application" is the main research direction of "4D-printed active composite structures", which has an absolute advantage over other clusters. With the maturity of 4D printing technology, "Active composite material", "On-demand local actuation," and "Permanent shape reconfigurability" will also become important research directions. To further demonstrate the focuses and trends in the three largest clusters mentioned above, we have chosen to visually analyze the cluster "4D-printed shape memory polymers" with the closest internal cluster relationship, and the results are shown in Figure 4. The arrow represents the situation where one cluster is referenced by another cluster, the dependencies between clusters. It can be seen that "Polymeric material" is at the center of "4D-printed shape memory polymers" and has a close dependence on other clusters. Other clusters are also interdependent and together form a research network of "4D-printed shape memory polymers".

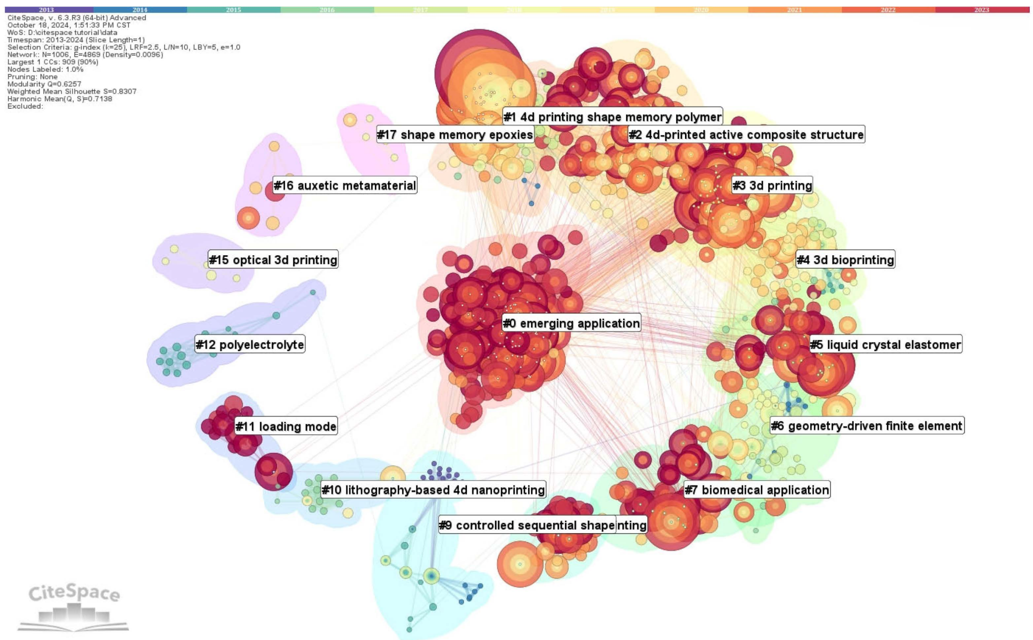


Figure 3. The intellectual landscapes of the 4D printing based on co-citation of the literature.

The network contains 2070 files from January 2013 to June 2024 and produces 17 clusters, the results of which are shown in Table 4. The silhouette in Table 4 reflects the quality of the cluster configuration. The higher the silhouette value, the better the quality of the clustering. The mean year is the average publication year of all literature in a cluster. The closer the average year, the more it represents the research frontier of 4D printing. The red line indicates the burst time interval of the reference. The dark blue line represents the publication time of the reference. In terms of the size of the clusters, the largest cluster, "#0 emerging applications" has 241 members, which indicates that "Emerging Applications" has a central position in the research on 4D printing technology. Moreover, "#1 4D-printed shape memory polymers" and "#2 4D-printed active composite structures" are important. In addition, there are 4 clusters with a scale of more than 100, which indicates a greater concentration of research and applications in 4D printing in terms of materials, structures, applications, and their relationship to 3D printing. In terms of the average year, "#0 emerging application, 2020", "#11 loading modo, 2022" and "#20 robotics application, 2020" undoubtedly represent the latest R&D directions of 4D printing technology. It is worth noting that "#6 geometry-driven fine element, 2013", "#9 controlled sequential shape, 2011", "#10 lithography-based 4D nanoprinting, 2013" and "#12 polyelectrolyte, 2012" were once popular research areas for 4D printing technology. However, few scholars have paid attention to this in recent years, and relevant research has shown a shrinking state, which reflects that these themes may not have much development potential in 4D printing technology.

Table 3. Themes of the largest three clusters.

Cluster Name	Emerging Applications	4D-Printed Shape Memory Polymers	4D-Printed Active Composite Structures
Theme	Comparative review Critical review Typical application Biological interface Emerging direction Shape memory material Fabrication material Advance Additive manufacturing Tissue engineering development Dawn	Polymeric material Smart polymeric composite Tissue engineering Controlled sequential shape Advanced properties Comprehensive review Biomedical application Democratizing 4D printing Loading mode Shape memory epoxies Reentrant honeycomb	Robotics application Active composite material On-demand local actuation Permanent shape reconfigurability Graphene-based polymer bilayer Ultrafast inverse design Controllable deformation design Bioinspired 4D printing 3D printing

