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Abstract

This study aims to review the STEM education intervention on the undergraduate level by applying CiteSpace software, an innovative tool for bibliometric analysis and visualization. The Web of Science (WOS) database was used and covers the period from January 2008 to August 2023. Based on keyword search, seven clusters with the largest research volume in the past 15 years were identified and analysed with relevant literature. The results revealed that the trending topics of STEM education research included racial and gender differences in STEM education, reform of STEM education assessment and motivation methods for undergraduates, strategies to improve STEM academic performance, and the impact of STEM education on undergraduate employment. Furthermore, a cluster analysis of keywords and references was conducted to explore the connections between the clustered themes and the core theme of STEM. The timeline visualization diagram was used to examine the duration and evolution of each research theme in STEM education, which provided useful information for identifying the direction of STEM research. Finally, through the citation burst analysis, the top 15 most cited references were determined, and the STEM research hotspots were discussed in relation to their literature, which were consistent with the STEM research hotspots derived from the high-frequency themes and node literature. The findings of this study offer important insights into the development trend of STEM education and provide an evidence base and reference for future research and development of STEM education particularly at the undergraduate level.

Introduction

STEM is an acronym for the four disciplines of Science, Technology, Engineering and Mathematics. Science aims to understand the world and explain the objective laws of nature; technology and engineering seek to transform the world based on respecting the laws of nature and achieving harmony with nature. Mathematics serves as a fundamental tool for technical and engineering disciplines. The term of STEM education first appeared in 1986 in the National Science Foundation’s report science, mathematics, and engineering undergraduate level, which was mainly intended to pursue and enhance higher education in the United States as the next generation of Americans could become world leaders in science and technology (National Science Board (US), 1986). After more than three decades of development, STEM education has penetrated all disciplines in higher education and exerted a significant influence on all aspects of undergraduate students’ learning and daily life applications (Arnado et al., 2022; Dignam, 2024; McSween, 2024; Razi & Zhou, 2022). It has also become a strategic choice for countries around the world to implement the new changes in education in the 21st century (Chesky & Wolfmeyer, 2015). Recent research has shown that undergraduate students related to STEM lead to more employment opportunities and higher incomes for the labour force (Canaan & Mouganie, 2023; Hastings et al., 2013; Kirkebøen et al., 2016). Besides, STEM curriculum also offers new approaches and resolutions for the successful implementation of hands-on courses during the COVID-19 pandemic (Tho et al., 2024). It is believed that the implementation of STEM education in universities has led to adjustments in the content and teaching methods, which has applied alternative teaching method into the boring and unchanged lecture-based method from higher education for a long period of time, and has improved the learning outcomes of undergraduate students. Developed countries such as the United States, the United Kingdom, and Germany have started to promote STEM education from a national strategic level in response to the need to enhance the global core competitiveness of the next generation of talents.

However, there are still many unexplored aspects of STEM development in the various STEM education-based studies conducted to date (Ali & Tse, 2023; Ayop & Hafiz, 2020; Chu et al., 2023b; Jamali et al., 2023; Xu & Ouyang, 2022). Moreover, the research trends and issues of engineering design process for STEM education in K-12 is analysed and reviewed (Ali & Tse, 2023). Besides, the application of artificial intelligence (AI) in STEM education (AI-STEM), as an emerging field, is confronted with a challenge of integrating diverse AI techniques and complex educational elements to meet instructional and learning needs (Xu & Ouyang, 2022). Besides that, the feasible approaches to STEM education in improving the quality of education and promoting sustainable development (Jamali et al., 2023). These are issues that need to be studied in depth, both recently and in the future.

Zhan et al. (2022) identified 1,718 papers from the WOS database for the period of 2006-2021 using the keywords "STEM education" or "STEAM Education", and analysed the temporal distribution, geographical distribution, research fields and citation frequency of these papers using VOSViewer and CiteSpace, to provide a general overview of the development of STEM education in the world. However, no further judgement was made on the current research hotspots and the development direction of STEM research. Kahraman (2023) also reviewed the data from the WOS database with the keywords "STEM education" and "Meta-analysis" from 2015 to 2023, and 38 papers were collected. The listed publications were then analysed using the bibliometric analysis tool VOSviewer based on the attributes of the literature based on authors, institutions and countries, and finally, 18 of these scientific publications were evaluated through content analysis, and the study found that the research questions most relevant to "STEM education" and "Meta-analysis" focused on "computer-based learning", "digital game-based learning", "academic achievement", "active learning", and "learning by doing". As identifying trends in STEM education is relatively challenging, Social Network Analysis (SNA) can be introduced and applied to visualise the interconnections between relevant studies (Chu et al., 2023a). SNA can show the connections between existing research papers, where each paper is an entity or domain. The links established help researchers understand the dependencies between fields and describe the impact of each research topic area on the overall research network. CiteSpace is a software applied to visualise scientific literature analysis and show new trends and dynamics of scientific development. Especially in scientific citation analysis, it can detect the research hotspots and analyse the research progress in the field by measuring and drawing visual maps of the literature in a specific field. It is a proven effective bibliometric tool for summarising the current status of field development, identifying the classic basic literature in the field and exploring the evolutionary path of field research (Chen, 2006; Chen et al., 2010; Chen et al., 2012; Chen, 2017). This study utilises CiteSpace software to conduct a bibliometric analysis and review study on the implementation of STEM education among undergraduate students, a study that is not currently available in the literature. This study helps readers to systematically understand the development trend of STEM education among undergraduate students and summarises the research hotspots and frontiers of STEM education in higher education based on the existing literature, with a view to providing objective and effective information support for the research of STEM education in higher education as well as reform strategies.

