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Research Progress and Trend Analysis of Concrete 3D Printing Technology Based on CiteSpace

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Abstract: As an emerging method in engineering construction, concrete 3D printing has experienced rapid development in recent years due to its advantages in terms of automation, digitization, and intelligence. In order to comprehensively understand the research progress of concrete 3D printing technology, the literature on concrete 3D printing technology published in the Web of Science core database from 2014 to 2023 is used as a data source, and the visualization tool CiteSpace is utilized to research and analyze these results from the following aspects: number of publications, collaboration networks, research hotspots, and evolutionary trends. The results show that the number of publications in the field of concrete 3D printing technology has been increasing from year to year, with a gradually accelerating growth rate. The top three journals in terms of publication volume are *Construction and Building Materials*, *Cement and Concrete Composites*, and *Materials*. Research in the field of concrete 3D printing technology is mainly conducted through collaborations among research groups or institutions, while there are relatively fewer interactions among researchers from different institutions, regions, and countries. The current research direction mainly focuses on 3D printing materials, process parameters, and technology. The research content has progressed from initial explorations of concrete 3D printing technology to detailed studies of 3D printing materials and their performance. Overall, the research in this field continues to add further details to our knowledge of concrete 3D printing technology, and its application in engineering is gradually increasing. The automated, digitized, and intelligent construction methods of concrete 3D printing technology serve as a powerful driving force for the transformation and upgrading of the field of architecture.

Keywords: 3D printing; construction technique; civil engineering; CiteSpace

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1. Introduction

In recent years, with the rapid development of our society and economy, the process of urbanization and industrialization has accelerated, and people's quality of housing has continuously improved. Green and environmentally friendly new types of buildings have become the mainstream trend in the development of the modern construction industry [1]. At the same time, the construction industry is facing problems such as extensive production, massive resource consumption, and severe environmental pollution. There is still a gap in this development model when it comes to efficiency, greenness, and intelligence [2]. In the face of the development needs of the construction industry and the introduction of sustainable development policies, seeking a more flexible, efficient, and green engineering construction method has become an important task at present [3]. The process of 3D printing, also known as additive manufacturing, solidifies digital models. It is widely used in industrial manufacturing [4], biomedicine [5], aerospace [6], and architecture [7]. The origin of concrete 3D printing technology can be traced back to the 1990s. As an intelligent construction method, it can simplify and expedite the design and construction process. It has advantages in terms of automated construction, fewer materials used, environmental friendliness, greater architectural freedom, higher accuracy, and safety. It provides an effective way to change the predominant mode of production, which currently has a high level of energy consumption and a low level of production efficiency, and can promote the transformation and upgrading of the construction industry [8–10].

With the increasing amount of research on concrete 3D printing technology, it is of great significance to systematically review the literature in the field of concrete 3D printing technology, as it helps scholars to quickly understand the research progress and development trends in this field and contributes to promoting the transformation and upgrading of the construction industry. Dey et al. [1] provided a comprehensive review of 3D-printed sustainable concrete, analyzing the influence of different industrial waste materials on its performance and discussing the potential for the successful application of industrial waste materials in 3D-printed concrete, which promotes the development of sustainable concrete materials. Lee et al. [11] used text mining techniques to extract keywords from the published literature over the past 20 years and conducted a statistical analysis on the research trends of concrete 3D printing technology, providing suggestions for future research. Zhang et al. [12] provided a detailed introduction to concrete 3D printing technology, reviewing its development in terms of aspects such as printability, mechanical performance, and architectural design and highlighting its tremendous potential in practical applications.

Currently, most scholars have conducted comprehensive analyses of concrete 3D printing technology from specific perspectives, with few scholars using bibliometric tools and a combination of qualitative and quantitative methods to systematically review the field of concrete 3D printing technology. Therefore, the literature related to concrete 3D printing technology from the Web of Science core database between 2014 and 2023 is selected as a data sample. CiteSpace is used to systematically analyze this data sample and explore the basic situation, research hotspots, and evolutionary trends of the research field of concrete 3D printing technology by using methods such as graph and knowledge graph analyses, which can provide a reference for future scholars' research.

2. Research Methods and Data Sources

2.1. Research Methods

CiteSpace, developed by Chaomei Chen's team based on the Java environment, is a knowledge visualization tool that offers functionalities such as information visualization, data mining, and literature management. It can transform a large amount of literature in a research field into a comprehensible knowledge map [13,14]. Therefore, in this study, CiteSpace was used for chart analysis, cooperation network analysis, and keyword co-occurrence analysis of the annual publication volume and journal publication volume of relevant literature in the field of concrete 3D printing technology. These analyses aim to explore and analyze the potential development mechanisms and to present the research hotspots and evolutionary trends in this field.