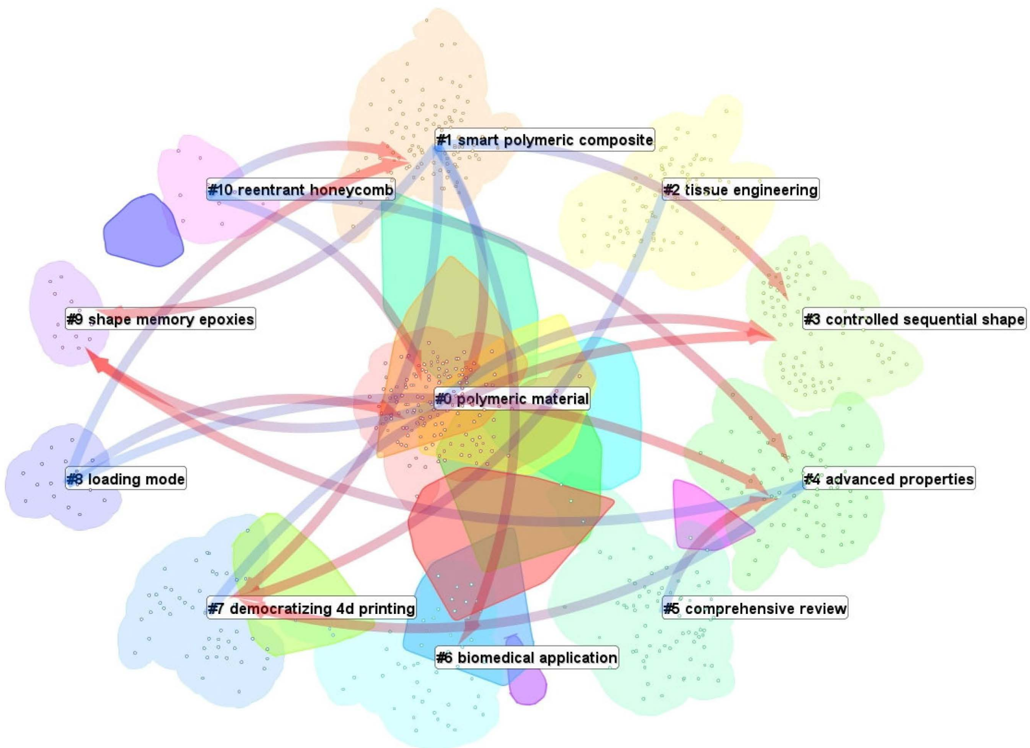


Figure 4. The co-cited reference network of the cluster "shape memory polymers".

Table 4. Summary of the 17 largest clusters.

Cluster lD	Size	Silhouette	Label (LLR)	Theme	Average Year
0	241	0.767	Emerging application	Application areas	2020
1	107	0.861	4D printing shape memory polymer	Shape memory polymer	2015
2	104	0.699	4D-printed active composite structure	Composite properties and structures	2018
3	102	0.726	3D printing	Medical device	2017
4	68	0.876	3D bioprinting	Hydrogel	2015
5	58	0.934	Liquid crystal elastomer	Bionic material	2019
6	48	0.920	Geometry-driven finite element	4D programming	2013
7	46	0.885	Biomedical application	Biomedical	2019
8	35	0.976	6D printing	Future trend	2019
9	29	0.982	Controlled sequential shape	Programming method	2011
10	18	0.995	Lithography-based 4D nanoprinting	Printing technology	2013
11	16	0.997	Loading mode	Design	2022
12	16	0.963	Polyelectrolyte	Smart materials	2012
15	6	0.996	Optical 3D printing	Optical applications	2014
16	6	0.998	Auxetic metamaterial	Artificial composite structural material	2017
17	6	0.985	Shape memory epoxies	Advanced materials	2016
20	3	0.998	Robotics application	Robotics	2020

3.2. Focuses and Trends Based on Keywords

Keywords can highlight the key points and core content of a paper, allowing readers to quickly grasp its theme [31]. By analyzing keywords, we can quickly grasp the dynamics of academic research and guide academic research. Therefore, visual analysis of keywords in reference documents can be used as an indicator to identify hotspots and emerging trends.

In VOSview, we determined the literature time from January 2013 to June 2024, selected "Create a map based on bibliographic data" then selected "Read data from bibliographic database files" and imported the data from the core collection of Web of Science. All keywords in co-occurrence according to the type of analysis were selected, and 10, 50, 100, and 200 were selected for the minimum number of citations of a document. Finally, we found that selecting 50 was more in line with the actual situation. We created a density visualization keyword map using VOSviewer. The final landscape map is shown in Figure 5, and the most highlighted keywords are listed in Table 5. The keyword mutation map created by VOSviewer contains a total of 15 projects, resulting in 4 clusters and 104 links, with a total link length of 4209. Figure 5 shows that 4D printing has obvious advantages for all keywords. Keywords such as 3D printing, 3D, and AM have higher citation rates than the other keywords. This is mainly because research on 4D printing has just gone through the initial stages of concept definition and scope determination. Technological development and applied research are still booming. In the early days of research on 4D printing technology, scholars mainly conducted research on the similarities and differences between 4D printing, 3D printing technology, and additive manufacturing technology. Most research has focused on the basic content of 4D printing technology, characteristics, and application methods. In the middle of the research on 4D printing technology, that is, the current stage, technological development and applied research are gradually emerging. The top keywords, such as "fabrication", "design", "composition" and "scaffolds" all represent scholars' research on promoting 4D printing technology. Future research on the application and technological development of 4D printing technology is an area with great potential.

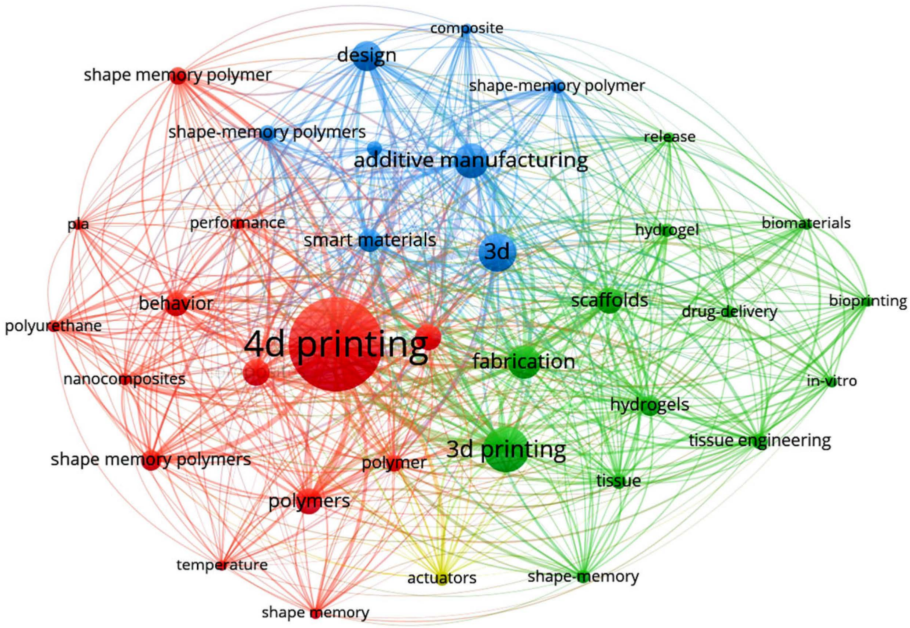


Figure 5. Co-occurrence keyword networks of the 4D printing.

Table 5. VOSviewer includes the 15 most prominent keywords.