Research Design

In recent years, as the advantages of STEM education have become more and more apparent, researchers have conducted a large number of studies and published a large number of studies in various international journals, and it is appropriate and valuable to conduct a systematic review of STEM education using CiteSpace software (Chu et al., 2023a). It is essential to study the STEM education that may have significant potential advantages in higher education that are waiting to be developed and explored. Therefore, it is necessary to conduct a systematic bibliometric analysis of research in the field of STEM education. To analyse its research profile and development, and to sort out the main development trends in the field, in order to provide a reference for further research and development on the integration of STEM education in higher education classrooms. Specifically, this paper attempt to answer the following five research questions:

RQ1. How is STEM education developing in undergraduate level?

RQ2. What are the main areas of research in STEM education related to undergraduate level?

RQ3. What contribution does STEM education make to undergraduate level?

RQ4. What are some of the top research hotspots in STEM education regarding undergraduate level?

RQ5. What are the papers with great influence (citation burst) on STEM education in undergraduate level?

Methodology

In this study, the core collection database of WOS was used as the source of literature. Firstly, we set the search condition as "Topic = (STEM education) AND Topic = undergraduate", and manually eliminated unnecessary documents, such as "stem cell" in the field of chemistry and biology, and refined publications to eliminate non-educational journals, as a total of 4,532 documents were extracted as the research sample. Subsequently, CiteSpace software was used to analyse the keyword co-occurrence and co-citation analysis of the sample literature data, in order to obtain the evolving relationship between the research hotspots and the knowledge base of STEM education, and to visualise the evolving trajectory of the research hotspots and cutting-edge topics using the time-zone view, in order to reveal the evolution of the research and the intrinsic connection of the literature in the key nodes. STEM education studies identified from the WOS database were imported into the CiteSpace software for analysis to detect citation bursts and track the evolution of the STEM education field through two complementary visualisation views, the cluster view and the time zone view. The burst terms were retrieved from titles, abstracts, descriptors, identifiers of bibliographic collections, and the frequency of the term bursts over time (Chen, 2006). The CiteSpace software uses the burst terms as labels for clustering and identifying other important highly cited articles not listed in the WOS database by cited references or bibliographic collections (Chen, 2006; Tho et al., 2017).

The objective of this study included searching for the important STEM education articles that were most cited for analysis. Figure 1 shows the setup for CiteSpace analysis. The processing conditions for this study were: the time interval was set to January 2008 to August 2023, the Year Per Slice was set to 1, and the Node Types were set to keyword and reference. With the CiteSpace software, users can select a single node type or multiple concurrent node types to generate multiple networks. After pruning the cut and merged networks, the selected node types included keywords and references of the articles. Based on the results of the study, 103642 valid references were detected from 4532 database records from 2008 to 2023. All anonymous authors were removed from the list because unidentified information does not contribute to the current analysis and these missing data may duplicate the same publication year with unidentified information set by the publisher. These data were further assigned to the identified clusters, and keywords for some of the major clusters are presented in the cluster visualisations and timeline visualisations. These keywords are extremely important for identifying emerging trends in recently active STEM education research as well as guidelines for future research. The strongest citation bursts in terms of intensity and duration were analysed to explore highly cited authors. A narrative summary was created to explore the largest cluster in STEM education based on the size, silhouette value, mean year and label based on frequency-inverse document frequency (TFIDF), log-likelihood ratio (LLR) and mutual information (MI) algorithm.

