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STEM pre-service teacher education: A review of research trends in the past ten years

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Abstract

The urgent need for high-quality STEM teachers put forward a high demand for STEM pre-service teacher education, which generates a variety of research. This study aims to systematically review relevant articles using the CiteSpace software to visualize the research trends and research hotspots of STEM pre-service teacher education. 166 articles were selected from the Web of Science core collection database from 2012 to 2021. The results show that the research hotspots mainly include single-discipline pre-service teacher training, the design of STEM pre-service teacher training programs, and the application of modern high technology in education. While the research trends are reflected in the interdisciplinary and integrated training of STEM pre-service teachers, the construction of an evaluation system of STEM pre-service teacher education, and the integration and degree of application of high technology. The results provide an objective research basis for subsequent studies.

Keywords: STEM, pre-service teacher education, CiteSpace, cluster analysis, review

INTRODUCTION

Since the concept of STEM (science, technology, engineering, and mathematics) was first proposed in 1986 by the National Science Foundation of the USA, it has been regarded as an effective method for cultivating high-tech talents. STEM education aims to integrate knowledge from multiple disciplines and emphasizes practice, and it is helpful to develop students' problem-solving skills and innovative thinking (Bybee, 2013; Khalil & Osman, 2017; Sen et al., 2018; Tytler, 2020). The "interdisciplinary" and "practice-oriented" of STEM education put forward high requirements for universities to ensure the cultivation quality of STEM pre-service teachers. Policies and programs in different countries have been introduced to ensure the quality and quantity of STEM pre-service teachers. The USA emphasized that the government should invest in STEM teacher education and strived to cultivate 100,000 teachers by 2020. In the UK, the Ministry of Education began to provide scholarships for STEM pre-service teachers in 2019 to attract students with STEM discipline backgrounds to become STEM teachers in the future. STEM teachers have been proven to be the key factors and the most basic resource in STEM education programs (Bybee, 2013).

The preliminary review of the existing articles on STEM pre-service teacher education shows that the research history of this topic is relatively short, and it has been a hot research topic since the early twenty-first century (Gul & Tasar, 2020). Moreover, the exciting research focused more on the topics of training objectives, training courses, and pedagogy, which aim to provide specific practical guidance for cultivating STEM teachers (Kim et al., 2015; Lin et al., 2021; Scaradozzi et al., 2019; Yildirim & Sidekli, 2018). Meanwhile, the existing research on STEM pre-service teacher training is mostly small-scale exploration and implementation in local contexts to provide more targeted research and guidance, with more local characteristics. However, it lacks extensive evidence support (Gul & Tasar, 2020). It is still far from meeting a wide range of practical needs and lakes universality. STEM pre-service teacher education is important in promoting the implementation and dissemination of STEM education and has received increasing attention from scholars. However, the research topics are scattered, and the development trend is not very clear as its short history. It is necessary to conduct a systematic review to summarize the research

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Contribution to the literature

- Research sorted out the mass literature on STEM preservice teacher education to provide readers with a global understanding of the current state.
- The study highlights the research hotspots and research trends in STEM preservice teacher education to provide a theoretical basis for further research.
- The study proposes suggestions for STEM preservice teacher education, emphasizing the importance of interdisciplinary and comprehensive training.

hotspots and research trends of the existing literature so that the researchers can have a clearer and more intuitive understanding of the connections and interactions of different studies.

A systematic review can help researchers explore the status and trends of research in a certain field, and help researchers narrow the scope of literature to provide more accurate evidence for research questions (Petticrew & Roberts, 2008). Hence, this study specifically aims to review the development of STEM pre-preservice teacher education by analyzing the existing articles related to STEM pre-service teacher education in the Web of Science core collection database from 2012 to 2021. With the use of CiteSpace software, the researchers further conducted visualization and cluster analysis to present the visual information of the knowledge base, research trends, and research hotspots of STEM pre-service teacher education, which provide a theoretical base for future studies.

LITERATURE REVIEW

STEM Education

The concept of STEM (originally abbreviated as SME&T) was proposed by the USA National Science Foundation early in 1986 and was regarded as more than a simple combination of mathematics, science, engineering, and technology, but also integrates the social behavioral sciences such as psychology, economics, sociology, political science, etc., the core characteristics of STEM is the "interdisciplinarity" and "integration" of different disciplines (Breiner et al., 2012). With the continuous implementation and promotion of STEM education, the researchers have found its advantages in cultivating high-tech talents, as STEM education can well integrate the knowledge of different disciplines and break the barriers, which can effectively help students to deal with different real-life issues from various perspectives and more comprehensively (Bybee, 2013). The issues in the 21st century are often of high complexity. Analyzing and solving such issues is difficult without knowledge of a single discipline. STEM education can help to cultivate high-tech talents with deep technical and personal skills to address the grand challenges of the 21st century (Kennedy & Odell, 2014; Langdon et al., 2011).

STEM Teacher Education

STEM teachers are crucial in strengthening students' literacy and capabilities through STEM teaching. Teachers' characteristics, knowledge and skills, and STEM experience will impact students' learning outcomes (Margot & Kettler, 2019). The individual characteristics of STEM teachers include age, gender, educational background, STEM learning experience, etc. Existing studies have shown that STEM teachers' age influenced their understanding of STEM and its application in the classroom. Generally, with the growth of age, teachers' intention to apply STEM concepts and knowledge in class will decline. The reason is that those subject teachers get used to the mode of subject education, and their intention to innovate and integrate STEM in class gradually declines (Nadelson & Seifert, 2013). Gender is another factor. Studies showed that female teachers are less willing than males to integrate STEM knowledge into their classrooms (Park et al., 2016). Educational and related subject backgrounds are also important factors influencing STEM teachers teaching STEM in class. The proportion of teachers with a high educational background current is not high. It is generally reflected that the STEM learning experience received in the pre-service stage is insufficient. The professional development in the in-service stage is inadequate, affecting both STEM teaching and, thus, affecting students' STEM learning outcomes (Al Salami et al., 2017).