Keyword	Occurrences	Total Link Strength
4D printing	1025	1680
3D printing	382	753
3D	296	752
additive manufacturing	268	657
fabrication	248	627
design	214	503
composites	183	476
scaffolds	182	472
polymers	182	468
mechanical-properties	178	404
behavior	154	361
smart materials	150	434
hydro-gels	133	298
shape memory polymers	129	292
shape memory polymer	107	241

We used CiteSpace to generate a keyword hotspot landscape map, as shown in Figure 6. The network contains 581 nodes and 3072 connectors. The color bar at the top of the figure indicates the time the literature was co-cited, with each color representing one year. The black text indicates the name of the generated theme, and the smaller the ordinal number in front of it, the greater the importance of the cluster. As shown in Figure 6, the keywords of 4D printing technology cover many fields, such as engineering and manufacturing, biomedicine, household products, food, culture, and creativity. Among the generated clusters, "#0 tissue engineering application" is still the most researched field, which indicates that tissue engineering applications are the most basic and important content in 4D printing research. The "#1 shape recovery" and "#2 liquid crystal elastomer" as basic research on the properties and materials of 4D printing, also have an extremely important position in the overall research field. This indicates that 4D printing technology has not yet been perfected in terms of technology, materials, and properties; that the technology itself still has great potential for development; and that research on 4D printing technology itself will still be the focus of future development. Notably, the "#4 future trend" has become an important area in the keyword research hotspot of 4D printing technology. This indicates that with the continuous improvement of the definition, characteristics, and technology of 4D printing, the prospect of its application has been gradually emphasized by scholars. In particular, "#3 bone tissue engineering", "#5 laser powder bed fusion" and "#7 cervical spine" were directly related to biomedicine and were among the most common keyword clusters. This is consistent with the results that, at the beginning of the advent of 3D printing technology, attracted attention in the medical field and resulted in numerous research results [62]. Biomedicine has become a key application in 3D printing. 4D printing is an emerging industry of "3D + time". Compared with 3D printing, it has the characteristics of autonomous response and intelligent evolution and has broader development prospects in the biomedical field. In the future, with the continuous improvement and promotion of 4D printing technology, there are revolutionary possibilities for the development and application of biomedical engineering medical devices, engineering instruments, and other fields. At the same time, "#6 4D food printing" and "#9 aesthetic planning" have gradually attracted increasing attention, expanding the prospects for the application of 4D printing technology.

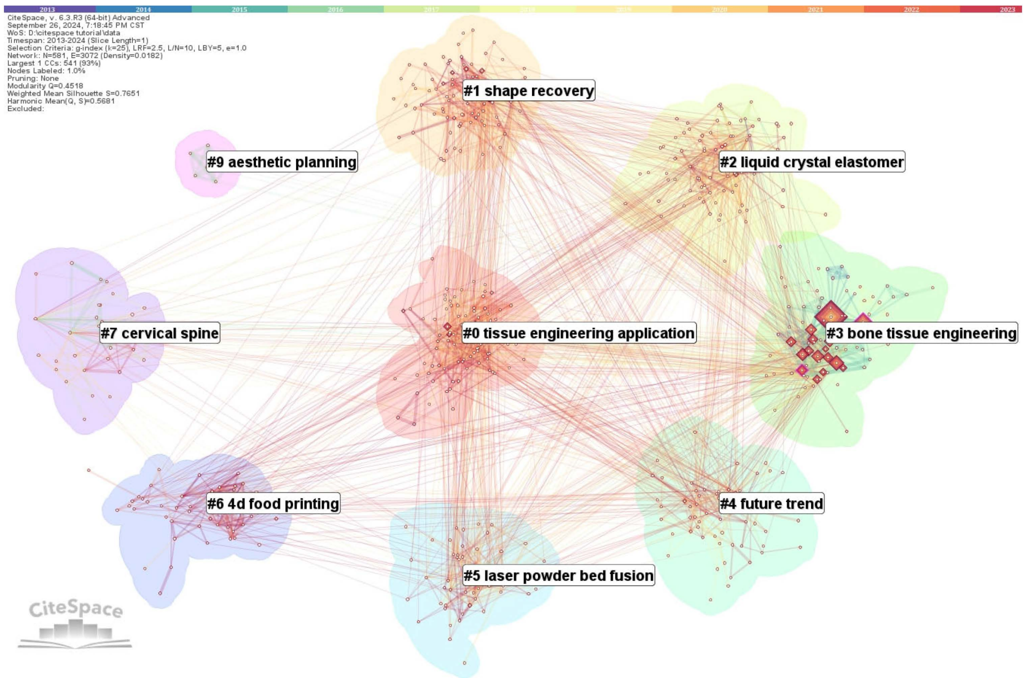
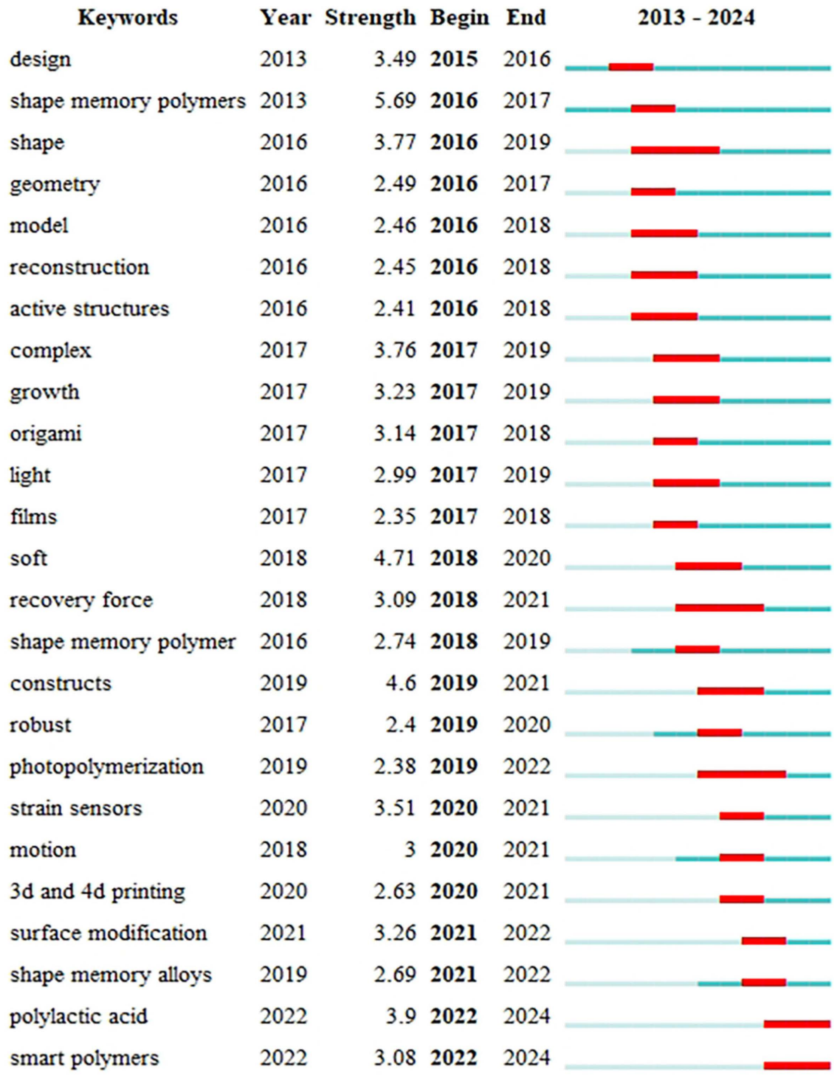