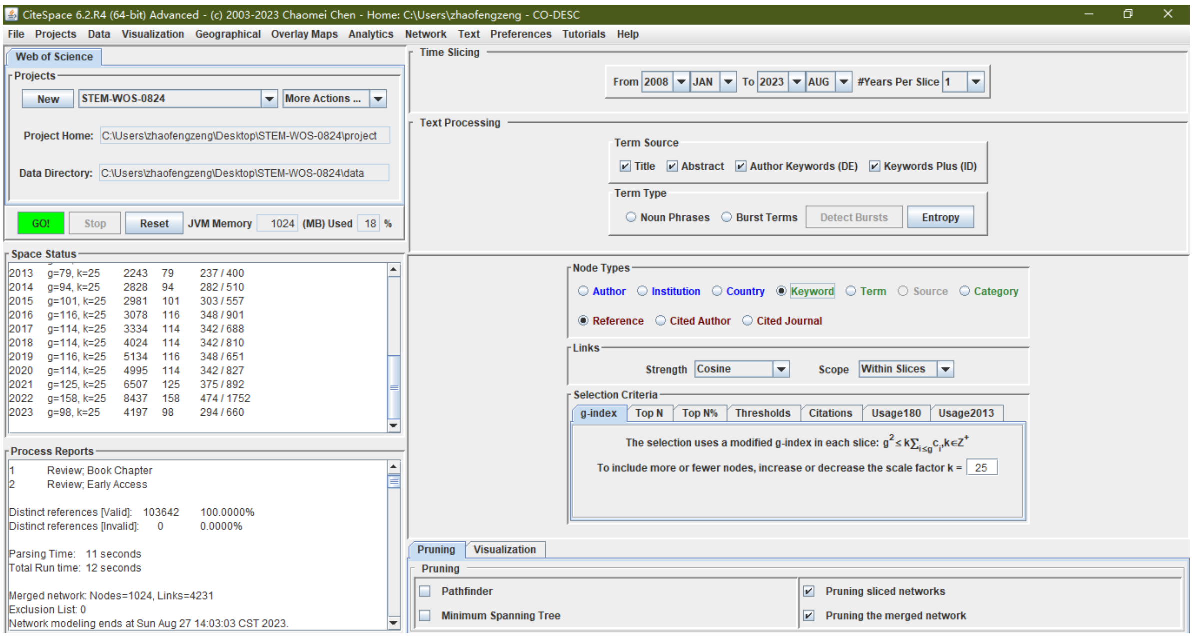

Figure 1. Set-up for *CiteSpace* analysis

Findings

WOS Database Search Process

The WOS database was accessed and searched for articles that met the criteria of this study, with the search results refined to articles published in English in the field of education educational research as Figure 2. The exported data were then filtered by research title and abstract based on the research questions and criteria used in the screening process. The selected articles were reviewed again by the other three researchers to ensure that the review criteria were met. The review process can therefore be described as accurate, reliable and transparent. Based on the needs of the study, the following search criteria were developed:

Date: 24 August, 2023
Results: 4532
TOPIC: (“STEM education” AND “undergraduate”)
Refined by: RESEARCH AREAS=(Education Scientific Disciplines or Education Educational Research)
Timespan=2008-2023*
Search language=English

Figure 2. WOS Database Search Result for the Topic STEM Education

*Note: Data for 2023 are as of August 2023 as the search was conducted on 24 August 2023. A total of 4532 articles were screened according to the pre-specified conditions.

CiteSpace Analysis using Keyword Clustering Analysis

Cluster analysis was first carried out using keywords and the results are shown in Figure 3. Figure 3 shows that there are eight major clusters out of 26 clusters of STEM education from 2008 to 2023. It is mainly depicts seven of the largest clusters, which have 627 nodes for key subject terms (all occurrences of the subject terms), 5245 inter-node links (indicating associations between subject terms), and an inter-node density of 0.0267.

Figure 3 also shows that the current research in this field is mainly focused on STEM and has formed distinct branches. The density of grey lines between each block represents the connection between each subject term and the central theme STEM. The whole keyword co-word network is densely connected, and the secondary nodes are prominent. This suggests that STEM education research has begun to take shape.

The main subject term clusters are centred around the 0# subject term STEM, which are #1 knowledge; #2 second-year undergraduate; #3 active learning; #4 curriculum development; #5 learning analytics; #6 quantum mechanics; #7 achievement motivation. These clusters largely coincide with the areas of development of STEM education that we are familiar with. This indicates that after 15 years of rapid development, STEM education has achieved a certain depth and breadth of research and has become a mainstream force that shapes the trend of education. A particularly noteworthy point is that from the #2 second-year undergraduate keyword cluster combined with the references, it can be seen that STEM education has made great progress and development in higher education, and has influenced and applied to all aspects of undergraduate students' learning and life (Fakayode et al., 2014; Groen et al., 2015; Peña-Calvo et al., 2016; Schneider et al., 2015).

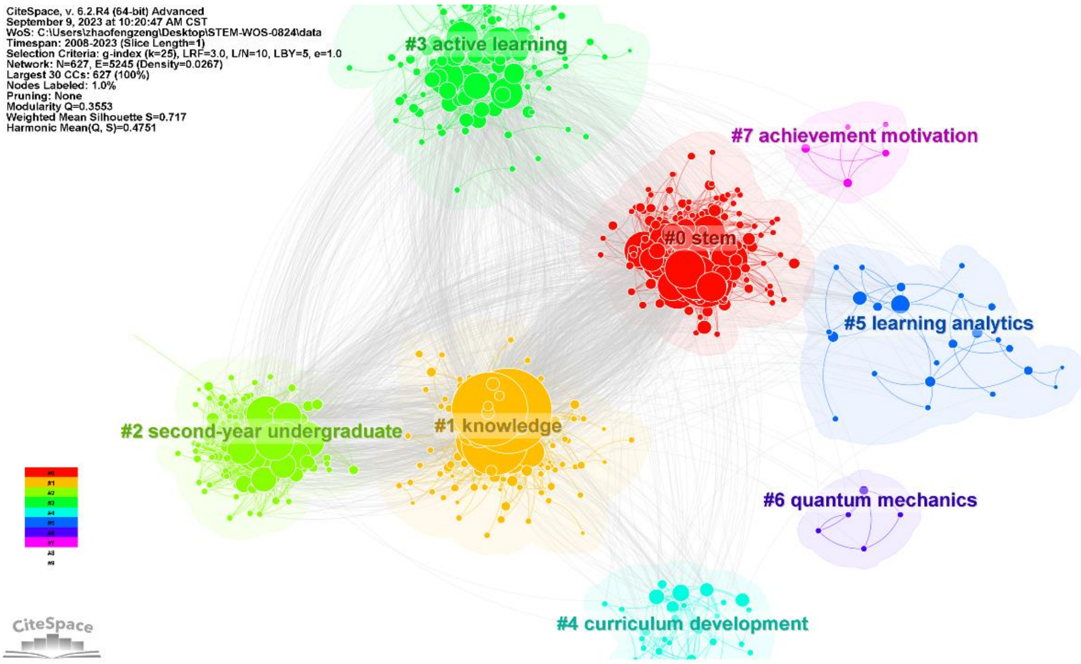

Figure 3. Terms Generated from 2008 to 2023 in Cluster Visualization

CiteSpace Analysis using Analysis of Research Hotspots

A research hotspot is a research question or topic explored by an intrinsically linked and relatively large set of literature within a given time of period. By using the number of citations and centrality of high-frequency topic terms, the research hotspots and hot topics in a research field can be analysed. In this study, the "Export-Network summary table" function is used to output the basic information on the frequency and centrality of STEM education research topic terms from 2008 to 2023, and then a table of high-frequency topic terms is derived. Secondly, we set the Cited Reference as the main network node, show networks by Time Slices for 1 year, and draw the network map of STEM research literature, as shown in Figure 4. In order to clarify the development of STEM education research hotspots, the key nodes of literature information are collated, and the top 20 high-frequency cited literature are selected and analyzed in Table 1.