The perception of STEM teachers is also an important factor affecting students' learning outcomes, mainly reflected in their understanding of the importance of STEM education and its core characteristics. Studies indicate that STEM teachers' perception of STEM education is an important prerequisite for them to carry out STEM education in the classroom. Suppose STEM teachers hold a positive attitude toward STEM education and accept it as a new teaching method in cultivating the innovative spirit and comprehensive skills of STEM talents. In that case, they will have a higher intention to transform their intention into teaching behavior (Bell, 2016). In addition, STEM teachers' perception of the core characteristics of STEM education can ensure STEM teachers' appropriate design of STEM classroom content and teaching methods (Ryu et al., 2019). The integration and interdisciplinary nature of STEM education and its high appeal to practicing have put forward higher requirements and new challenges for teachers' knowledge reserve, teamwork, and classroom implementation. STEM teachers' correct perception of STEM education can promote teachers' continuous promotion of their STEM literacy and teaching capability to improve the classroom's effectiveness and positively impact students' learning outcomes (Zhao, 2015).

The learning and design of pedagogies in STEM education are the key factors that affect the effectiveness of STEM classrooms and ultimately affect students' learning outcomes (Bartels et al., 2019). Some studies have explored the pedagogies in STEM classroom teaching. For example, some scholars have approved that PBL can effectively reflect the integrated characteristics of STEM education and integrate the knowledge of related disciplines, to solve practical problems from an integrated perspective (Lin et al., 2021). Some scholars tried to summarize the teaching methods used in STEM classrooms, including cooperative learning, discussion learning, field trips, and so on (Smith et al., 2015). The research results show that selecting appropriate teaching methods combined with STEM knowledge can effectively improve the effectiveness and efficiency of STEM classrooms and improve students' learning outcomes in STEM classes.

Based on the preliminary analysis of the previous research, some scholars have proved that STEM teachers influence students' learning outcomes. They believed that high-quality STEM teachers could effectively promote the implementation and development of STEM education, promote students' learning outcomes, and cultivate many high-quality STEM talents (Lawner et al., 2019). However, there are different opinions on the specific influencing factors and influencing mechanisms. Whether it can be used as a practical guide for STEM teacher education still needs a lot of evidence.

However, the actual situation showed that there should be a large shortage of high-quality STEM teachers in the K-12 stage, which has become a major obstacle to implementing STEM education in primary and secondary schools. The existing STEM in-service teachers are unable to meet the actual needs of STEM education, so STEM pre-service teacher education appears to be urgent and necessary. Therefore, it is necessary and urgent to sort out the research on STEM pre-service teachers, to provide theoretical guidance for strengthening the education of STEM pre-service teachers, and better solve the double gap between the quality and quantity of STEM teachers.

STEM Pre-Service Teacher Education

Referring to traditional teacher education research, existing research on STEM pre-service teacher education contained various aspects. For example, it should be important to clarify the core literacy of STEM pre-service teachers. Yildirim and Sidekli (2018) studied the core literacy of STEM pre-service teachers. They concluded that STEM pre-service teachers should have not only disciplinary literacy but also interdisciplinary ideas and thinking to solve comprehensive problems in real situations. Second, some scholars expressed that it is necessary to strengthen the pedagogy education of STEM pre-service teachers to help them to use appropriate teaching methods in the STEM teaching process, such as the project-based STEM teaching model (Capraro & Slough, 2013), the cycle 6E model (Zhu, 2020), etc. Meanwhile, some scholars emphasized that STEM teaching should be combined with ICT, robotics, computer, and other modern technologies to expand teaching methods (Gunbatar & Bakirci, 2019; Sisman & Kucuk, 2019). Additionally, assessing STEM pre-service teachers is key to ensuring quality. Some scholars have made out different assessments to evaluate the STEM pre-service teacher education programs through questionnaires, interviews, and self-reports, to make sure the access mechanisms and graduation standards of STEM teachers (Zhu, 2020). The research contents and objects are broad.

STEM pre-service teacher education has received increasing attention and obtained some results, but it still has not formed a highly unified result. Though different stakeholders and communities have been aware of the importance of STEM pre-service teacher education, most STEM pre-service teachers still lack the perception of the core characteristics of STEM and STEM education due to the lack of an integrated STEM curriculum system corresponding to theoretical guidance in universities. Researchers have tried to build standard curricula and comprehensive assessments to ensure the quality of STEM pre-service teachers. However, it still lacks sufficient evidence and is far from meeting the realistic requirements to be universal. The research on STEM pre-service teacher education is fragmented, so it is important to clarify the development trend of the different aspects and the connection and interaction between different researchers and studies before further studies.

METHODS

The preliminary analysis of existing studies shows that research on STEM pre-service teacher education is gradually gaining attention and has shown a trend of diversification in recent years. Using software to conduct a bibliometric analysis of the existing literature can help researchers summarize the research status and research trends in STEM pre-service teacher education and provide a systematic and reasonable literature basis for further in-depth research. Therefore, this study used the basic analysis function of the WOS database to conduct a descriptive statistical analysis of the literature and further used the CiteSpace software to visualize and analyze the literature to summarize the existing literature systematically.