Figure 6. Keyword hotspot network.

Figure 7 lists the 25 main keywords with the strongest citation bursts generated by CiteSpace. The red line represents the outbreak period. The dark blue line represents the time of keywords from publication to now in the field of 4D printing. The results show that "design" (2015–2016) and "deposits" (2015–2017) broke out earliest and attracted much attention from scholars in 2015. Basic research is a hotspot for 4D printing in the early stages of research. At the same time, we also see that "shape", "stereo-lithography", "motion", "recovery force", "metadata" and so on, have relatively long outbreak periods. There is no doubt that 4D printing technology is still in the process of continuous improvement and in-depth research, and has attracted great attention from all walks of life. However, in recent years, these hotspots have gradually subsided. In contrast, emerging hot spots such as "polylactic acid" and "smart polymers" have begun to erupt and become key research trends since 2022. From the perspective of burst intensity, "shape memory polymers" have significantly greater intensity than other keywords, indicating that smart materials are still the main problem plaguing the development of 4D printing technology. However, the outbreak period of "shape memory polymer" research was relatively short, indicating that shape memory polymers attracted the focuses of research by scholars during 2016–2017 and made breakthrough progress.



Keywords	Year	Strength	Begin	End	2013 - 2024
design	2013	3.49	**2015**	2016	
shape memory polymers	2013	5.69	**2016**	2017	
shape	2016	3.77	**2016**	2019	
geometry	2016	2.49	**2016**	2017	
model	2016	2.46	**2016**	2018	
reconstruction	2016	2.45	**2016**	2018	
active structures	2016	2.41	**2016**	2018	
complex	2017	3.76	**2017**	2019	
growth	2017	3.23	**2017**	2019	
origami	2017	3.14	**2017**	2018	
light	2017	2.99	**2017**	2019	
films	2017	2.35	**2017**	2018	
soft	2018	4.71	**2018**	2020	
recovery force	2018	3.09	**2018**	2021	
shape memory polymer	2016	2.74	**2018**	2019	
constructs	2019	4.6	**2019**	2021	
robust	2017	2.4	**2019**	2020	
photopolymerization	2019	2.38	**2019**	2022	
strain sensors	2020	3.51	**2020**	2021	
motion	2018	3	**2020**	2021	
3d and 4d printing	2020	2.63	**2020**	2021	
surface modification	2021	3.26	**2021**	2022	
shape memory alloys	2019	2.69	**2021**	2022	
polylactic acid	2022	3.9	**2022**	2024	
smart polymers	2022	3.08	**2022**	2024	

Figure 7. Top 25 burst keywords on 4D printing in 2013–2024.

To further delve into the research directions of different keyword clusters, Figure 8 was generated with CiteSpace to depict a visual timeline of 4D printing keywords from 2013 to 2024, which contains 581 nodes and 3072 links. The "diamond" represents the emergent keyword nodes of each cluster on the Timeline, and the outline size represents the degree of keyword explosion. In this section, we found nine keywords, such as "tissue engineering application" and "shape recovery" which are the most prominent hot themes. In addition, we show the evolution process of some keywords' hot spots.