2.2. Data Sources

This study utilized the Web of Science (WOS) core database as the data sample for the field of concrete 3D printing technology. The search was conducted using an abstract approach, with a retrieval period from January 2014 to August 2023. The document type is article or review, and the language is English. In the WOS database, keywords "3D Printing or Three-dimensional Printing or Additive Manufacturing or digital fabrication" and "Architecture or Civil Engineering or Concrete or Mortar or Cement-based or Cementitious material" were used for our cross-search, and the number of collected articles or reviews was 2875. By reviewing the titles and abstracts of literature, duplicates and literature not related to concrete 3D printing technology were excluded. Finally, 1214 relevant collected articles and reviews from the WOS database were selected.

3. Results and Analysis

3.1. Subsection

Annual Publication Volume and Journal Publication Volume

The annual publication volume can provide a visual representation of the development speed and future trends in a field. Using data retrieved from the Web of Science (WOS) database, a trend graph depicting the annual publication volume of the literature on concrete 3D printing technology is shown in Figure 1.

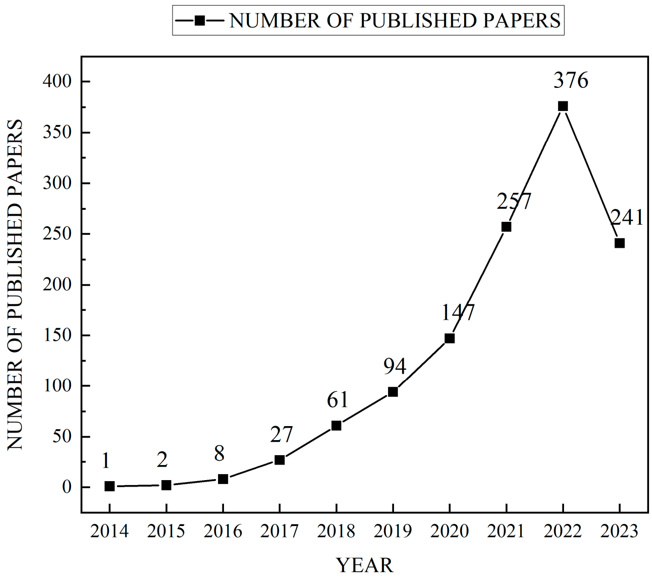

Figure 1. Trend graph of annual publication articles (until August 2023).

As shown in Figure 1, the trend of publication volume can be divided into three stages. In the first stage (2014–2015), the publication volume was minimal and at a low level. The publication volume in this stage accounted for only 0.25% of the total, with an average annual publication volume of 1.50 articles. This indicates limited research focus on concrete 3D printing technology and limited research outcomes. In the second stage (2016–2020), with the increasing number of applications of concrete 3D printing technology, this topic has garnered more attention from scholars, leading to a period of rapid development in related research [15,16]. The publication volume in 2017 was 3.38 times that of 2016, the publication volume in 2018 was 2.26 times that of 2017, the publication volume in 2019 was 1.54 times that of 2018, and the publication volume in 2020 was 1.56 times that of 2019. In the third stage (2021–2023), concrete 3D printing technology entered a phase of rapid development, with the publication volume reaching its peak at 376 articles in 2022. As the literature cutoff date was August 2023, the publication volume in 2023 decreased. The publication volume in this stage accounted for 71.99% of the total, with an average annual publication volume of 291.33 articles. A significant number of articles and reviews in the literature on concrete 3D printing technology emerged, greatly promoting the development of the construction industry.

The literature on concrete 3D printing technology is distributed across 171 journals. The journal *Construction and Building Materials* ranks first in terms of publication volume with 209 articles, followed by *Cement and Concrete Composites* (108 articles), *Materials* (91 articles), *Cement and Concrete Research* (72 articles), and *Automation in Construction* (71 articles). The combined publication volume of these five journals accounts for 45.39% of the global total, indicating that they are important publishing journals in the field of concrete 3D printing technology. Table 1 presents the top twelve journals by publication volume, which can help scholars understand the core journal group and major research directions in this field and provide references for literature searches and to aid in platform selection for publication.

Table 1. Top twelve journals by number of publication articles.