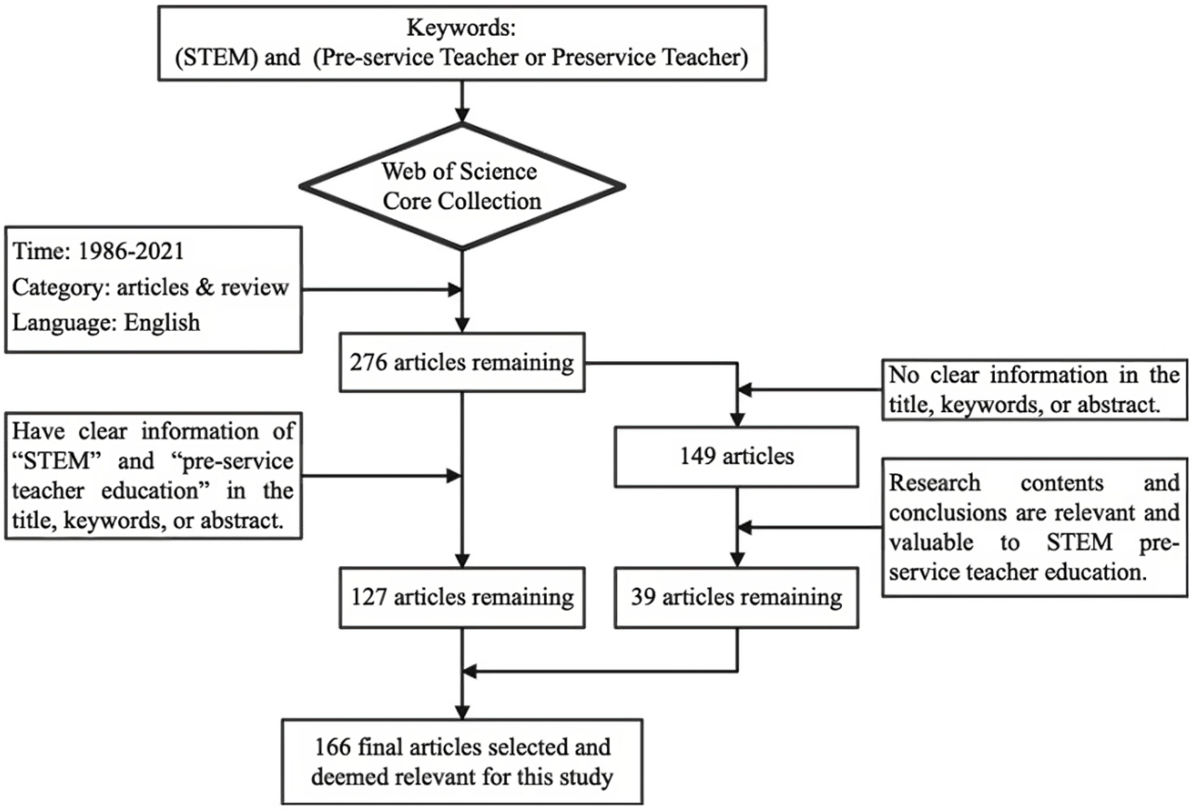

Figure 1. Literature screening flowchart (Source: Authors' own elaboration)

Data Selection Process

This study utilized the Web of Science core collection as the database in accordance with the protocol of prior studies (Marín-Marín et al., 2021; Martín-Páez et al., 2019; Li et al., 2022; Hsu et al., 2023). Web of Science is the world's leading information platform for citation search and analysis (Li et al., 2018). It is a reputable source containing the most prestigious journals in STEM education research (Hsu et al., 2023). The literature selection process is as follows: First, by reading classical literature and sorting out other documents and materials, the following combinations of words are determined as search keywords: "STEM & pre-service teacher" or "STEM & preservice teacher". Then set the time from 1986 to 2021, as the concept of STEM was first proposed in 1986 in the Neil Report. Further refined the articles in the categories of "article" and "review" and the language in English, got a total of 276 articles.

Finally, systematically read the titles and abstracts of the selected articles, excluding those that did not conform to the topic of STEM pre-service teacher education. Specific criteria are to find clear information on "STEM" and "pre-service teacher education" in the title, keywords, or abstract, and to read the full text of the articles that cannot find clear information in these three parts. Finally, this research got 166 sample articles. The text is exported as a basic sample for subsequent analysis. **Figure 1** shows the selection result of each step.

Data Analysis Tools

The research methodology used in this study was bibliometric analysis, as it can present a panoramic view of the research status, research areas, and research hotspots (Chen, 2016). Unlike systematic literature reviews, bibliometric analysis can quantify and analyze the literature from a database quickly and precisely through quantitative techniques (Marín-Marín et al., 2021). It also allows researchers to analyze large volumes of literature while avoiding bias from researchers with different backgrounds (Tosun, 2022).

The bibliometric analysis of this research can be divided into two parts: First is the descriptive statistical analysis of the data from the Web of Science core collection database. The data statistics and analysis function of the WOS database mainly completes this part. The second is cluster analysis by the CiteSpace software. CiteSpace is a visualization software developed by Professor Chen Chaomei using Java language. Using co-occurrence analysis, co-citation analysis, and other theories to measure literature in specific fields, it can explore the critical path of the evolution of subject fields and their knowledge inflexion points (represented by key articles) (Chen, 2016). And through a series of visual atlas to explore the potential power and development frontier of the discipline fireworks, suitable for the overall comprehensive analysis (Chen, 2014).

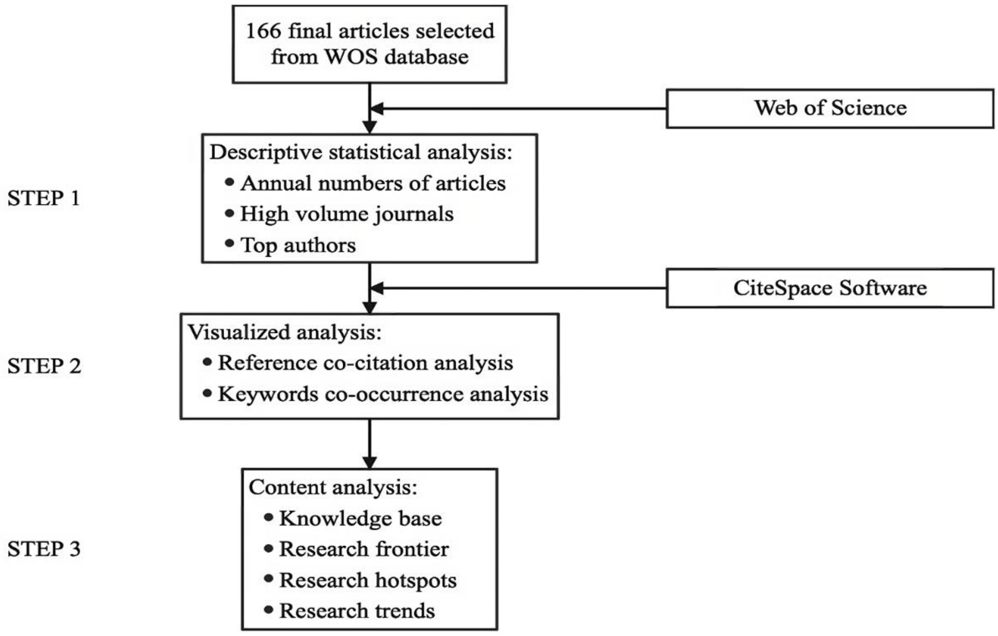

Figure 2. Data analysis process (Source: Authors' own elaboration)

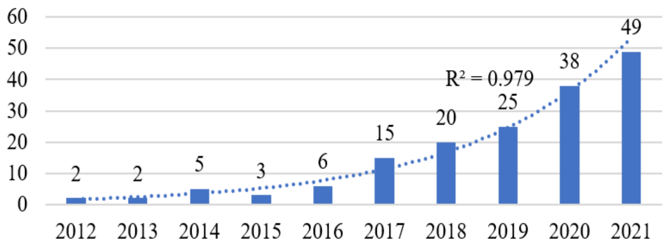

Figure 3. Annual numbers of articles on "STEM pre-service teacher education" (Source: Authors' own elaboration)