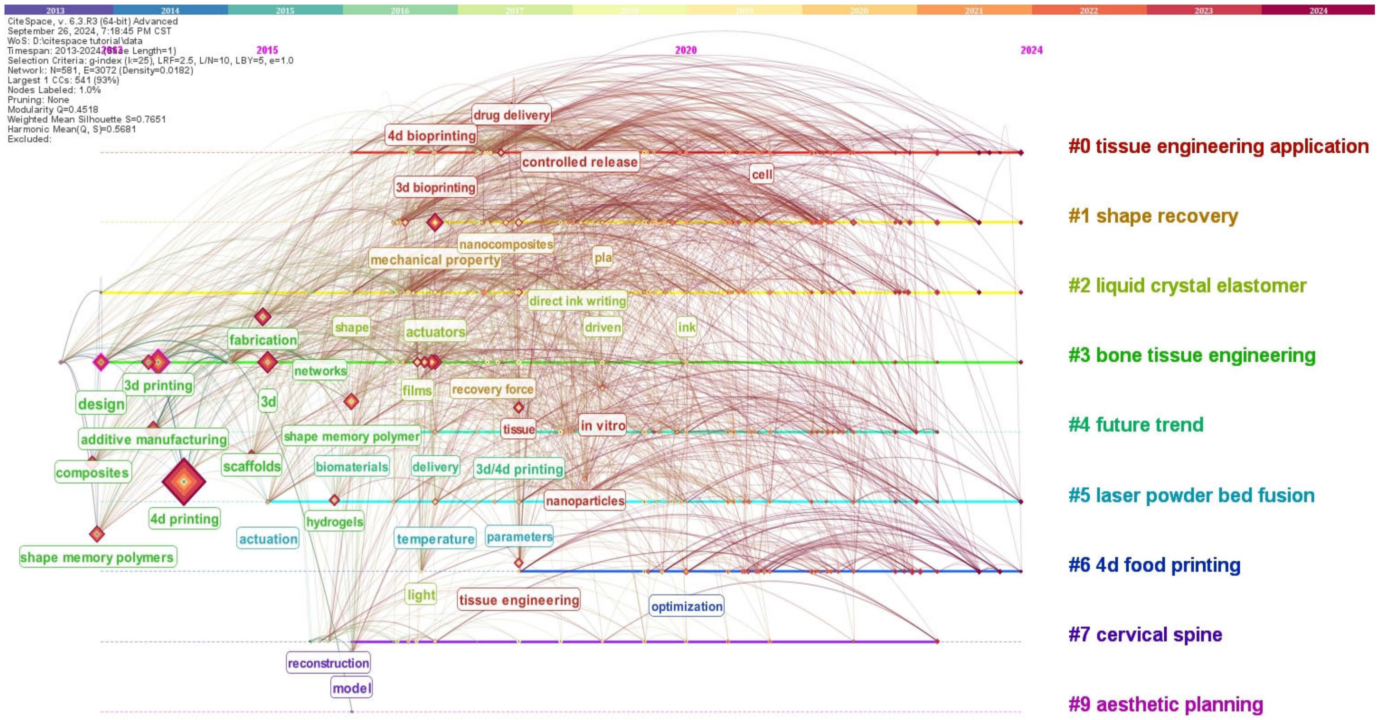


Figure 8. Timeline view of 4D printing keywords.

From 2013 to 2015, hot spots such as "shape memory polymers" and "composites" evolved into "fabrication". From 2015 to 2018, hot spots became "technology", "tissue engineering", etc. After 2018, "poly-lactic acid", "cellulose", "regenerative medicine", etc., became emerging hot spots. In addition, "elastomer", "4D food printing", "time", "biomedical application", "orientation", "energy absorption", "smart polymers" and so on are also significant hot spots. "5D printing", "stability", "implants" etc., may become emerging trends in the future. The specific visualization results are shown in Figure 8. The elements in a map include nodes, timelines, links, and clusters. Nodes represent keywords; the color of connections represents the time when the connected nodes first co-occurred; and to the right of each timeline are clusters containing nodes. The smaller the sequence number is, the larger the cluster and the more nodes it contains. We can see that "tissue engineering application", "shape recovery", "liquid crystal elastomer", "bone tissue engineering", "future trend", "laser powder bed fusion", "4D food printing", "cervical spine" and "aesthetic planning" are the top nine keyword focuses. "Tissue engineering application" is the greatest research hotspot. From a timeline perspective, "4D food printing" is an emerging trend. We will focus our research on the evolution of the keywords "#0 tissue engineering application" and "#1 shape recovery". In the cluster "#0 tissue engineering application", keywords evolved from "3D printing" and "matrix" before 2016 to "membrane" and "shape memory composites" and then to "cellulose" by 2024. By 2016, 4D printing had completed the first stage of evolution. This confirms that 4D printing is an emerging and constantly improving innovative process. The emergence of the keyword "3D printing" shows that in the development of 4D printing, it is necessary to learn from the existing research results of 3D printing and combine the needs of development in various fields to continuously innovate and develop new technologies. From 2015 to 2020, the vigorous development of 4D printing technology occurred. At this stage, 4D printing technology was not limited to the initial biomedical and engineering manufacturing fields, but "4D + food", "4D + cultural creation", "4D + life" and "4D + clothing" have gradually become active in academic research [24,63,64]. The original 4D printing technology was influenced by the demands of different fields, and its technical development gradually began to diversify under the guidance of demand [26]. Biomedical care, as the initial and most fruitful field of 4D printing technology, began to develop explosively after 2015. After 2015, hot keywords such as “hyaluronic acid”, “poly-lactic acid” and “regenerative medicine” appeared frequently in Cluster “#0 tissue engineering application” which also reflects that interdisciplinary research has become more frequent and in-depth since 2015. This is strong evidence of the application prospects of 4D printing technology. Finally, in recent years, the popular keywords of 4D printing technology have increasingly diversified and been used in multiple domains. Especially in the cluster “#4 Future Trends” some scholars have put forward the idea of “5D printing”. After a comprehensive analysis, we believe that research on 4D printing is developing according to the route of “basis-technology-application”. Its application prospects gradually present the development trend of “3D application field-multifield field-cross field”. In the future, with the maturity of 4D printing technology, its research results will gradually affect many fields, such as the military industry, art, culture, and clothing, and will ultimately lead to a situation in which multiple disciplines and multiple fields cross and develop and promote each other. In addition, we used CiteSpace to generate Figure 9 to better present the evolutionary relationship of keywords. Each circle in the graph represents a keyword that is the year that first appeared in the analyzed dataset. The lines represent connections between keywords. This connection makes the time zone chart have a time factor. As indicated by Figure 9a, the stage of formation for 4D printing was prior to 2020. At this time, research on 4D printing focused mainly on its essence and application. In order to better study the relationship between 4D printing, 3D printing and additive manufacturing, and to explore the research hotspots of 4D printing at different times, selecting terms such as “3D printing”, “4D printing” and “additive manufacturing” respectively (Highlighted red text in Figure 9), Figure 9b–d are obtained. Figure 9b–d respectively reflect the hot keywords of “additive manufacturing”, “4D printing” and “3D printing” in different periods. It can be seen that the early research on 4D printing focused mostly on the comparison between 3D printing and additive manufacturing. However, since 2020, research on the correlation between 4D printing “3D printing” and “additive manufacturing” has gradually decreased, and more emerging hotspots, such as “6D printing” and “lacor”, have been formed.