Rank	The Name of Journals	The Number of Published Papers
1	*Construction and Building Materials*	209
2	*Cement and Concrete Composites*	108
3	*Materials*	91
4	*Cement and Concrete Research*	72
5	*Automation in Construction*	71
6	*Additive Manufacturing*	64
7	*Journal of Building Engineering*	51
8	*Buildings*	45
9	*Journal of Cleaner Production*	28
10	*Sustainability*	24
11	*Composites Part B; Engineering*	22
12	*ACI Materials Journal*	21

3.2. Analysis of Author Collaboration Network

The network map of author collaboration can be used to identify the key figures and research teams in a field, showcase the collaborative relationships between different researchers and teams, and help us better grasp overall research directions. Based on the literature from the Web of Science (WOS) database from 2014 to 2023, using the "Author" function in CiteSpace, a network analysis of author collaborations in the field of concrete 3D printing technology was conducted, and a visual map was drawn as shown in Figure 2. There are a total of 364 nodes and 526 links, with a network density of 0.008. In the map, the nodes represent authors who have published papers, and the larger the node, the more papers the author has published. The node color represents the year, and different colors represent different years. The network density indicates the degree of connectivity of the nodes in the graph. The higher the network density, the more partnerships there are. The links between the nodes represent collaborations between authors, and the thicker the link, the closer the collaboration. Table 2 shows the top twelve authors in terms of research paper output in the field of concrete 3D printing technology in the WOS database. The centrality is calculated using the function "Compute Node Centrality" in Citespace, and the higher the centrality, the more important and influential the node is.

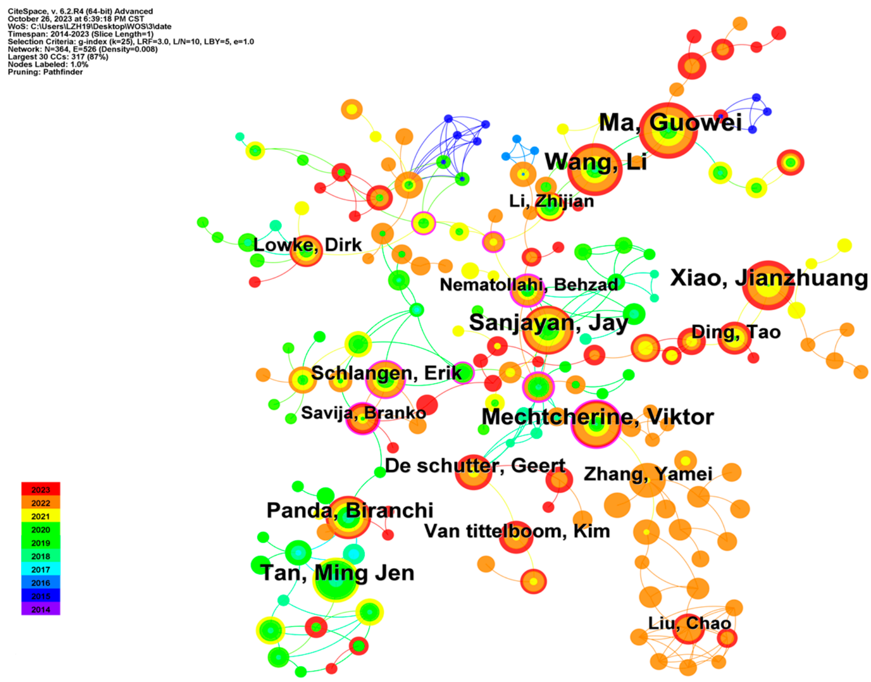

Figure 2. Knowledge graph of author collaboration networks.

Table 2. Top twelve authors by number of publication articles.

Rank	Count	Centrality	Author
1	49	0.07	Ma Guowei
2	42	0.09	Wang Li
3	39	0.02	Sanjayan Jay
4	37	0.04	Xiao Jianzhuang
5	34	0.12	Mechtcherine Viktor
6	31	0.01	Tan Ming Jen
7	28	0.09	Panda Biranchi
8	21	0.03	De Schutter Geert
9	19	0.16	Schlangen Erik
10	18	0.10	Zhang Yamei
11	17	0.05	Ding Tao
12	17	0.01	Van Tittelboom Kim