Data Analysis Process

Based on the descriptive statistical analysis and knowledge mapping visualized analysis, this study further analyzed the contents of the selected samples to explore trends and hotspots of STEM pre-service teacher education. The analysis can be divided into three steps: First, use the keywords to conduct the topic search in WOS, and finally, select 166 articles according to corresponding standards. The basic functions of WOS carried out descriptive statistical analysis of relevant data to summarize the annual numbers of articles, high volume journals, and top authors of STEM pre-service teacher education. Second, 166 articles from the WOS database were exported for visualized analysis through the CiteSpace software. When exporting, select "full record and cited reference" of the record content and save it in plain text format, which can be directly imported into CiteSpace software. After importing the data, set the node type to "cited reference" to perform reference co-citation analysis and "keyword" to perform keyword co-occurrence analysis. Third, use literature analytical methods and content analysis to describe the frontier literature in STEM pre-service teacher education, to reveal the knowledge base, research frontier, research hotspots, and research trends, which contributed to the development of STEM pre-service teacher education. The detailed steps and analysis contents are summarized in **Figure 2**.

FINDINGS

Descriptive Statistics

The descriptive statistical analysis mainly scans the literature in the field of "STEM pre-service teacher education" from the annual numbers of articles, high volume journals, top authors. The data is obtained directly from the Web of Science core collection database.

Annual numbers of articles

Figure 3 shows that the number of articles on STEM pre-service teacher education is generally on the rise, from two articles in 2012 to 49 in 2021, and showing a significant growth trend after 2016, but the whole development process is relatively short. The overall trend shows that the research on STEM pre-service teachers has received sustained attention from researchers. Meanwhile, it can be predicted from the coefficient (R^2=0.979) in **Figure 3** that the number of articles on STEM pre-service teachers will continue to increase in the future.

High volume journals

The statistics of journals are summarized in **Table 1**. Through sorting out the sample articles, it can be found that the publications are mainly concentrated in the journals named "School Science and Mathematics" (nine), "Journal of Science Education and Technology" (nine), "International Journal of Technology and Design

Table 1. High volume journals (number of articles >5)

No	Journal name	Number of articles
1	School Science and Mathematics	9
2	Journal of Science Education and Technology	9
3	International Journal of Technology and Design Education	7
4	International Journal of Science and Mathematics Education	5
5	Frontiers in Education	5
6	International Journal of Science Education	5

Table 2. Top-authors (number of articles >3)

No	Author	Number of articles	Institution/Country	Total citations
1	S. Blackley	5	Curtin University, Australia	43
2	S. Aydin-Gunbatar	4	Yuzuncu Yil University, Turkey	12
3	R. Sheffield	4	Curtin University, Australia	40
4	J. Radloff	4	SUNY Cortland, USA	33
5	B. Ekiz-Kiran	3	Gaziosmanpasa University, Turkey; Yuzuncu Yil University, Turkey	12
6	D. Gonzalez-Gomez	3	Universidad de Extremadura, Spain	10
7	J. S. Jeong	3	Universidad de Extremadura, Spain	10
8	R. Koul	3	Curtin University, Australia	40
9	K. Y. Lin	3	National Taiwan Normal University, China	17

Education" (seven), "International Journal of Science and Mathematics Education" (five), "Frontiers in Education" (five), and "International Journal of Science Education" (five). Most of the journals focus on issues related to science education, mathematics, and technology.

Top-authors

The authors with more than three articles about STEM pre-service teacher education are listed in **Table 2**, as well as their affiliations. The top-four authors are S. Blackley, S. Aydin-Gunbatar, R. Sheffield, and J. Radloff. They have published four or more articles related to STEM pre-service teacher education. And the analysis of their affiliations and countries showed obvious cooperation between authors in the same universities or countries, especially Curtin University. STEM pre-service teacher education is a relatively new field, but some consensus has begun to emerge. There is a great space and potential for researchers.

Citation Cluster Analysis

This study focuses on the importance and necessity of STEM pre-service teacher education. It is expected to clarify the key information, such as the research basis and hotspots in this field, by sorting out and analyzing the existing literature to provide a basis for subsequent studies. Therefore, CiteSpace visualization software was used in this study to draw and quantitatively analyze the visualization atlas of these 166 sample articles, to obtain the key literature, keyword co-occurrence map, and time zone map of STEM pre-service teacher education in recent 10 years. The key information of STEM pre-service teacher education, such as research basis and research hotspots, were summarized below.

Node types: Cited reference

"Cited reference" is selected as the node type to analyze the knowledge base and research frontier of STEM pre-service teacher education (Li & Chen, 2016). The knowledge base is composed of the collection of co-cited literature, while the research frontier is composed of the collection of cited literature that cited these knowledge bases. **Table 3** summarizes the most highly co-cited articles (top-10), and **Figure 4** shows a visualization of these co-cited articles. These highly co-cited articles are widely recognized theories and knowledge bases in STEM pre-service teacher education.

As shown in **Table 3**, the most highly co-cited article in STEM pre-service teacher education is the next generation science standards (NGSS), which provided a unique three-dimensional architecture that included science and engineering practices, subject core ideas, and interdisciplinary concepts to measure expected student performance, providing teachers and curriculum with information that goes beyond the traditional single criteria, and now serving as an important basis for STEM teachers' teaching and judging criteria (National Research Council, 2013). The book written by Bybee (2013) named "The case for STEM education: Challenges and opportunities" ranked second with 14 co-citations. In the book, Bybee sorted out the historical reforms and challenges of STEM education and discussed the proper roles of the government, universities, and teachers in STEM education, providing reference and help for STEM teachers to formulate and implement teaching plans in their STEM courses (Bybee, 2013). The article of Kelley and Knowles (2013) follows Bybee (2013), with 12 citations, discussing the important role of educators in STEM education, and how teachers establish links between STEM subjects to improve students' interest in learning (Kelley & Knowles, 2016). Other topics of the

Table 3. Most highly co-cited articles (top-10)

