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Mapping the Future of Innovation: A Bibliometric Analysis of STEM Education Trends in K-12

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Abstract. With the increasing global emphasis on science, technology, engineering, and mathematics (STEM) education, it is crucial to systematically assess research trends and thematic developments in this field. This paper utilizes bibliometric analysis to examine the scholarly landscape of K-12 STEM education, analyzing 2,645 articles from the Web of Science Core Collection between 2019 and 2023. By analyzing citation metrics, author productivity, institutional and country contributions, and exploring word co-occurrence networks, the study identifies predominant themes and patterns in the field. The findings reveal that advanced countries dominate STEM education research, reflecting significant scholarly interest and investment. The analysis also highlights the role of technological advancements and educational reforms in shaping research trajectories. Additionally, a robust pattern of international collaboration is uncovered, where strategic partnerships across diverse institutions utilize multidisciplinary approaches to effectively address educational challenges. The study suggests the need to broaden research databases to include non-English sources and extend analysis over longer periods for a better understanding of evolving trends. Furthermore, the study recommends embracing interdisciplinary methods and integrating emerging technologies to enhance teaching practices.

Keywords: bibliometric analysis; STEM education; K-12 education; Citations; research articles

1. Introduction

STEM education, encompassing science, technology, engineering, and mathematics, is increasingly recognized as essential for equipping students with the skills necessary to meet the challenges of the 21st century (Felder & Brent, 2024). In K-12 education, STEM is crucial for preparing students to thrive in a

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rapidly evolving, technology-driven world (Falloon et al., 2020). It develops a range of capabilities, from discipline-specific knowledge to critical thinking and problem-solving skills, which are vital for personal and professional success in contemporary and future societal contexts (McDonald, 2016). Furthermore, STEM education plays a key role in addressing global challenges such as environmental sustainability, economic stability, and security, requiring a shift from traditional teaching methods to integrated, real-world problem-solving approaches (Kelley & Knowles, 2016). Promoting STEM education from an early age is crucial for nurturing the next generation of innovators and problem solvers. In today's technology-driven society, STEM skills are becoming increasingly essential. Introducing K-12 students to STEM concepts through interdisciplinary and inclusive education prepares them for future challenges and career opportunities in a rapidly evolving world (Noonan, 2017). Engaging in hands-on, inquiry-based learning in STEM helps develop students' critical thinking, problem-solving, and analytical skills (Crippen & Archambault, 2012). Additionally, STEM education promotes interdisciplinary learning, encouraging students to recognize the practical applications of academic concepts (Schweingruber et al., 2014).

Despite the importance of research in STEM education, there is still a lack of synthesis in this field, especially in the k-12 context. Therefore, the purpose of this study is to conduct a bibliometric analysis to synthesize the literature on STEM education research in the k-12 context. Our goal is to identify current research trends, areas of focus, and prominent research in order to gain insight into research clusters, flagship institutions, and publication venues over the past five years. The results of our study will be valuable for both novice and experienced researchers, as they will provide an understanding of the existing research in the field of STEM education in the k-12 context and highlight areas that have been underrepresented. This knowledge will inform future research plans and help researchers identify appropriate publication venues for their work. To achieve this, we will address the following research questions:

Q.1. What are the trending research issue of STEM education research in the context of K-12 during the period between 2019-2023?

Q.2. What the most productive territories, countries, authors, source of publications, and collaboration addressed in STEM education research in the k-12 context during the last five years period**?**

2. Literature Review

A solid foundation in STEM during K-12 education prepares students to pursue STEM fields at the higher education level and meet the evolving demands of STEM industries (Noonan, 2017). Early exposure to STEM also promotes diversity and inclusivity, encouraging students from underrepresented groups to explore STEM careers. Research shows that participation in STEM-related activities, such as science clubs or math competitions during K-12, increases the likelihood of pursuing a STEM degree (Maltese & Tai, 2011). The National Academy of Sciences highlights the importance of integrating STEM subjects in early education to reflect the interdisciplinary nature of real-world STEM professions and develop essential skills (Schweingruber et al., 2014).