As shown in Table 2, the top five authors by publication volume are Ma Guowei (49 papers), Wang Li (42 papers), Sanjayan Jay (39 papers), Xiao Jianzhuang (37 papers), and Mechtcherine Viktor (34 papers). Professor Ma Guowei from Hebei University of Technology has close collaborations with Wang Li and Li Zhijian. By analyzing the literature, it was found that this team has made significant contributions in the field of environmentally friendly materials and material properties [17–20]. Next is the research team led by Sanjayan Jay and Nematollahi Behzad from Swinburne University of Technology, which has conducted extensive research on the interlayer bond strength of 3D-printed concrete and steel reinforcement technology [21–23]. The team led by Xiao Jianzhuan from Tongji University has studied the application of recycled materials in concrete 3D printing technology, promoting the sustainable development of the construction industry [24–26]. Other major collaboration networks include the team led by Mechtcherine Viktor from Dresden University of Technology, the team led by Panda Biranchi and Tan Ming Jen from Nanyang Technological University, and the team led by De Schutter Geert from Ghent University. In addition, the highest centrality was achieved by the team of Schlangen Erik at Delft University of Technology, indicating that their research content is highly influential in the field. Overall, research teams in the field of concrete 3D printing technology have started to take shape, with a growing number of researchers.

3.3. Analysis of Institution Collaboration Network

Our analysis of research institutions and collaboration relationships helps us understand the research capabilities and impact of relevant institutions in the field of concrete 3D printing technology. The "Institution" function in CiteSpace is used to analyze the network of institution collaboration in the literature obtained from the WOS database, and a visual graph was generated, as shown in Figure 3. The network consists of 262 nodes and 306 links, with a network density of 0.0089. Table 3 presents the top twelve research institutions ranked by publication output.

As shown in Table 3, the top five institutions in terms of publication output are Tongji University (67 articles), Hebei University of Technology (58 articles), Swinburne University of Technology (54 articles), Nanyang Technological University (52 articles), and ETH Zurich (50 articles). Their total publication output accounts for 23.15% of the literature globally, indicating they have made significant contributions to the development of concrete 3D printing technology. A further analysis reveals that all of the top ten institutions in terms of publication output are universities, indicating that research in the field of concrete 3D printing technology is primarily focused on theoretical methods and technological research, with less integration into engineering practice. In the future, it is necessary to strengthen collaborations between different institutions to continuously address practical issues and achieve the industrialization of advanced technologies. Additionally, among the top twelve institutions in terms of publication output, there are four institutions with centralities greater than 0.1: Indian Institute of Technology (0.3), Southeast University (0.25), Swinburne University of Technology (0.12), and ETH Zurich (0.11). This indicates that these three institutions hold important positions in the field of 3D printing concrete technology and their related research has a high degree of international influence.

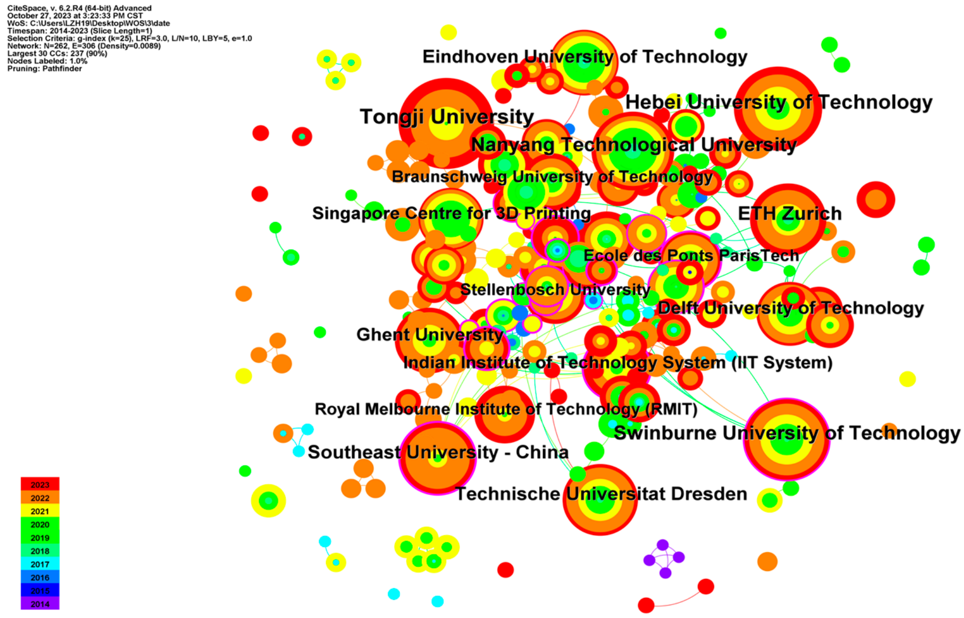

Figure 3. Knowledge graph of institution collaboration networks.

Table 3. Top twelve institutions by number of publication articles.