Based on the glossary of high-frequency topics and combined with the analysis of key node literature and citation literature, it is summarised that the hotspots of STEM research are mainly in the following areas: (1) racial and gender differences in STEM education (Estrada et al., 2016; Estrada et al. 2018; Rainey et al., 2018; Stains et al., 2018; Theobald et al., 2020); (2) reforms in the way undergraduate students are assessed and incentivised in STEM education (Auchincloss et al., 2014; Eagan et al., 2013; Henderson et al., 2011; Linn et al., 2015; Thiry et al., 2019); (3) strategies to improve STEM academic performance (Freeman et al., 2014; Graham et al., 2013) and (4) the impact of STEM education on employment (Rodenbusch et al., 2016), among other aspects.

Table 1. Top 20 High-Frequency Cited References

No	Count	Centrality	Year	Cited reference
1	159	0.05	2014	Freeman S, 2014, P NATL ACAD SCI USA, V111, P8410, DOI 10.1073/pnas.1319030111
2	88	0.08	2018	Stains M, 2018, SCIENCE, V359, P1468, DOI 10.1126/science.aap8892
3	76	0.05	2020	Theobald EJ, 2020, P NATL ACAD SCI USA, V117, P6476, DOI 10.1073/pnas.1916903117
4	69	0.09	2022	R Core Team, 2022, R LANG ENV STAT COMP, V0, P0
6	56	0.02	2012	Presidents Council of Advisors on Science and Technology, 2012, ENGAGE EXCEL PRODUCI, V0, P0
7	50	0.02	2015	Linn MC, 2015, SCIENCE, V347, P0, DOI 10.1126/science.1261757
8	49	0.02	2014	Miles MB, 2014, QUALITATIVE DATA ANA, V3rd, P0
9	42	0.13	2018	Creswell JW, 2018, RES DESIGN QUALITATI, V0, P0, DOI 10.2307/1523157
10	41	0.01	2014	Auchincloss LC, 2014, CBE-LIFE SCI EDUC, V13, P29, DOI 10.1187/cbe.14-01-0004
11	40	0.01	2018	Rainey K, 2018, INT J STEM EDUC, V5, P0, DOI 10.1186/s40594-018-0115-6
12	40	0.06	2011	Henderson C, 2011, J RES SCI TEACH, V48, P952, DOI 10.1002/tea.20439
14	38	0.01	2013	Graham MJ, 2013, SCIENCE, V341, P1455, DOI 10.1126/science.1240487
15	36	0.02	2019	Seymour E, 2019, TALKING LEAVING REVI, V0, P0, DOI 10.1007/978-3-030-25304-2
16	35	0.02	2018	Estrada M, 2018, CBE-LIFE SCI EDUC, V17, P0, DOI 10.1187/cbe.17-04-0066
17	33	0.01	2016	Rodenbusch SE, 2016, CBE-LIFE SCI EDUC, V15, P0, DOI 10.1187/cbe.16-03-0117
18	32	0	2013	Eagan MK, 2013, AM EDUC RES J, V50, P683, DOI 10.3102/0002831213482038
19	31	0.05	2018	Ong M, 2018, J RES SCI TEACH, V55, P206, DOI 10.1002/tea.21417
20	29	0.01	2016	Estrada M, 2016, CBE-LIFE SCI EDUC, V15, P0, DOI 10.1187/cbe.16-01-0038

CiteSpace Analysis using Keyword and Cited Reference Cluster Visualization

The narrative overview was created by using keywords and reference search, as shown in Figure 4, the network was distributed into 46 co-citation clusters. The 12 largest clusters were automatically labelled with their size, identity number and silhouette value in brackets. The size of the cluster reflected the number of articles published within the cluster, and the mean year indicated the time span of the cluster's update. The silhouette value ranged from -1 to 1 and measured the homogeneity of the cluster, with a value of 1 indicating perfect isolation from other clusters, where no article was assigned to more than one cluster (Chen et al., 2010; Chu et al., 2023a; Rousseeuw, 1987).

Chen et al. (2010) also stated that 'cluster labelling or other aggregation tasks will become more straightforward for clusters with the silhouette value in the range of 0.7-0.9 or higher' (p. 1391). The largest twelve clusters identified were STEM (#0, 0.692), with 229 papers; first year undergraduate/general (#1, 0.8), with 160 articles; knowledge (#2, 0.737), with 139 articles; active learning (#3, 0.77), with 123 articles; undergraduate research (#4,0.883), with 79 articles; disclosure (#5, 0.857), with 57 articles; physics education (#6, 0.956), with 50 articles; sustainable design (#7, 0.922), with 32 articles; energy (#8, 0.928), with 32 articles; educational change (#9, 0.988), with 13 articles; standards (#10, 0.998), with 5 articles; limit theorems (#11, 0.996), with 11 articles; instruments (#12, 0.987), with 5 articles.