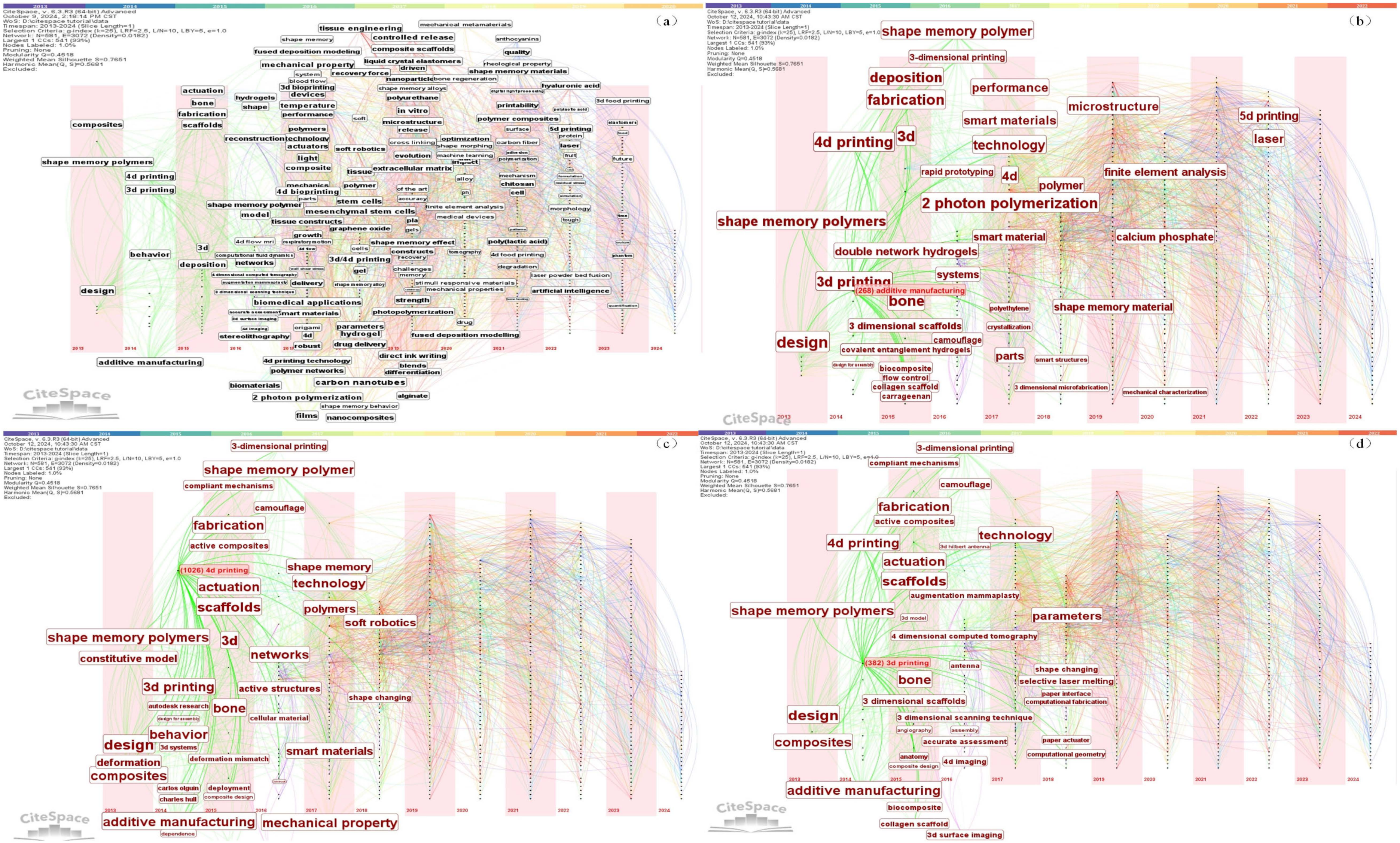


Figure 9. Time zone view of 4D printing keywords.

4. Prospects

Through the previous analysis of the research focuses of 4D printing, we found that the current research on 4D printing has gone through the basic research stage and developed into the technology application stage. Therefore, studying the application prospects of 4D printing has research significance and theoretical value. Analysis using VOSviewer and Citespace software revealed that engineering manufacturing, biomedicine, food and cultural and creative life accounted for a relatively high proportion of the overall research cluster. We will analyze the application prospects of 4D printing from four aspects: engineering manufacturing, biomedicine, food and cultural and creative life.

4.1. Engineering Manufacturing

As an emerging manufacturing technology, 4D printing is opening up the possibility of intelligent manufacturing in the future, heralding major changes in production methods. In the field of engineering manufacturing, 4D printing focuses on basic research. At the beginning of 4D printing research, the main research focused on 4D printing itself, such as technology [65], characteristics [64], materials [55], etc. As 4D printing technology has matured, scholars have also begun to pay attention to its application prospects in engineering manufacturing. For example, Haleem et al. [64] studied the characteristics and workflow of 4D printing technology and proposed that 4D printing technology is a more practical and better production method in engineering manufacturing and can minimize manufacturing labor costs. In the future, these materials can be used in the manufacturing of smart goods, comfort car seats and airbags, smart plumbing devices, transformations, design freedom, enhanced production possibilities, smart water valves, complex assemblies, enhanced market growth of manufacturing, and wide use in many fields, such as improving reliability and performance [64]. 4D printing can self-deform objects under specific environmental conditions, allowing large-scale engineering products to automatically adapt to environmental changes, which is considered by some scholars to be a revival of technology and manufacturing [7]. At present, 4D printing is playing an increasingly important role in the most cutting-edge fields of engineering and manufacturing, such as robots [12], aerospace [66], national defense and military [67], sensors [21], and the automobile industry [14]. In particular, 4D printing can process smart materials into dynamic structures with various stimulus-responsive behaviors, making it possible for scientists to create single-material soft robots that do not require any other processing procedures and can move unfettered materials, thereby ensuring stable and powerful robot rolling [68]. However, some scholars have also suggested that 4D printing applications still face technical, material and design challenges [69]. For example, 4D printing materials are limited to several types of materials, such as hydrogels, thermally responsive, photoresponsive, electrically responsive, magnetically responsive materials, piezoelectric materials, and pH-responsive materials [69]. This undoubtedly limits the application areas of 4D printing technology. In the future, if we can further strengthen basic research on 4D printing, especially AM processes, materials, stimuli, interaction mechanisms and modeling, it will greatly expand the application and applicable fields of 4D printing in the field of engineering and manufacturing.