Rank	Count	Centrality	Institution
1	67	0.07	Tongji University
2	58	0.04	Hebei University of Technology
3	54	0.12	Swinburne University of Technology
4	52	0.01	Nanyang Technological University
5	50	0.11	ETH Zurich
6	44	0.25	Southeast University
7	41	0.03	Technische Universität Dresden
8	37	0.05	Eindhoven University of Technology
9	36	0.01	Ghent University
10	34	0.02	Delft University of Technology
11	33	0.3	Indian Institute of Technology
12	32	0.01	Singapore Centre for 3D Printing

3.4. Analysis of Collaboration Network between Countries

Analyses of the network map of collaborations between countries can reflect the overall research level and development status of a country in a certain field to some extent and intuitively demonstrate the degree of connection between different countries and regions. The "Country" function in CiteSpace is used to analyze the network map of collaborations between countries in the literature obtained from the WOS database, and a visual graph was generated as shown in Figure 4. There are a total of 73 nodes and 75 links, with a network density of 0.0285. Table 4 shows the top twelve countries in terms of publication volume.

Our data analysis of the network map of collaborations between countries reveals that a total of 188 countries and regions have conducted research on concrete 3D printing technology. Among them, China ranks first with 373 articles, accounting for 30.72% of the total publication volume. The United States comes second with 169 articles, accounting for 13.92% of the total, followed by Australia with 146 articles, accounting for 12.03% of the total. As the network map shown, China is the largest node, indicating that China's research in this field is more extensive compared to other countries. However, its centrality is only 0.05, suggesting that Chinese scholars' participation in international cooperations still needs improvement. Among the top twelve countries, South Korea has the highest centrality, followed by France and Switzerland, with centrality values of 1.11, 0.93, and 0.84, respectively. This indicates that these three countries have close collaborations with other countries and have a higher level of international influence.

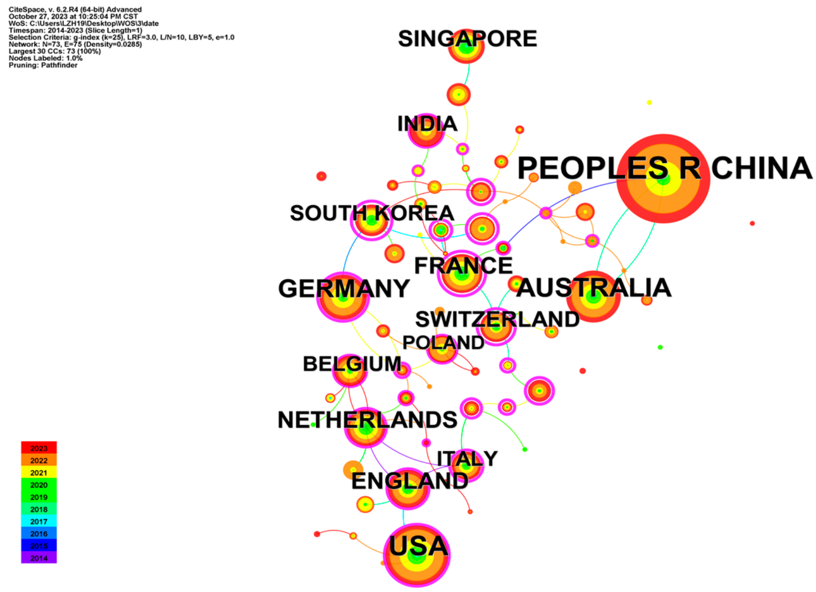

Figure 4. Knowledge graph of collaboration networks between countries.

Table 4. Top twelve countries by number of publication articles.

Rank	Count	Centrality	Country
1	373	0.05	China
2	169	0.2	USA
3	146	0.01	Australia
4	104	0.53	Germany
5	77	0.93	France
6	75	0.25	Netherlands
7	74	0.29	England
8	69	0.01	Singapore
9	55	0.84	Switzerland
10	51	0.15	India
11	49	1.11	South Korea
12	46	0.1	Belgium

3.5. Analysis of Research Hotspot

The frequency of keywords appearing in a particular field can reflect the core content of research in that field. The "Keyword" function in CiteSpace is used to conduct a co-occurrence analysis of the literature data on journals concerning concrete 3D printing technology in the Web of Science (WOS). A network map of research was generated, as shown in Figure 5. The map contains 557 nodes and 969 links. The size of each node represents the frequency of the corresponding keyword, and the links between nodes represent the strength of the associations between keywords. The purple outer circle within each node represents its centrality, with a thicker purple circle indicating a node has a higher level of centrality and is of greater importance. The top twelve keywords in terms of frequency are listed in Table 5 according to the statistical results.