According to the centred circular view cluster visualisation shown in Figure 4, stem (cluster #0), first year undergraduate/general (cluster #1), knowledge (cluster #2), active learning (cluster #3), undergraduate research (cluster #4) and disclosure (cluster #5) were strongly connected, while (cluster #6), (cluster #7) and (cluster #8) had weaker connections with the main cluster. (Cluster #9), (cluster #10), (cluster #11) and (cluster #12) had little connections with the main cluster. For example, (cluster #12) had only two weak intersections with the main cluster, and upon further examination of its literature, it was found that: one of the two articles in this cluster point (Wilcox & Lewandowski, 2017) focused on a new method of data processing for physics education in undergraduate level; the other investigated beliefs about experimental skills and physics concepts in physics laboratory classes (Holmes et al., 2015).

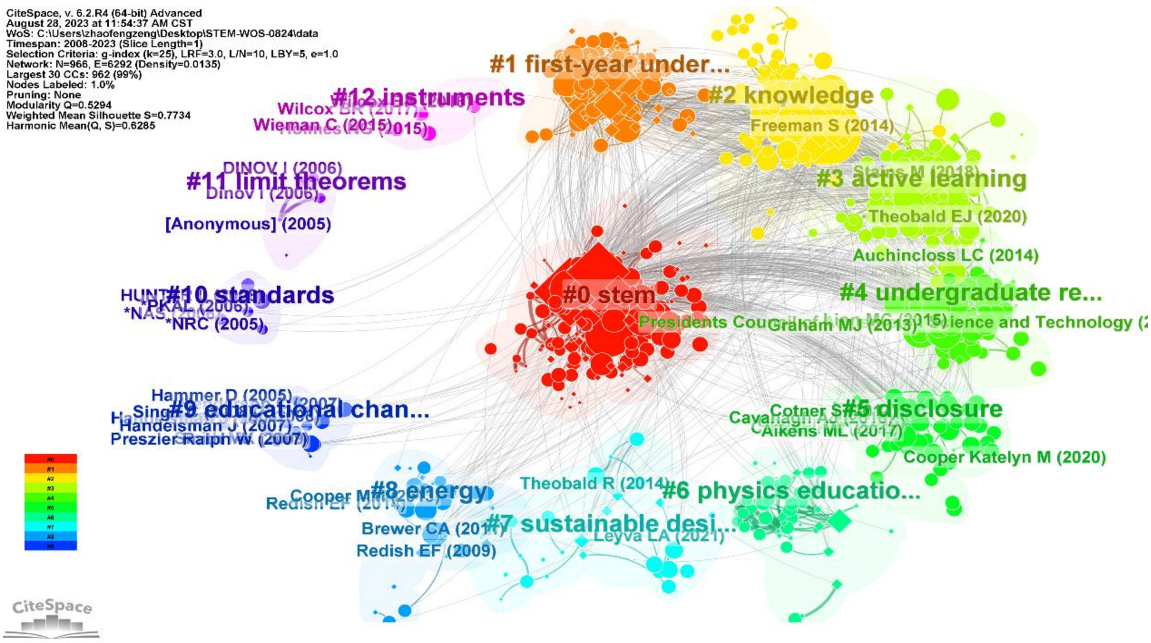

Figure 4. Keyword and Cited Reference Generated from 2008 to 2023 in Cluster Visualization

CiteSpace Analysis Using Analysis of Research Issues in Different Countries and Regions

The countries were analysed by clustering according to keywords, as shown in Figure 5 and Table 2. The whole is divided into four major regions. Region 0# is labelled as future direction, where the United States dominates with a high number of citations (4,049) and centrality degree (1.11), which surpasses other countries in all research areas. This indicates that American researchers have absolute leadership in the field of STEM research at the undergraduate level, which is consistent with the current trend of STEM education development and research.