Several conceptual studies aim to address thematic issues in the related literature to gain a comprehensive understanding of the most important research issues in STEM education, particularly K-12 (binti Zakeri et al., 2023; Kaur et al., 2022; Prieto-Rodriguez et al., 2020; Sungur Gül et al., 2023). The synthesis of research from these systematic review studies emphasizes the significance of STEM integration and targeted interventions in enhancing engagement and closing gender gaps in STEM education. These studies collectively demonstrate that cohesive STEM curricula (binti Zakeri et al., 2023), sustained engagement, and the presence of female role models are essential in fostering STEM identities and inclusivity (Prieto-Rodriguez et al., 2020). Emerging themes such as critical thinking and adapting to modern challenges like COVID-19 (Sungur Gül et al., 2023) underscore the need for evolving educational strategies that prepare students for future demands. The findings support a focused approach to STEM education that promotes inclusivity and long-term participation, necessary for addressing gender disparities and improving educational outcomes. Despite the extensive research syntheses and systematic reviews in STEM education, there is a noticeable lack of bibliometric studies analyzing various research metrics to identify the most trending themes in K-12 STEM education literature. To better understand the concept of bibliometric analysis and how it was conducted in the context of STEM education in K-12, the following subsection provides an outline.

Bibliometric analysis

Bibliometric analysis is a quantitative approach to studying literature in a specific scientific discipline. It uses mathematical and statistical methods to assess and measure the impact and structure of scholarly publications (Chain et al., 2019). This method is important for identifying current research trends and gaps, which helps guide future research in unexplored areas (Ellegaard & Wallin, 2015). By analyzing citations, it evaluates the influence of research, identifying important works and leading contributors who have shaped knowledge in the field (Waltman, 2016). Citations are crucial in the scientific community as they serve as a measure of the impact and relevance of research. They are used to track the evolution of science, evaluate the accomplishments of researchers, and understand how knowledge is integrated (Hansen, 2016; Mohsen et al., 2024). Despite their limitations, citations remain essential for assessing the quality of articles and journals (Baird & Oppenheim, 1994).

In addition, bibliometric analyses provide insights into collaboration networks, showing the interconnectedness of scholars, institutions, and nations. This reveals important clusters of academic cooperation and interdisciplinary efforts (Leydesdorff & Rafols, 2009). These insights are vital for informing policy decisions, guiding strategic academic planning, and optimizing resource allocation across academic, governmental, and industrial sectors. Moreover, bibliometric indicators such as the h-index and journal impact factors serve as benchmarks for academic evaluations, influencing decisions related to promotions, tenure, and funding allocations (Hirsch, 2005). Overall, bibliometric analysis provides a comprehensive view of research activities and their development, supports evidence-based decision-making, facilitates strategic planning, and highlights the collaborative and dynamic nature of knowledge production (Aria & Cuccurullo, 2017).In the field of STEM education, there have

been limited attempts to analyze the subject using bibliometric methods. These analyses aim to discover current research trends and identify various metrics related to research productivity, such as geographical distribution, author and institution productivity, publication and citation numbers, collaboration, and word co-occurrence. The series of bibliometric analyses conducted by (Jamali et al., 2023; Muhammad & Triansyah, 2023; Su & Yang, 2023; Zhan et al., 2022) collectively shed light on the extensive and evolving landscape of STEM education research, covering all educational stages from early childhood to higher education. These studies utilize large databases like Scopus and Web of Science, employing rigorous methodologies to outline trends, thematic focuses, and geographical distributions within the realm of STEM education.

Muhammad and Triansyah's (2023) study on high school STEM education research highlights a significant increase in scholarly interest, particularly between 2016 and 2021, with Indonesia emerging as a noteworthy contributor. This study emphasizes research themes such as outcomes, motivation, and critical thinking, underscoring an academic focus on the cognitive aspects of STEM learning in high schools. Similarly, Su and Yang's (2023) investigation into early childhood education within the STEM domain reveals a concentration of research in developed countries, with primary research clusters focused on robotics and mindstorms. This analysis expands the discussion to the intersection of STEM with psychology in early childhood, suggesting a need for interdisciplinary approaches in future research, emphasizing the importance of early education as a foundation for STEM literacy.