No	Title	Author	Year	CCC
1	Next generation science standards: For states, by states	National Research Council	2013	23
2	The case for STEM education: Challenges and opportunities	R. W. Bybee	2013	14
3	A conceptual framework for integrated STEM education	T. R. Kelley & J. G. Knowles	2016	12
4	Teacher STEM perception and preparation: Inquiry-based STEM professional development for elementary teachers	L. S. Nadelson et al.	2013	11
5	STEM education K-12: Perspectives on integration	L. D. English	2016	10
6	STEM integration in K-12 education: Status, prospects, and an agenda for research	National Research Council	2014	9
7	Characterizing STEM teacher education: Affordances and constraints of explicit STEM preparation for elementary teachers	C. R. Rinke	2016	8
8	Robotics to promote elementary education pre-service teachers' STEM engagement, learning, and teaching	C. Kim et al.	2015	7
9	What is STEM? A discussion about conceptions of STEM in education and partnerships	J. M. Breiner et al.	2012	7
10	Introducing STEM education: Implications for educating our teachers in the age of innovation	M. S. Corlu	2014	7

Note. CCC: Co-cited count

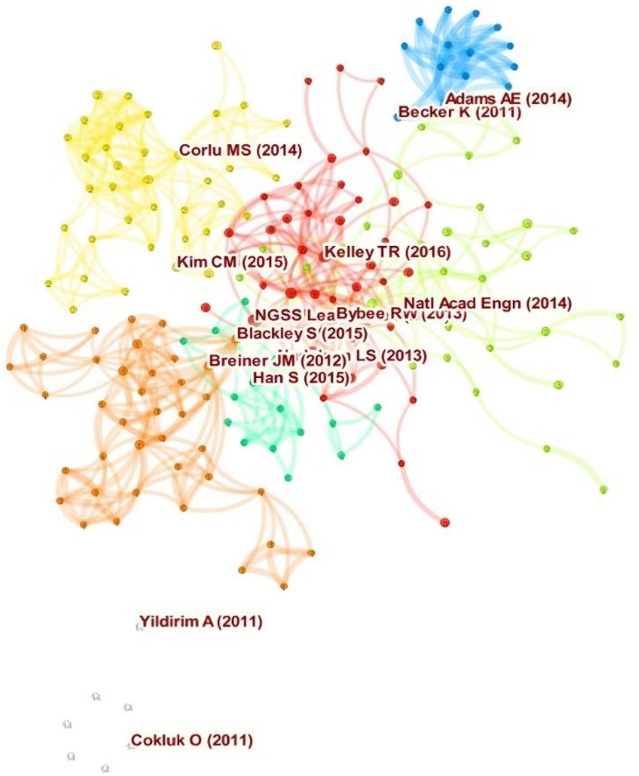

Figure 4. Highly co-cited articles (Source: Authors' own elaboration)

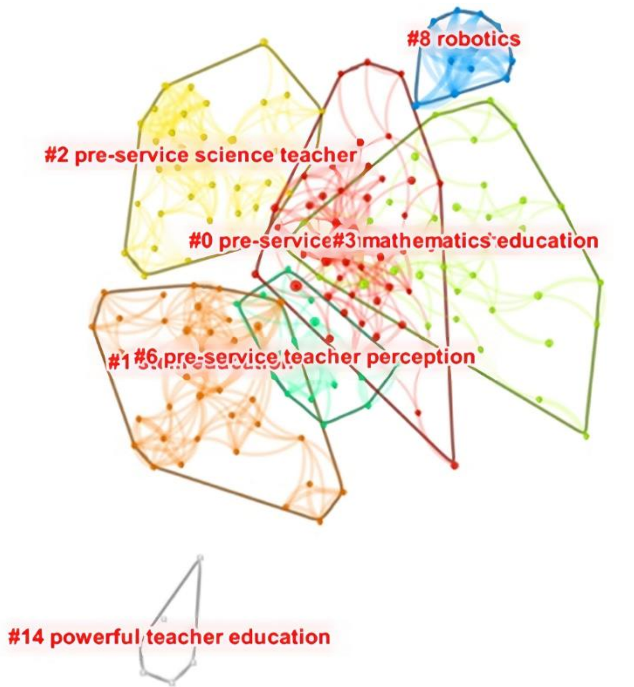

Figure 5. Cluster analysis of the cited reference (Source: Authors' own elaboration)

highly co-cited articles are the teachers' awareness and perceptions, characteristics, robotics, etc.

The cluster naming of cited references can be considered the research frontier, mainly determined by the nominal words extracted from cited literature. The results are shown in **Figure 5**.

The research frontiers of STEM pre-service teacher education can be summarized into seven aspects: pre-service chemistry teacher, STEM education, pre-service science teacher, mathematics education, pre-service teacher perception, robotics, and powerful teacher education. Most frontier research focused on the education of single-subject (especially chemistry, science, and mathematics) pre-service teachers and the combination of modern technologies. But the results also showed that some scholars have begun to pay attention to the perception of STEM pre-service teachers, and the robotics used in the teaching practice. In addition, some scholars also explored and constructed powerful STEM pre-service teacher education, including objectives, literacy, standards, etc. But to dissect and embody the integrated and interdisciplinary STEM education, there is still much room for development in the future.

Table 4. Summary of the co-words (count >5)

No	Keywords	Year	Count
1	Education	2012	41
2	STEM education	2015	29
3	Science	2015	28
4	Pre-service teacher	2012	24
5	Knowledge	2012	20
6	Pre-service teacher	2013	19
7	Student	2014	18
8	Teacher education	2013	18
9	Belief	2014	17
10	Mathematics	2015	14
11	Professional development	2015	13
12	Attitude	2012	13
13	Technology	2020	13
14	Inquiry	2014	12
15	Framework	2012	11
16	Design	2016	10
17	Pedagogical content knowledge	2018	10
18	Impact	2012	10
19	Self-efficacy	2017	10
20	Science education	2017	8
21	Perception	2019	8
22	Computational thinking	2017	8
23	Conception	2015	7
24	Achievement	2018	7
25	School	2014	6
26	Pre-service	2014	6
27	Ability	2015	5
28	Thinking	2021	5
29	Model	2012	5
30	Classroom	2017	5
31	Implementation	2015	5

Node types: Keyword

"Keyword" is selected as the node type to analyze the research hotspots and trends of STEM pre-service teacher education. The mining analysis of co-words is mainly carried out on the main body of the literature. Through co-word analysis, some topics of common concern to scholars in this field can be further inferred, and the research hotspots in this field can be obtained from the time, frequency, and length of the words.