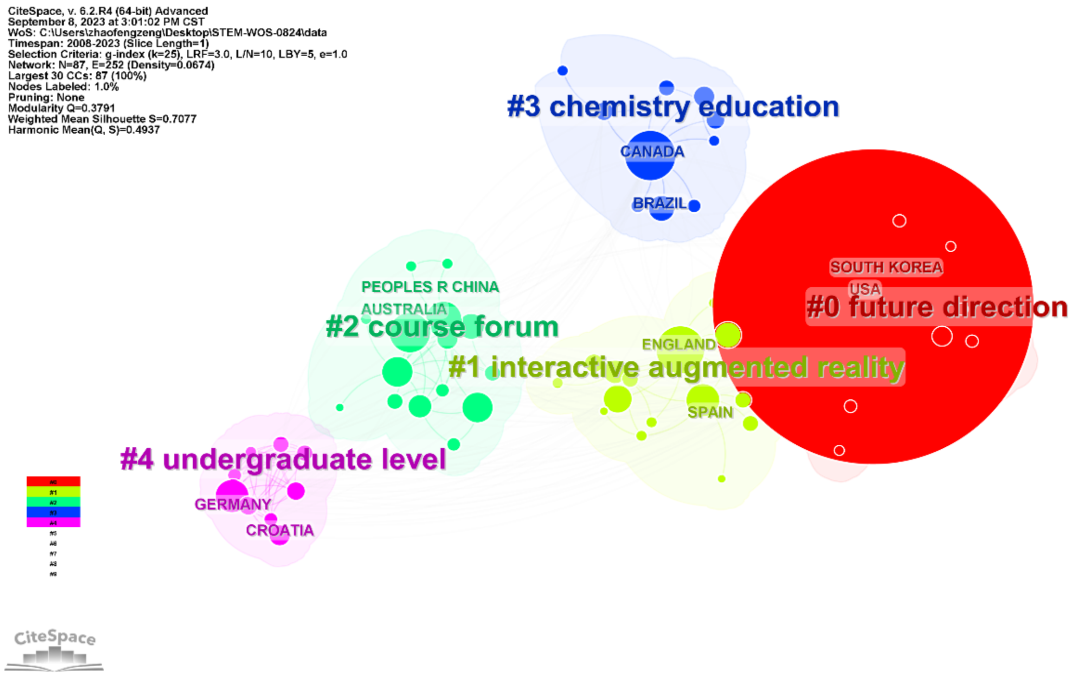

Figure 5. Cluster Analysis of Countries by Keywords

Since STEM was promoted in the United States in 1986, they have been at the forefront of STEM research, guiding its direction and development. Region 1# is labelled as interactive augmented reality, where England and Spain have more research; Region 2# is labelled as course forum, where China and Australia have more citations. Since around 2007, STEM education has entered the vision of Chinese education researchers. The Chinese government and education researchers have been promoting STEM education by launching several national policies, such as the White Paper on STEM Education in China of 2017, the “China STEM Education 2029 Innovative Action Plan”, and the Compulsory Education Physics Curriculum Standard (MOE, China, 2022, p. 67), which requires that a full range of physics courses will be taught at the compulsory education level.

After more than a decade of development, STEM education in China has made some achievements, and the research topic is mainly about the implementation of STEM curriculum and the integration of traditional curriculum. Region 3# is labelled as chemistry education, where Canada has more research and the second highest number of citations among countries, maintaining a certain leading position. Region 4# is labelled as undergraduate level, where Germany and Croatia are mainly focused.

Table 2. Citation of Country Cluster Analysis

No.	Count	Centrality	Year	Country	No.	Count	Centrality	Year	Country
1	4049	1.11	2008	USA	7	37	0.05	2012	SPAIN
2	97	0.09	2009	CANADA	8	34	0.08	2008	IRELAND
3	88	0.10	2009	ENGLAND	9	31	0.00	2012	NORWAY
4	57	0.00	2009	AUSTRALIA	10	26	0.00	2009	TURKEY
5	46	0.08	2010	CHINA	11	23	0.00	2012	BRAZIL
6	40	0.02	2011	GERMANY	12	22	0.00	2013	MEXICO

CiteSpace Analysis using Keyword Burst Analysis

Setting the parameter $\gamma = 1.0$, there are a total of 102 keywords burst in this study, and among the top 10 with the greatest burst intensity "hands-on learning ranks" first with an intensity of 13.02, which appeared from 2011 to the end of 2015, emphasising one of the important characteristics of STEM education, which transforms traditional classroom theoretical knowledge into concrete practice to solve real-world problems is an important feature of STEM education. It played an important role in promoting the transition from theoretical to practical teaching in higher education between 2011 and 2015 (Branson & Thomson, 2013; Chen et al., 2011; Christensen et al., 2015; Connor et al., 2014). "Physics" came second with an intensity of 11.49, which appeared in 2010 and closed in 2015. Physics (as an important subject in science) is play an important role in STEM education, many researchers focused on Physics by researching the engineering and technology into Physics teaching during 2010-2015. Arranging the keyword bursts in reverse chronological order according to the cut-off time can reveal the keywords that continue to the present day (in the year of 2023), as shown in the Table 3, which illustrate the current hot directions and hot issues in the field of STEM research. The keywords are largely consistent with the previous analysis. Some keywords began to appear and have continued to this day, such as support, undergraduate science, environment, decision making, and etc. Some of the keywords appeared at an earlier time but did not become a hotspot during that time, and have exploded in recent years, such as science identity, quality, online, stereotype threat, career choice, problem solving, and etc.

Table 3. Strongest Citation Bursts Keyword

Top 10 Keywords with the Strongest Citation Bursts					Keywords with the Strongest Citation Bursts extending to 2023（Top 10）				
Keywords	Year	Strength	Begin	End	Keywords	Year	Strength	Begin	End
hands-on learning/ manipulatives	2011	13.02	2011	2015	decision making	2021	6.32	2021	2023
physics	2010	11.49	2010	2015	science identity	2016	5.48	2021	2023
inquiry-based/discovery	2011	11.12	2011	2016	sense	2017	5.4	2021	2023

Top 10 Keywords with the Strongest Citation Bursts					Keywords with the Strongest Citation Bursts extending to 2023（Top 10）				
Keywords	Year	Strength	Begin	End	Keywords	Year	Strength	Begin	End
learning									
second-year undergraduate	2011	10.89	2012	2015	student success	2021	3.95	2021	2023
organic chemistry	2010	9.74	2011	2016	quality	2011	3.94	2021	2023
general chemistry	2012	8.66	2012	2018	support	2019	3.76	2019	2023
high school/ introductory chemistry	2011	7.88	2011	2016	undergraduate science	2020	3.75	2020	2023
evolution	2008	7.65	2008	2013	online	2017	3.71	2021	2023
laboratory instruction	2011	7.34	2011	2015	experiential learning	2021	3.55	2021	2023
physical chemistry	2011	6.86	2011	2017	instructional change	2021	3.55	2021	2023

CiteSpace Analysis using Timeline Visualisation Analysis

Moreover, Figure 6 shows a timeline visualisation that reveals a significant evolution in STEM education research throughout history by displaying clusters between 2003 and 2023. The timeline image indicates that 0#stem has been a consistent theme throughout the research timeline and has maintained a high number of nodes and dense connections. Two timelines have emerged for research on undergraduates: 1# the first year undergraduate and 4#undergraduate research. 2#Knowledge, 3 #Active learning and 5#Disclosure are also focused on undergraduates, and all five themes persist from 2008 to the present, which demonstrates that undergraduate STEM education research has been a hot spot in STEM education research. 6#Physics education has been prevalent since about 2004 and has shown intensive research.