Complementing these findings, Jamali et al.'s (2023) assessment of integrated STEM education's impact on educational quality from 1993 to 2020 identifies a growing trajectory in STEM education research, with the United States leading the way. Their findings highlight significant research areas in early childhood education, computing education, and environmental education, indicating a broadening scope of STEM education research that goes beyond traditional disciplinary boundaries.

Building on these insights, Zhan et al.'s (2022) comprehensive analysis of documents from 2004 to 2021 provides a global overview of the distribution and thematic evolution of STEM education. This analysis confirms the trend towards interdisciplinary collaboration in STEM research and distinguishes the varied research focuses across different educational levels, offering insights into the nuanced approaches to STEM education across the educational spectrum.

While these attempts provide insights into the bibliometric studies of STEM education in general, there seems to be no single study that has thoroughly investigated the field using bibliometric analysis in the context of K-12 education. This gap in the literature highlights the need for comprehensive bibliometric analyses to better understand the evolution of research themes and guide future investigations in STEM education. It is important to address emerging trends and gaps systematically in order to advance the field. Given the significance of STEM education in the K-12 stage on one hand, and the lack of bibliometric studies in this context on the other, it is crucial to study how the issue of STEM is being addressed in the context of K-12 education in the

literature. Our interest lies in examining different bibliometric indicators to explore how this issue has been researched in the previous five years, including the most productive geographical territories, authors, and publication venues. Additionally, we are interested in analyzing word co-occurrence, the surge of publications, and citations to understand the impact of research on this issue.

3. Methods

Database and search

To conduct a bibliometric analysis focusing on STEM education in the K-12 context, we utilized the Web of Science Core Collection (WSCC) database and its indices: the Social Science Citation Index (SSCI) and the Science Citation Index Expanded (SCIE). These indices are known for their rigorous criteria when it comes to indexing journals (Mohsen, 2021; Mohsen & Ho, 2022). Following the approach of Mohsen and Ho (2022), our research was confined to four specific education research categories within the WSCC. These categories are: Education & Educational Research, Education, Scientific Disciplines, Education, and Special, and Psychology, Educational.We employed the following key terms to search for relevant studies addressing STEM in K-12 education: TS=("STEM" or "STEAM" OR "STEM Education" OR "Science Education" OR "Technology Education" OR "Engineering Education" OR "Mathematics Education") AND TS=("k-12 education" or "school" or "elementary education" or "secondary education" or "pupil") AND WC=("education & educational research" or "Psychology, Educational" or "Education, Scientific Disciplines" or "Education, Special") And PY=(2019-2023).

We have chosen this timespan due to the emergence of advanced technologies, such as immersive technology (augmented reality, X reality, virtual reality), and generative artificial intelligence. Only the type of article was considered crucial in academia because it provides insights into research methodologies and analysis (Mateu Arrom et al., 2018). Therefore, other documents such as review articles, conference proceedings, letters to the editor, and corrections were excluded from the study panel. The search was concluded on April 2, 2024, yielding 2645 articles, which were scrutinized by the authors for appropriateness and suitability for analysis.

Software

The entire document was downloaded from the WSCC using a tab-delimited file that is compatible with bibliometric software used for visualizing some of the current analysis. VOSviewer (Van Eck & Waltman, 2010) is widely used in the world of bibliometric studies to visualize findings and construct clusters based on co-citation analysis (Mohsen & Alangari, 2024; Mohsen et al., 2024), which indicate trending research issues and provide research metrics such as co-citation, collaboration, and research productivity. The dataset was also downloaded using Microsoft Excel 365 for manual analysis and compatibility with Bibexcel software, which is used for calculating metrics like the Hirsch-index. Productivity metrics were analyzed using number of articles published as indicated by the WSCC. Citation metrics were calculated using frequency of citations as indicated by the WCCO and co-citations were analyzed using

VOSviewer software. Finally, co-occurrence analysis was performed based on the authors' keywords recorded by the WSCC.