The co-words (count>5) in cited articles are summarized in **Table 4** and **Figure 6**. Co-words can also be considered as the hot keywords, which summarize the core content of existing literature. The analysis of effective co-words can reflect the research hotspots in STEM pre-service teacher education.

The results of **Table 4** show that apart from the usual words such as "STEM education" and "pre-service teacher", "science" should be a major research hotspot as it appeared twenty-eight times in 2015 and nine more times in 2017. It not only appeared frequently but also became a continuous topic over time. Mathematics (14) was a hot topic around 2015, while technology (13) was in 2020.

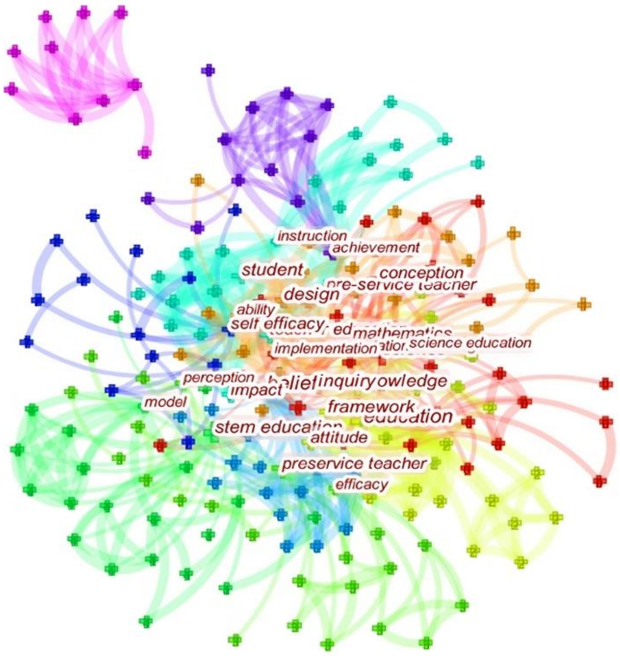

Figure 6. Visualization of the co-words (Source: Authors' own elaboration)

In addition, the research hotspots in the recent five years (2017-2021) also included self-efficacy (10), thinking especially computational thinking (eight), achievement (seven), and classroom (five). By further content analysis, it can be found that researchers in recent years have focused on the self-efficacy of STEM pre-service teachers as influencing their intention to choose STEM careers in the later periods. Besides, some scholars believed that the rapid development of information technology and computing machines could effectively promote the practice and realization of concepts and ideas of STEM pre-service teachers, so it is important to strengthen the computational thinking of STEM pre-service teachers. In addition to the theoretical knowledge education of STEM pre-service teachers, researchers have also paid attention to their practical teaching capability and classroom design to ensure students' learning outcomes. This practical research provided a variety of successful teaching and curriculum design cases for STEM teacher education.

Co-word analysis mainly extracts nominal terms from titles, keywords, and supplementary keywords in databases to analyze the relationship between authors and research. Co-word clustering results are generally considered to show the hot topics in the related field. The analysis of **Figure 7** shows that the research hotspots of STEM pre-service teacher education can be clustered and summed up into 10 categories, and **Figure 8** shows the hotspots in the timeline view.

The first research trend cluster is pedagogical practice, which includes a series of research hotspots like professional development, integration, motivation, content knowledge, design as knowledge, gender, higher education, and so on between 2014 to 2021.

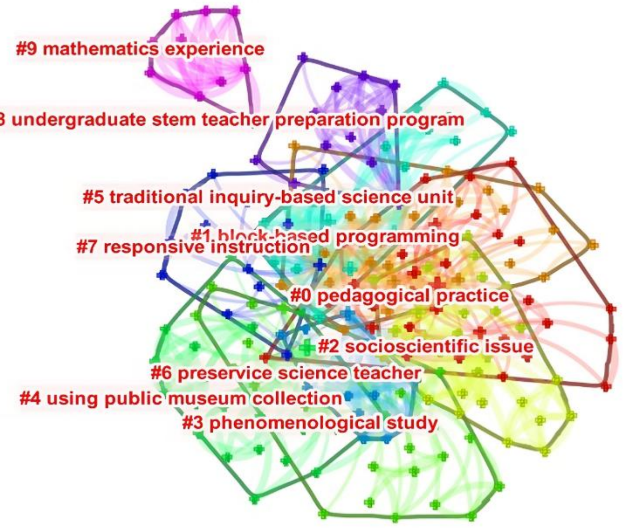

Figure 7. Cluster analysis of the keywords (Source: Authors' own elaboration)

The second research trend cluster is block-based programming, also from 2014 to 2021, and includes the hotspots like elementary education, robotics, inquiry, design, computational thinking, engineering standard, culturally responsive pedagogy, block-based coding teachers and teaching, and so on. The third is socio-scientific issue, which lasts a long time from 2012 to 2020, and focuses more on the industrial placement, attitude, argumentation, and carbon footprint, as well as various learning methods like placement learning, experiential learning, project-based learning, etc. The fourth is phenomenological study, this is an issue that has always been concerned from 2012 to 2021, the hotspots of this cluster are relatively concentrated, mainly concentrated, as follows: career, teacher training, choice, applicant attraction, as well as meta-analysis and women competence. The fifth is using public museum collection from 2012 to 2020, the hotspots included in this cluster are China adoption, citizen science, curriculum, Algodoo software, disciplinary language, classification and framing, etc. The sixth cluster named the traditional inquiry-based science unit, but have a short history from 2012 to 2016, which includes the hotspots of physics, nature of science, literacy, and standard, etc. Like the first and second research clusters, the seventh research cluster is pre-service science teacher from 2014 to 2021, the hotspots including graduate student development, pedagogical content knowledge, pre-service science teacher, and so on. The eighth research cluster naming responsive instruction has been developed in recent years from 2016 to 2021, which includes curriculum material, middle level education, self-efficacy, challenge, active learning, university, and so on. The ninth research cluster focus on undergraduate STEM teacher preparation program from 2017 to 2021, including community, achievement, mathematics achievement, performance and thinking. The last research cluster is mathematics experience from 2014 to 2017, including the research hotspots such as stereotype, preparing teacher, African and American.