4.2. Biomedical

After reviewing the research results of 4D printing through VOSviewer and CiteSpace software, we found that biomedicine plays a very important role in its application. Among the largest clusters generated by CiteSpace, “#3 bone tissue engineering”, “#5 laser powder bed fusion”, and “#7 cervical spine clusters” are all directly related to biomedicine and rank among the top clusters formed. In addition, other top-ranked clusters also indirectly intersect with biomedicine, and their results have had an important impact on biomedicine. Notably, among the top three clusters in biomedicine, “#3 bone tissue engineering” has great research results. For example, Chen et al. [24] regarded 4D bioprinting as a representative next-generation bone repair technology, and in their work, they used 4D-printed biological scaffolds to achieve advanced orthopedic surgery, proposing that 4D bioprinting combined with programmable biomaterials, living cells and bioactive factors provide greater potential for building dynamic, personalized and precise bone tissue engineering scaffolds through the complex structural formation and functional maturity. You et al. [34] used 4D printing technology to create a multi-response bilayer deformable membrane composed of a shape memory polymer (SMP) layer and a hydrogel layer by remotely adjusting the fate of stem cells, which can be accurately switched between proliferation and differentiation to promote bone formation and match specific macro bone shapes in clinical scenarios, thereby improving the formation of deformable membranes in new bone and accelerating bone healing in vivo. In other fields of biomedicine, 4D printing technology also plays an important role [30]. In the field of stomatology, 4D printing technology has expanded the application of dental materials, such as shape memory alloys, smart ceramics, smart composites, glass ion-based cement, etc., improving dental restoration technology, which can rely on the biocompatibility of 4D printing, the elastic modulus and the thermal layer expansion coefficient to simulate the body structure to prevent adverse physical reactions such as swelling, inflammation or ischemic reactions [70]. In the field of implantable organs, some scholars have carried out theoretical research in the areas of cardiovascular and cerebrovascular [6] systems, regenerative organ tissues [71], etc., but this technology is still in its infancy, and the application of 4D printing in manufacturing human organs requires further research to achieve clinical application in the neural field. Currently, Cui et al. [28] have used 4D printing technology to develop a neurogenic nerve conduit with self-driving capabilities by immobilizing neurogenic factors in situ on a printed structure with aligned microgrooves. Neurogenic guidance can be used for nerve regeneration. In addition, 4D printing technology has also played an increasingly important role in other fields, such as minimally invasive surgery [8,72], drug delivery [73], tissue engineering [22], and skin reconstruction [74]. In the future, with the continuous improvement of 4D printing technology, it will also have broad application prospects in other fields, such as smart textiles (such as orthopedic plaster), manufacturing actuators and sensors [62].

4.3. Food Printing

Food printing is an emerging field in 4D printing applications, but it quickly attracted the attention of scholars, and numerous research results have erupted. At present, research on 4D printing technology in the field of food printing has focused mainly on food interactivity, food characteristics (including flavor, nutrition or color), food production, and food transportation and storage [35]. In terms of food interactivity, 4D printing can be used to construct suspended structures, such as blooming flowers. The transformation of flowers from closed to blooming makes eating more interesting, thus attracting more consumer attention; for example, for picky eaters, 4D-printed food provides new ideas for the design of interactive food and enhances the interaction between diners and food materials [75]. In terms of food characteristics, the color, taste, texture and shape of 4D-printed food samples can lead to food characteristics such as color, taste, aroma, texture and shape in response to various stimuli (such as temperature, pH, light, and ionic strength). Change, giving consumers a better eating experience [13]. In terms of food production, 4D printing can effectively control structural changes during the drying process, thereby making some healthy snacks [35]. In addition, while realizing the automated production of food, 4D printing technology is combined with digital cooking to customize it according to individual needs for food shape, structure and flavor, realizing the combination of automated production and customized production [63]. In terms of food transportation and storage, companies can prepare deformed food through 4D printing to achieve flat packaging, reducing transportation costs and storage space [29].

4.4. Cultural and Creative Life

With its astonishing development speed, 4D printing technology has spread from pure engineering and medical applications to the textile and fashion industries [10]. In particular, for fashion goods such as textiles and jewelry, researchers have prepared products that make the wearer feel comfortable based on the adaptability of the environment or requirements [11]. Compared with a traditional cultural and creative life, the main advantages of 4D printing technology include: first, geometric flexibility, which allows for the improvement and optimization of product functions and structural characteristics; second, modification of microstructure characteristics through metamaterial methods; third, use less raw materials; fourth, cost and resource efficiency of small-scale production; fifth, cloud manufacturing shortens the supply chain due to more localized production, which has important sustainability benefits [76]. Despite advances in 4D printing technology, applying 4D printing to textiles remains challenging. This is mainly due to the technical gap between specialty prototypes and manufacturing scalability. Unfortunately, research on textile applications of 4D printing is still in the infancy of research and technology development (R&TD) [77]. Although 4D printing has full potential in different applications in the apparel field, such as the development of functional filament fibers/wires, 4D printing of textiles, and 4D printing of finished garments and 4D textiles, further development is still needed [78]. If 4D printing technology can be applied to the clothing field, the cost and resource efficiency of small-scale production can be optimized through localized production, and the supply chain and demand-driven manufacturing can be shortened, which can be customized and expanded, taking into account cost and environmental sustainability [79]. 4D printing also plays an important role in other fields of cultural and creative life [27]. For example, when 4D printing is combined with culture and education, there will be different kinds of chain reactions occur. In addition to the function of the product itself, cultural and creative products printed in 4D add the story of the product because of its shape memory effect, which plays an auxiliary role in learning historical and cultural knowledge [69]. When 4D printing is combined with VR, AR and other augmented reality technologies, it will provide more immersive experience services to users [80]. The application and development of new 4D printing technology in the literature and entertainment has a broad market.

5. Conclusions

In this research, we studied the research focuses and emerging trends of 4D printing. We used VOSviewer and CiteSpace software to visually analyze 4D printed documents collected from SCI, SSCI, AHCI, CPCI-S, CPCI-ssh, ESCI, CCR-EXPANDED and IC collections on the Web of Science. Through the analysis of co-cited document networks, sudden keywords, and other indicators, we generated a knowledge landscape of 4D printing technology and explored hot spots and trends in related fields. We answered the following questions surrounding 4D printing technology: hot spots, trends, applications, and future development; we made some new findings.