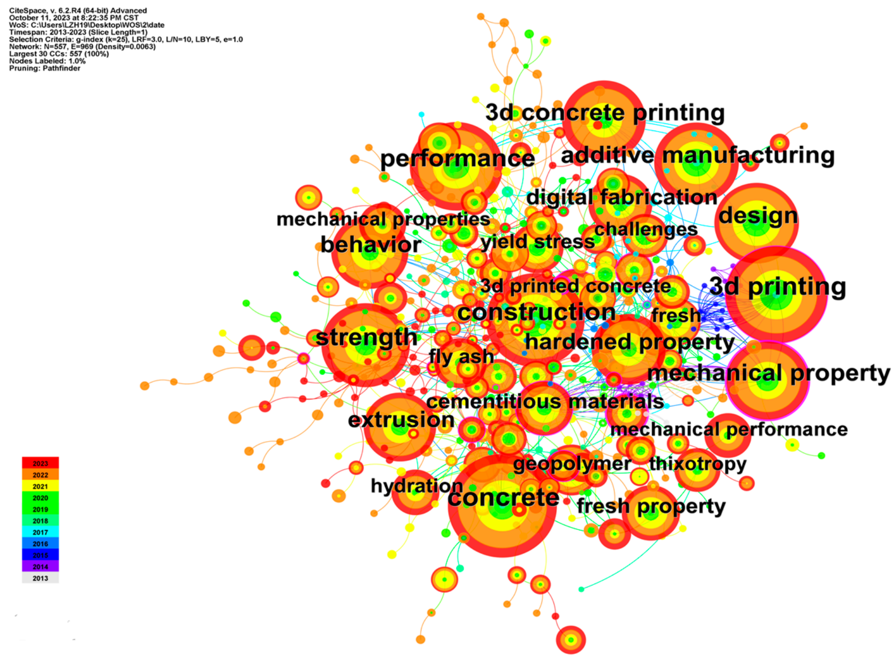

Figure 5. Knowledge graph of research hotspots.

Table 5. Top twelve keywords.

Rank	Count	Centrality	Keyword
1	399	0.02	concrete
2	357	0.15	3D printing
3	322	0.03	construction
4	290	0.02	performance
5	274	0.06	strength
6	240	0.08	additive manufacturing
7	239	0.02	design
8	239	0.3	mechanical property
9	234	0.1	3D concrete printing
10	203	0.02	behavior
11	188	0.01	hardened property
12	183	0.02	extrusion

Combining the research hotspots, knowledge graph, and high-frequency keyword list, excluding directly related keywords such as "concrete", "3D printing", "construction", "additive manufacturing", "3D concrete printing", and "digital fabrication", the top five high-frequency keywords are determined as "performance" (290 times), "strength" (274 times), "design" (239 times), "mechanical property" (239 times), and "behavior" (203 times). According to these high-frequency keywords, it can be seen that the research on concrete 3D printing technology mainly focuses on materials' characteristics. Many scholars start with material proportion designs, use experimental validation methods, and develop cement-based materials suitable for 3D printing. They also study and analyze their materials' work performance and mechanical properties, providing a large amount of experimental data for the development of 3D printing materials in architecture [18,27–29]. Some scholars also study the influence of printing parameters such as printing rate and printing time interval on concrete properties from the perspective of the 3D printing process. They found that both material and process parameters are important factors affecting the performance of printed components, providing a new perspective for improving the performance of 3D-printed components [21,30–32]. Further reading and analyses of the literature reveal that, to meet the requirements of green building development, some scholars start from the perspective of green construction and sustainability, using industrial waste materials such as slag, fly ash, and limestone powder as raw materials to prepare geopolymer mortars suitable for 3D printing, providing references for the comprehensive utilization of low-carbon green materials [33–35]. Simultaneously, some scholars are utilizing local materials, such as construction waste, nano-clay, and kaolin as raw materials to prepare mortars suitable for 3D printing. This not only achieves the recycling of resources but also significantly reduces transportation costs [36–38]. In addition, among the top twelve keywords, those with a centrality greater than 0.1 include "3D printing", "mechanical property", and "3D concrete printing", indicating that mechanical properties are the focus of current research and have a high level of influence in the field of concrete 3D printing technology.

3.6. Analysis of Frontier Trend

A time zone graph consists of a series of vertical bands representing time zones, which can visually display the development history and main research topics of relevant studies from a temporal perspective and intuitively show the evolutionary trend of the field, capturing the direction of industry development. The "Time Zone" module in CiteSpace was used to analyze the keywords and generate a time zone graph of research hotspots in the field of concrete 3D printing technology, as shown in Figure 6. The nodes and links in the graph have the same meanings as those in the co-occurrence graph of keywords.