Based on reference studies, it was found at this stage physics acted as an important medium for STEM education as the role of science in STEM education. The study of how the concepts of STEM education are integrated into physics education was consistent with the results seen in the keyword burst. Research in this area continued until 2015 when it ceased completely and has not reappeared in recent years. 7#Sustainable design has appeared since 2004, but has shown a sluggish research trend, with a slight increase in the number of studies in recent years. 8#Energy has had a small number of studies appearing from 2008-2018, with very few new research nodes appearing in recent years. 9#Education change, 10#standards and 11#limit theorems emerged from about 2004 until about 2009, and have appeared sporadically in the last decade, and the phase nodes that have appeared do not have a very dense relational pulse in the research literature. 12#Instruments flashed briefly around 2015-2018, and not much research has been done.

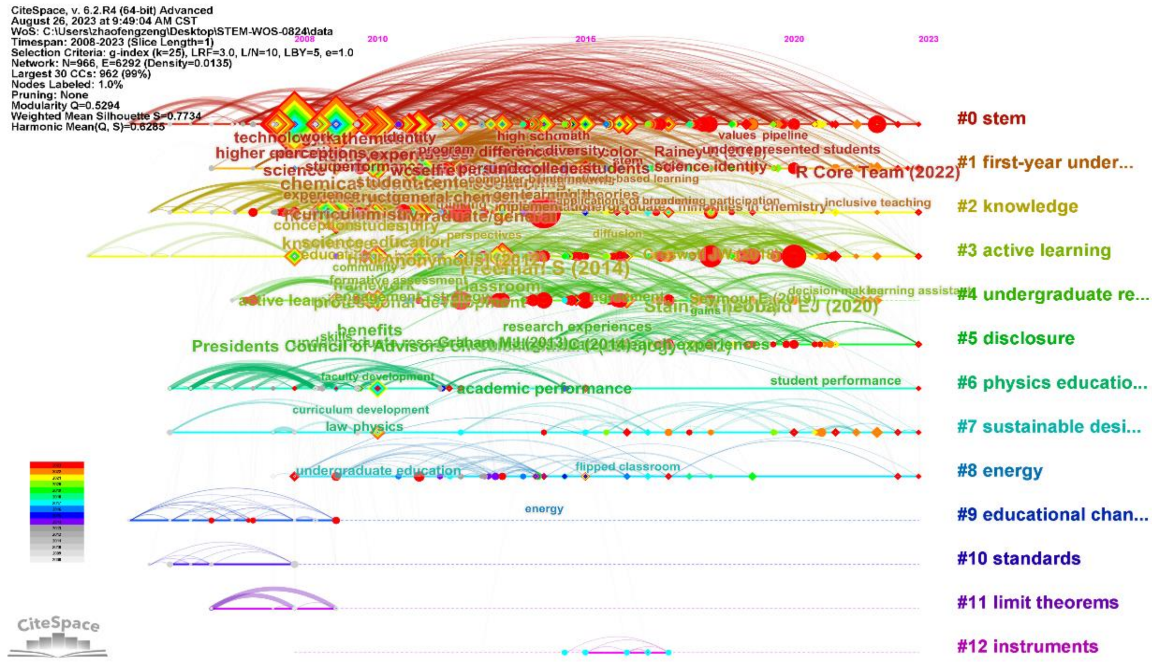

Figure 6. Terms Generated from 2008 to 2023 in Timeline Visualization

CiteSpace Analysis using Citation Burst Analysis

A citation burst is a sudden increase in the frequency of citations to an article over a period of time, indicating that it is a research hotspot or an emerging topic. Figure 7 shows the citation burst intensity values and citation burst duration for the top 15 papers with the strongest citation bursts. The analysis reveals highly cited authors in the field of STEM education. Based on the intensity values, the following are the highly cited articles in the field of STEM education (Auchincloss et al., 2014; Brewer et al., 2011; Cooper, 2015; Eagan et al., 2013; Estrada et al., 2016; Freeman et al., 2014; Graham et al., 2013; Henderson et al., 2012; Linn et al., 2015; Rainey et al., 2018; Sargent & Shea, 2012; Seymour et al., 2019; Stains et al., 2018; Theobald et al., 2020). The citation intensity values of the selected articles published in the last few years range from 9.43 to 52.36. Among them, Freeman et al. (2014) had the highest intensity value (52.36), with its study showing that active learning can greatly improve students' performance in STEM learning, and researchers have successively sought ways in which students can be motivated to take initiative in learning, which has gained the attention of the research community during this period and continues to do so until 2019. In addition, among these 15 articles in the high-burst literature, four articles have continued until 2023 (Rainey et al., 2018; Seymour et al., 2019; Stains et al., 2018; Theobald et al., 2020), and the retrieval of these four articles reveals that the research mainly focuses on STEM education's current problems and solutions (Seymour et al., 2019; Stains et al., 2018), gender and racial differences in STEM education (Rainey et al., 2018), teaching strategies in STEM education, and teaching effectiveness (Theobald et al., 2020), which are the direction and hot issues of current STEM research. Besides, it can be observed that the majority of the articles experienced citation bursts only after several years of publications, which was justified in the study by Li et al. (2020) stating STEM education research developed significantly after 2010.