5.1. New Findings

In terms of the hotspots of 4D printing, we found that as the research on the raw materials of 4D printing technology continues to deepen, the encoding method and the manufacturing method have gradually become the focus of scholars' research direction. This is consistent with Cerbe et al. [17] research on the technical parameters of fused deposition modeling (FDM) for 4D printing. Of the 19 most cited references we created using VOSview, all of them are related to the manufacturing methods and applications of 4D printing, and these findings further support Ahmed et al. [69]. Therefore, the external stimulation, modeling, and simulation design of 4D printing technology has great development potential and may become a research hotspot in 4D printing technology in the future [17,34]. Meanwhile, we intuitively found through the co-cited reference network and hotspot clusters created by CiteSpace that "emerging applications", "4D-printed shape memory polymers", and "4D-printed active composite structures" are the three largest clusters reflecting that they are the largest research hotspots for 4D printing technology. Others, such as liquid crystal elastomers [81], geometry-driven finite elements [82], and biomedical applications [30], are also hot research areas for 4D printing. In addition, we have noticed that the research on materials, structures, applications of 4D printing, and its relationship with 3D printing has become more concentrated. Moreover, by visualizing the hotspots and emerging trends in keywords, we found that keywords such as “3D printing”, “3D” and “additive manufacturing” have higher citation rates compared to other keywords through the web visualization keyword mutation map and highlighted keywords created by VOSview. At the current stage of 4D printing research, technology development and application research are gradually coming to the forefront, and the keywords of “fabrication”, “design”, “composites” and “scaffolds” are at the top of the list, all show that scholars are researching on advancing 4D printing technology. Finally, by using the keyword hotspot Timeline view created by CiteSpace, we analyzed that “tissue engineering application” and “shape recovery” are the most prominent hotspots in 4D printing.

In terms of research trends in 4D printing: By visualizing the hot and emerging trends in the references, we find that “#0 Emerging Applications, 2020”, “#11 Loading Patterns, 2022” and “#20 Robotic Applications, 2020” in the clusters represent the latest research and development directions in 4D printing technology. And more importantly, “#6 geometry-driven finite elements, 2013”, “#9 controlled sequential shapes, 2011”, “#10 4D nano-printing based on laser technology, 2013” and “#12 polyelectrolytes, 2012” used to be the hot areas of 4D printing technology. However, few scholars have paid attention to them in recent years, and the related research has shown a contraction, which reflects that the development potential of these themes in 4D printing research may not be large. At the current stage of 4D printing research, technology development and application research are gradually emerging, and the keywords of “fabrication”, “design”, “composites” and “scaffolds” in the top rankings all show that scholars are interested in advancing 4D printing technology, which is in line with Bajpai et al. [62] and Kabirian et al. [6]. Therefore, we infer that the application prospects and technological development around 4D printing technology will be a very promising area of research. Meanwhile, we analyzed the keyword hotspot network and highlighted keywords created by CiteSpace, and the keywords of 4D printing technology cover many fields such as engineering and manufacturing, biomedical, lifestyle products, food, and cultural and creative industries. Cluster “#0 tissue engineering application” is still the most researched field, which is the most basic and important content in 4D printing research. Cluster “#1 shape recovery” and “#2 liquid crystal elastomer”, as the basic research on the characteristics and materials of 4D printing, are also extremely important in the overall research field. Cluster “#4 future trend” has become an important area in the keyword research hotspot of 4D printing technology, indicating that the technical application prospect of 4D printing has also been gradually emphasized by scholars. In addition, the medical-related clusters in the formed keyword clusters account for a relatively large proportion and rank high, such as “#3 bone tissue engineering”, “#5 laser powder bed fusion”, “#7 cervical spine” and so on. Some emerging fields such as “#6 4D food printing” and “#9 aesthetic planning” are also gaining attention.

In terms of the current status of 4D printing applications: One hand, by analyzing the application prospects of 4D printing technology in the four fields of engineering manufacturing, biomedicine, food printing, and cultural and creative life, we found that 4D printing is a very disruptive emerging manufacturing technology because of its adaptability and proactive response characteristics, showing great application potential in these fields. On the other hand, there is still a large space for research on the technology, materials, and design of 4D printing, which limits the prospect of its application in existing fields and its expansion to more fields [12,27,30].

In terms of the future development of 4D printing, over time, the initial hotspots of 4D printing, such as “shape memory polymers” and “composites” have gradually evolved into “poly-lactic acid” and “composites”. “Poly-lactic acid”, “cellulose”, “regenerative medicine” and “5D printing” have become emerging hotspots. “5D printing”, “stability” and “implants” may become emerging trends in the future. Moreover, combining the time evolution of 4D printing keywords hotspots, we infer that: first, the original 4D printing technology is affected by the needs of different fields, and its technological development has gradually begun to diversify under the guidance of demand. Secondly, 4D printing has become more frequent and in-depth in cross-disciplinary and cross-field research after 2015. Thirdly, the hot keywords of 4D printing technology in recent years are more diversified and multidisciplinary.

5.2. Theoretical and Practical Significance

By collecting research results on 4D printing from databases SCI, SSCI, AHCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED and IC in the core collection of Web of Science and visualizing and analyzing them by using VOSviewer and CiteSpace software, we can provide readers with a more intuitive and comprehensive understanding of the research hotspots and emerging trends in 4D printing rather than simply analyzing the research results of 4D printing technology in a particular field [8,34,75]. This facilitates scholars who wish to conduct research in this field. For example, by analyzing the prospects of 4D printing applications, we can enable scholars in the field of biomedicine to focus on bone tissue engineering [34] and further minimally invasive surgery [8,65], drug delivery [66], tissue engineering [15], skin reconstruction [67], and other emerging fields. Moreover, by using scientometrics to visualize and analyze 4D printing, the development direction of 4D printing can be clarified, which leads to the conclusion that the application prospects and technological development will be the future promising research focuses of 4D printing, which is in line with other scholars' research on 4D printing [7,17,35] and provides references for other scholars' subsequent research. In addition, we obtained cluster maps and landscape maps by visualizing and analyzing the hotspots and emerging trends in references and keywords related to 4D printing technology. For the first time, many hotspots and emerging trends were identified through co-cited reference networks and exploded keywords, which fills the gap in the academic community's systematic research on existing research results related to 4D printing through visualization. The relevant conclusions can not only further enrich the related theories of 4D printing but also provide new insights for the development of 4D printing.

5.3. Limitations and Future Research

Although we used multiple perspectives and multiple indicators to obtain more comprehensive and accurate conclusions, there is no guarantee that all the results will be obtained. Therefore, there may be omissions or deviations in the conclusions regarding the research focuses and emerging trends of 4D printing. In addition, although the database we have chosen well covers the current high-quality literature around the world, there may still be some important studies that have been missed because they are not in these databases, which will also have a certain impact on our research. In summary, we will further optimize the relevant parameters in subsequent research, expand the data range, and continuously improve the quality of the research.

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