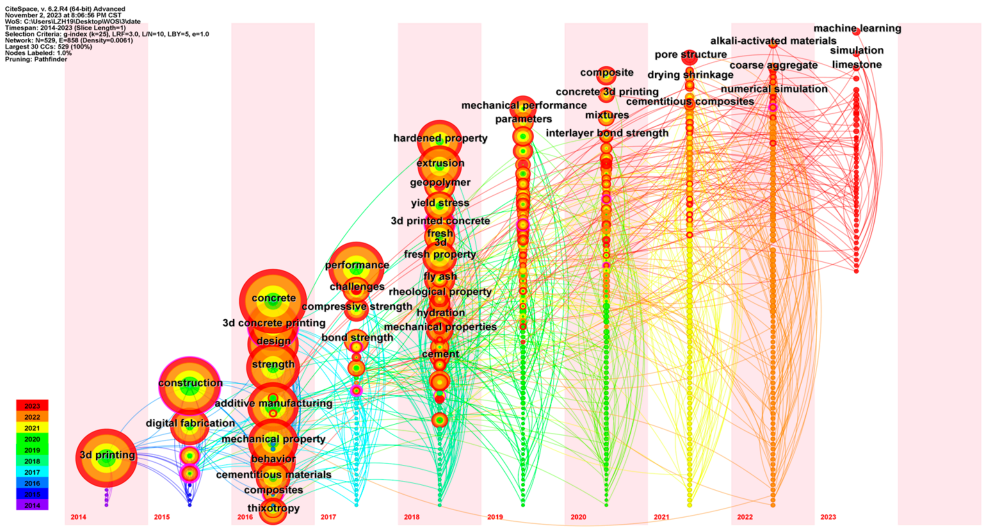

Figure 6. Research hotspot time zone graph.

According to the research hotspot time zone diagram and our literature review, the research on concrete 3D printing technology can be divided into three stages. In the first stage, from 2014 to 2015, 3D printing technology was in its initial development in the construction industry. The frequently mentioned keywords in this stage include "3D printing", "digital fabrication", and "construction". Upon reviewing the literature, it is found that scholars in this stage investigated the feasibility of applying concrete 3D printing technology in the construction industry, starting from existing technologies. Gesaretti et al. [39] successfully printed a part of a wall in a lunar simulation environment using D-shape technology, verifying the feasibility of 3D printing technology for lunar habitat construction.

In the second stage, from 2016 to 2019, the frequently mentioned keywords include "concrete", "performance", "hardened property", and "mechanical performance". Research in this stage mainly focused on 3D printing materials. Scholars improved testing methods for 3D printing material properties and developed printable concrete materials. Many keywords emerged during this period. Concrete 3D printing technology developed rapidly in this stage. Perrot et al. [40] studied the role of cement-based materials' layer-stacking performance in concrete 3D printing technology, proposed a theoretical framework to predict the optimal construction rate, and verified its effectiveness through experiments.

Kazemian et al. [41] proposed a laboratory testing framework for 3D printing material properties, studying the printability of materials in regards to aspects such as print quality, shape stability, and printing time. They also proposed two test methods to evaluate shape stability. Ma et al. [17] proposed an environmentally friendly cementitious mixture using waste and recyclable materials as the main raw materials and verified the printability of the mixture through experiments. Panda et al. [42] studied the influence of nano-attapulgite on the printability, mechanical properties, and microstructure properties of fly ash mortar. They found that an appropriate amount of nano-attapulgite significantly improved the thixotropic properties of fly ash mortar and enhanced its printability.

In the third stage, from 2020 to 2023, the development of concrete 3D printing technology further progressed. The frequently mentioned keywords in this stage include "composite", "pore structure", "alkali-activated materials", and "machine learning". Based on the research on concrete materials, scholars studied the influence of porosity, pore volume distribution, and pore geometric characteristics on the performance of 3D printing materials from a microscopic perspective. Liu et al. [43] analyzed the pore structure of 3D-printed recycled coarse aggregate concrete using X-CT technology, proposed a multi-zone model, and established the relationship between pore structure characteristics and cracks. Liu et al. [44] characterized the microscopic failure mechanism of 3D-printed concrete using X-CT and DIC technology and analyzed the relationship between the pore structure and mechanical properties of 3D-printed concrete. Alkali-activated materials are a cement substitute that can reduce the consumption of cement. Dai et al. [45] used alkali-activated brick dust as a binder for geopolymer mixtures and investigated the effect of brick dust waste on the printability of the mixtures. They found that geopolymer concrete significantly reduced carbon emissions compared to ordinary silicate cement. Some scholars also used machine learning techniques to predict the mechanical properties of 3D-printed materials by establishing mathematical models. Yao et al. [46] studied the influence of steam curing conditions on the mechanical properties of 3D-printed concrete and used their experimental results to establish a machine learning model to predict the mechanical properties of steam-cured concrete. Ghasemi et al. [47] established a mathematical model using multiple regression and artificial intelligence algorithms to quantify the relationship between properties like sample age, fine aggregate content, and compressive strength, providing a pathway for customized functional concrete. The application of machine learning in the field of concrete 3D printing technology can be useful in achieving efficient and intelligent construction methods in the field of architectural engineering.