Top 15 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	2008 - 2023
Freeman S, 2014, P NATL ACAD SCI USA, V111, P8410, DOI 10.1073/pnas.1319030111, DOI	2014	52.36	2016	2019	
Theobald EJ, 2020, P NATL ACAD SCI USA, V117, P6476, DOI 10.1073/pnas.1916903117, DOI	2020	25.4	2021	2023	
Presidents Council of Advisors on Science and Technology, 2012, ENGAGE EXCEL PRODUCI, V0, P0	2012	22.92	2014	2017	
Henderson C, 2011, J RES SCI TEACH, V48, P952, DOI 10.1002/tea.20439, DOI	2011	18.04	2013	2016	
Stains M, 2018, SCIENCE, V359, P1468, DOI 10.1126/science.aap8892, DOI	2018	15.64	2019	2023	
Auchincloss LC, 2014, CBE-LIFE SCI EDUC, V13, P29, DOI 10.1187/cbe.14-01-0004, DOI	2014	14.77	2016	2019	
Graham MJ, 2013, SCIENCE, V341, P1455, DOI 10.1126/science.1240487, DOI	2013	14.49	2015	2018	
Linn MC, 2015, SCIENCE, V347, P0, DOI 10.1126/science.1261757, DOI	2015	13.88	2016	2020	
Seymour E, 2019, TALKING LEAVING REVI, V0, P0, DOI 10.1007/978-3-030-25304-2, DOI	2019	13.58	2021	2023	
Estrada M, 2016, CBE-LIFE SCI EDUC, V15, P0, DOI 10.1187/cbe.16-01-0038, DOI	2016	12.83	2020	2021	
Eagan MK, 2013, AM EDUC RES J, V50, P683, DOI 10.3102/0002831213482038, DOI	2013	12.19	2015	2018	
Henderson C, 2012, PHYS REV SPEC TOP-PH, V8, P0, DOI 10.1103/PhysRevSTPER.8.020104, DOI	2012	11.8	2014	2017	
Rainey K, 2018, INT J STEM EDUC, V5, P0, DOI 10.1186/s40594-018-0115-6, DOI	2018	11.78	2020	2023	
Cooper MM, 2010, J CHEM EDUC, V87, P869, DOI 10.1021/ed900004y, DOI	2010	9.98	2012	2015	
Brewer CA, 2011, VIS CHANG UND BIOL E, V0, P0	2011	9.43	2013	2016	

Figure 7. Top 15 References with Strongest Citation Bursts

Conclusion and Recommendations

This study provides an overview of recent research on STEM education for undergraduate students using CiteSpace software to analyse literature from the Core Collection database in the WOS search platform. The practicality and feasibility of these procedures have been demonstrated by providing a well-defined review of research methodologies and findings, which are useful in analysing various areas of empirical studies. The following preliminary conclusions were drawn from this study:

(1) Through the analysis of keyword clustering, it is found that STEM education has achieved a certain depth and breadth of research in the context of undergraduate level, and has gradually become a mainstream force influencing the trend of education. Based on the references, it can be seen that STEM education has made great development and progress among undergraduate students and has been applied to all aspects of their learning and daily life applications.

(2) Based on the glossary of high-frequency topics and the analysis of key node literature and citation literature, it is summarised that the hotspots of STEM research are mainly in the following areas: racial and gender differences in STEM education, reforms of undergraduate STEM education assessment and motivation methods, strategies to improve STEM academic performance, and the impact of STEM education on undergraduate student employment.

(3) The connection between each clustered theme and the central theme (0#STEM) was investigated through centered circular view cluster visualisation and cluster silhouette value, demonstrating the research lineage and the relationship between the themes.

(4) The timeline visualisation chart analyses the historical duration and significant evolution of the various research themes in STEM education, which can be informative in determining the direction of STEM research studies.

(5) The top 15 references with the strongest citation bursts were studied through citation bursts, and STEM research hotspots were analysed in the context of the literature, and the conclusions were basically consistent with the STEM research hotspots obtained from the analysis of high-frequency subject

headings and nodal literature. These citation bursts' papers are useful for future discussion and reading materials after data analysis process for related research studies.

Although CiteSpace software was used in this overview, and the articles selected to reduce selection bias were limited to those in the WOS database from 2008 to 2023, it is still difficult to avoid its one-sidedness, and the next step could be to expand the sources of literature, such as a comparative analysis of the dual databases of WOS and SCOPUS, which would have the effect of cross-checking each other. In addition, this study only focuses on STEM education at the undergraduate level, and future analysis could explore the similarities and differences between STEM education research at the undergraduate level compare to the primary and secondary levels, where STEM education has been conducted at an unusually high volume of studies and has achieved many successes. Finally, more research studies are required to explore other aspects of practices in STEM education intervention, along with the aspects of understanding, attitude and gender, as well as dropout intention from STEM majors who received minimal attention in empirical STEM studies.

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