The results of the co-word analysis show that there are ten research trend clusters. Each cluster contains a series of hot topics or hot words, indicating that STEM pre-service teacher education has received the attention of researchers and has begun to show certain research themes. However, though researchers have paid attention to some common topics to make useful contributions to STEM pre-service teacher education, the various clustering results and hotspots in each cluster indicate that the research related to STEM pre-service teacher education has not formed a highly unified consensus at the level of research basic and cutting-edge knowledge and need more comprehensive and in-depth research.

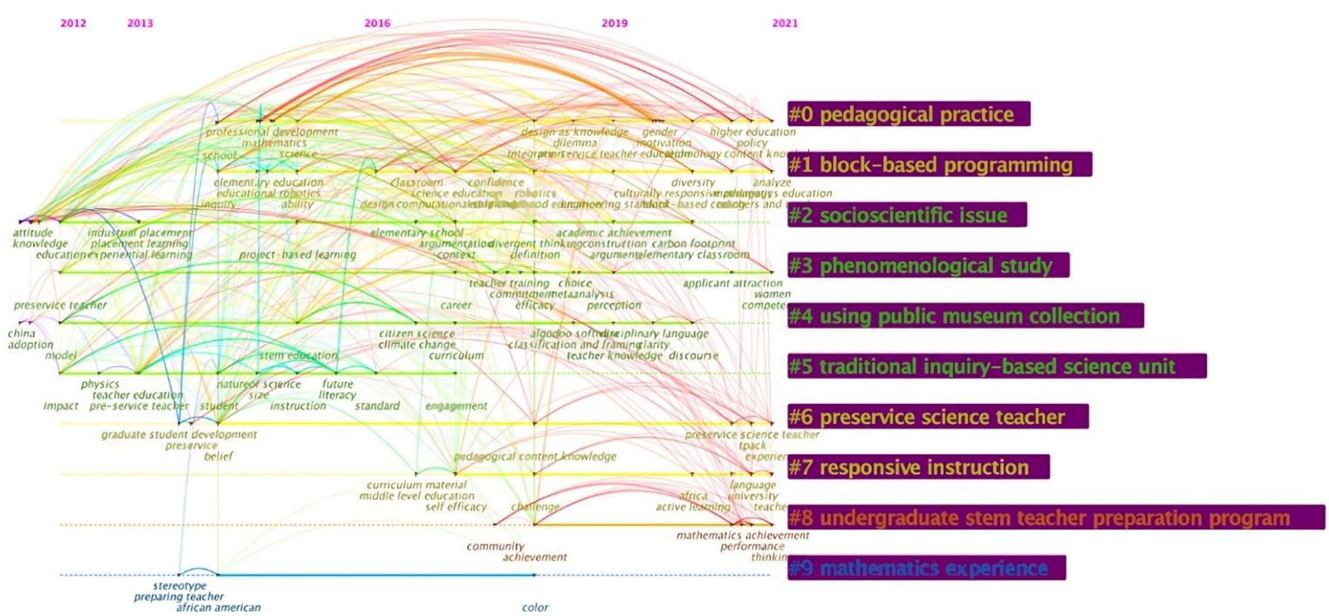

Figure 8. Cluster analysis of the keywords (timeline view) (Source: Authors' own elaboration)

DISCUSSION

This study analyzed and visualized the cited references of the target literature through CiteSpace software to obtain the knowledge base and research frontier of STEM pre-service teacher education. It can be summarized in three aspects: pre-service teacher education of a single subject related to STEM, the design of STEM pre-service teacher education programs, and the combination of STEM pre-service teacher education with modern technologies.

First, using single-discipline STEM preservice teachers as research subjects remains the dominant form of research in the field. Pre-service chemistry teachers, pre-service science teachers, and mathematics education are shown as three main clusters, occupying a core part of the visual graph. Students majoring in science (including physics, chemistry, and biology) and mathematics, which are the mainstream subjects, are often the subjects chosen by researchers. For example, Buber and Coban (2020) conducted a study on a group of third-grade preservice science teachers to explore the classroom design and development of science preservice teacher training. Similarly, López-Banet et al. (2021) started with actual scientific inquiry and mathematical modeling activities to explore what activities pre-service teachers of corresponding disciplines could adopt to promote students' participation in STEM fields. Students of a single discipline as research objects are conducive to the research design and development of researchers, but also, to a certain extent, convenient for researchers to follow up the observation of research objects and mutual comparison. The research shows that the core characteristics of STEM are its interdisciplinary and integrated nature, and the research starting from a single discipline will not reflect the training requirements of STEM pre-service teachers well. This indicates that the research on STEM pre-service teachers should focus on integrating the research on students from different disciplines, overcome the disciplinary barriers and reflect their core characteristics.

Second, scholars have tried to design the cultivation programs of STEM pre-service teachers to ensure their effectiveness, including cultivation objects, knowledge structure, and training methods et al. Some researchers conducted studies on students majoring in STEM at the undergraduate level and demonstrated that participation in STEM programs could effectively improve preservice teachers' confidence and teaching (Lewis et al., 2021). When considering the knowledge structures for STEM pre-service teacher education, subject knowledge, pedagogical theories, and subjects integration have been the focus of researchers and are important foundations for the effective implementation of pre-service teacher education programs (Aydin-Gunbatar et al., 2020; Kaplon-Schilis & Lyublinskaya, 2020). The training method of STEM pre-service teachers is an important part of ensuring the effectiveness of programs. Researchers have attempted to explore and optimize training programs to verify the effectiveness of existing programs and how they can be improved to meet the actual needs of program participants (Allen et al., 2019; Belardo et al., 2017; Lavi & Dori, 2019). The design of STEM pre-service teacher education programs has been the focus of researchers and an important part of enhancing the current curriculum, but because the number of universities that have offered STEM pre-service teacher training programs is small and relatively concentrated in educationally advanced countries, the development is uneven and not universal, there is still much room for future research.

In addition, the combination of STEM pre-service teacher training and modern technology has become the research focus of scholars, including ICT, computers, and robotics. The use of modern technology (especially Internet technology and robotics) to assist in STEM instruction can make the classroom and knowledge more vivid and intuitive, thus increasing students' engagement and learning. Some scholars have long tried integrating robotics-related knowledge into STEM preservice teacher training programs to help teachers learn how to use modern technology to design and implement STEM classes (Kim et al., 2015). Jocius et al. (2021) examined the role of ICT in STEM teaching and showed that STEM pre-service teachers could better design their classrooms and overcome barriers in teaching when using ICT technology. Modern technologies such as the Internet, robotics, and VR are often used as aids to STEM classroom design and delivery. Research has confirmed and supported the use of these technologies in STEM classrooms, making the awareness and mastery of these skills by STEM preservice teachers particularly important (Kim et al., 2015; Jocius et al., 2021). A large body of research has confirmed effective role of modern technologies as aids, and further exploration can be conducted regarding how and to what extent they are utilized (Gunbatar & Bakirci, 2019; Kalogiannakis & Papadakis, 2020).