4. Discussion

Based on the WOS core database, CiteSpace was used to conduct a visual analysis of the literature on concrete 3D printing technology from 2014 to 2023, including the number of publications, collaboration patterns, research hotspots, and evolutionary trends.

The number of publications in the field of concrete 3D printing technology has been increasing from year to year, with a gradually accelerating growth rate. Among the 171 journals related to concrete 3D printing technology, *Construction and Building Materials*, *Cement and Concrete Composites*, *Materials*, *Cement and Concrete Research*, and *Automation in Construction* are the top five journals in terms of publication volume. Researchers can learn about the research progress in this field through these journals. An analysis of journal types reveals a tendency towards materials-related publications. This further confirms that material-related issues are both the challenges and focal points of application of concrete 3D printing technology.

In terms of network maps of collaboration, research in the field of concrete 3D printing technology is mainly conducted through collaborations between research groups or research institutions. There is close contact between researchers within the same university or research team, while there is less contact between researchers from different research institutions, regions, and countries. In the future, it is recommended to strengthen cooperation and communication among institutions, regions, and countries to achieve resource sharing and promote the development of concrete 3D printing technology.

In terms of research hotspots, high-frequency keywords from the WOS journal sources are focused on topics such as "performance", "strength", "design", "mechanical property", and "behavior". A closer look at the literature reveals that research in the field of concrete 3D printing technology is concentrated in three aspects. First, there is research on 3D printing materials. Concrete 3D printing technology requires materials with good workability and mechanical properties to ensure the continuous and uniform extrusion of materials from the nozzle without bending or deformations, thus ensuring the safety and quality of printed buildings. Researchers improve the performance of 3D printing materials through the incorporation of additives [48], blending materials [36], and special fibers [49]. Second, there is research on 3D printing process parameters. The quality of 3D-printed components is not only related to the properties of the materials themselves but also to the printing process parameters. Researchers have studied the impact of process parameters such as printing time intervals, material deposition rates, and printing directions on the performance of printed components, providing new methods for improving the performance of 3D-printed structures [50,51]. Third, there is research on 3D printing technology itself. Due to the uniqueness of 3D printing technology, it is difficult to achieve the synchronous placement of rebar during the printing process. Therefore, the integration and printing of rebar in the construction process are challenges for achieving the automation and intelligent development of the construction field. Some researchers have enhanced and toughened concrete materials by adding various fibers and controlling the distribution of fibers' orientation [18,52,53]. Although these methods are simple, they have shown limited improvement in the performance of concrete materials and there is still a significant gap compared to traditional cast reinforced concrete. Other researchers improve the performance of concrete materials by automatically placing wires between layers, manually placing wire meshes, and 3D printing rebars [54–57]. However, there are still various limitations, and further in-depth research is needed.

In terms of evolutionary trends, researchers have gradually progressed from initial explorations of concrete 3D printing technology to detailed studies on 3D printing materials and performance. In recent years, with the gradual maturity of research of concrete 3D printing technology, its application in the construction field has increased. Automated and digitized construction methods have become a powerful driving force for the transformation and upgrading of the construction industry [58,59].

5. Conclusions

The relevant literature in the field of concrete 3D printing technology from the WOS database is used as our data sample, and analyses of publication patterns, cooperation network maps, and keyword co-occurrence are conducted to organize and visually analyze the existing achievements in this field. We revealed the development status of concrete 3D printing technology and clearly demonstrated updates to and the mutual influence of the literature, providing a reference for future research by relevant scholars. Currently, research on concrete 3D printing technology is mainly focused on concrete materials, printing processes, and printing techniques. Related studies are gradually maturing. However, there are still significant limitations in practical applications, such as the difficulty of achieving the simultaneous printing of rebar. Extensive experimental verification and practical experience can be utilized to address practical applications, thereby promoting the application and popularization of concrete 3D printing technology.

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Conflicts of Interest: The authors declare no conflicts of interest.

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