The research further took "keywords" as the node to analyze the co-words and word frequency of existing articles (**Table 4**) and visually presented them to obtain the research hotspots in the STEM pre-service teacher training field and provide a certain theoretical basis and idea expansion for future research. Combined with data and map analysis, following conclusions are drawn:

First, STEM pre-service teacher training must be closely integrated with social science issues, and make reasonable use of public social resources, to reflect the practice orientation of STEM teacher education. STEM education aims to cultivate high-level scientific and technological talents for social and scientific progress (Bybee, 2013; Kennedy & Odell, 2014; Langdon et al., 2011), so STEM pre-service teacher training should be closely integrated with social-scientific issues.

In designing STEM pre-service teacher education programs, scholars have shown that starting from the critical issues that need to be solved can make the STEM pre-service teacher training program more goal-oriented and the purpose clearer (Altan et al., 2018; Lee et al., 2012). At the same time, scholars and other stakeholder groups are actively working to mobilize or link-local resources to help universities design more flexible and diverse STEM pre-service teacher education programs and develop more diverse training methods and channels (King et al., 2018). Thus, researchers can design STEM pre-service teacher education programs from the perspective of addressing the stuck problem of social science development and focus on interdisciplinarity and innovation in the design process. Meanwhile, they can broaden their horizons by strengthening the participation and linkage of various stakeholder groups to enhance practicality.

Second, researchers should focus on the interdisciplinarity and integration of STEM pre-service teacher education programs when designing them. The core features of STEM education are interdisciplinary and integration, aiming to cross disciplinary barriers and integrate knowledge to solve practical problems (Bybee, 2013), so as the training of STEM pre-service teachers. Most of the existing studies have been conducted from a single discipline or simple integration of common basic disciplines (e.g., science and mathematics, physics and mathematics, etc.) to design STEM pre-service teacher education programs (Aydin-Gunbatar et al., 2020; Cinar et al., 2016), but few of them have discussed interdisciplinarity and integration. Interdisciplinary education already has a certain foundation in pedagogical research and practice, which can provide some reference for STEM preservice teacher education (Hall & Weaver, 2001; Klaassen, 2018). Thus, researchers can attempt to fully reflect and ensure the interdisciplinary and integrative nature of STEM pre-service teacher preparation programs in a range of ways, including the target population (pre-service teachers from different disciplinary backgrounds), design goals (interdisciplinarity and knowledge integration as one of the goals), program delivery (the ability to meet the needs of a wide range of participants from different disciplines), and evaluation systems (the design of assessment of interdisciplinarity and integration).

Third, researchers should pay attention to the adaptability of STEM pre-service teacher education and educational technology changes and also pay attention to the evaluation system of STEM preservice teacher education to ensure quality. The rapid application of Internet technology, artificial intelligence technology, and a series of technologies such as robotics and cloud computing in education have brought new opportunities and challenges for STEM education (Kim et al., 2015; Wu & Albion, 2019). However, the reality is that STEM teachers have not been fully prepared for the rapid development of educational technology (Scaradozzi et al., 2019). Thus, the questions of how modern technology can be introduced into STEM pre-service teacher preparation programs, how it can assist in program design and delivery, and how it can be evaluated for effectiveness are all issues that need to be urgently studied. In addition, evaluation is another important topic and drew more attention in STEM preservice teacher education. Researchers have tried exploring the evaluation content, model, and techniques. In addition to evaluating individual-level indicators such as knowledge, skills, cognition, and beliefs of STEM pre-service teachers (Berisha & Vula, 2021; Jeong et al., 2020), they also evaluate the design, implementation, and effectiveness of the training programs (Koehler et al., 2013). Although some results have been achieved, a complete and unified evaluation system has yet to be formed, and it lacks certain credibility and universality. The construction and improvement of the evaluation system is a key link to guaranteeing the quality of STEM pre-service teacher education, and further exploration by researchers is urgently needed.

Limitation and Future Study

This study selected the Web of Science core collection d as the database. The sample articles were analyzed using the statistical function of the Web of Science and CiteSpace software to reduce the research bias. However, the keywords used in searching for articles could still be refined as using only "STEM pre-service teacher" and "STEM preservice teacher" may not cover all research objectives. The keywords "STEM" and "preservice teachers" can be expanded to collect as many samples as possible. For example, "STEM" can include similar terms such as "STEAM" and even discipline-specific terms. "Teacher candidates" or "prospective teachers" can also mean pre-service teachers. Articles on STEM-related disciplines, teacher education, or STEM talent development could also be screened to supplement the existing literature sample. As STEM pre-service teacher education has become the focus of STEM education and teacher education, more relevant studies will be produced in the future, so it is necessary to update sample data to reflect the development trend and provide a more reliable literature base and reference.

CONCLUSIONS

In summary, this study used CiteSpace software to visually analyze the literature related to STEM pre-service teacher education in the Web of Science database to obtain the research hotspots and research frontiers. The findings suggested that the research history of STEM pre-service teacher education is relatively short. The clusters obtained with the nodes of "co-cited reference" and "keywords" have not yet formed core research themes. The analysis of the clustering results shows that most of the existing studies on STEM pre-service teacher education have been conducted from one of the STEM-related disciplines as an entry point; researchers have tried to design and implement STEM preservice teacher education programs and evaluate their effectiveness; the interaction and integration of modern technology and STEM preservice teacher education is also a focus of researchers. Therefore, future research should focus on the practical orientation of STEM pre-service teacher training and reflect its interdisciplinarity and integration more in designing training programs, while constructing a more reasonable and perfect evaluation system to ensure the quality of STEM pre-service teacher education. This study systematically analyzed and composed the existing articles on STEM pre-service teacher education with the help of software and presents the research hotspots and cutting-edge analysis in this field through a more intuitive visual mapping, which can provide a more objective literature basis for further research.

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