Data refinement

Prior to processing the data, hyphenated terms like 'science-education' and 'professional-development' were combined to ensure the reliability of the findings. Spelling mistakes in country names, such as 'Turkie' corrected to 'Turkey', were fixed. Singular and plural forms of words, like 'curriculum' and 'curricula', 'school' and 'schools', were standardized. Publisher notations, for example, 'Published by Elsevier Ltd', that were appended to some abstracts, were removed. In addition, addresses from England, Scotland, Northern Ireland, and Wales were consistently categorized under UK affiliation to maintain uniformity (Mohsen et al., 2017).

Data Analysis

The refined data, in CSV format, were imported into VOSViewer 8 for further analysis. VOSViewer is widely used software for analyzing research metrics in recent bibliometric studies (see Mohsen & Ho, 2022; Mohsen et al., 2021). It is well-known for its capabilities in identifying research clusters, calculating various metrics, and visualizing results.

4. Results

4.1 Publications frequency

There is an increasing number of STEM education publications from 2019 to 2023. In 2019, there were 409 published articles, and this number reached its peak in 2023 with 730 articles, indicating a growth rate of 56%. Table 1 and Figure 1 provide a summary of the publication numbers.

Table 1. Frequency of published articles during the period between 2019-2023

Publication Year	Count of Publication Year
2019	409
2020	468
2021	523
2022	515
2023	730
Total	2645

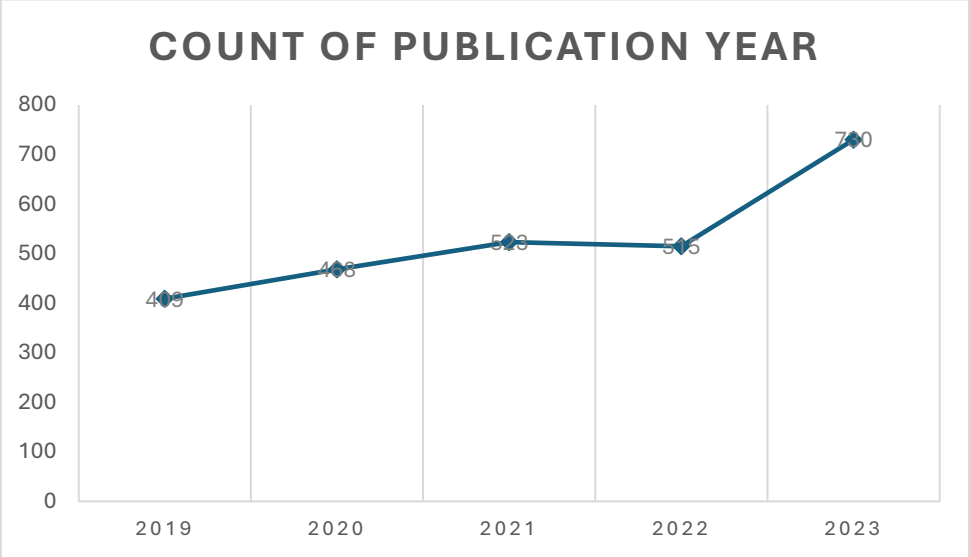

Figure 1. distribution of published articles over the years 2019-2023

Journals metrics

The results indicate that there were 2,645 research articles on STEM education published in 229 different sources over the past five years, covering four related educational categories (see Supplementary Material A). Leading the way is the *International Journal of Science Education*, with 146 articles, accounting for a 5.11% accumulation rate. Following closely behind are *Research in Science Education* with 119 articles and *the International Journal of Science and Mathematics Education* with 118 articles. Ranked fourth is the *International Journal of Technology and Design Education*, which published 108 articles. The top five is completed by the *Journal of Research in Science Teaching,* which has shown a strong commitment to publishing research on STEM education. For a summary of the top 10 journals that published STEM education research between 2019 and 2023, please refer to Table 2.

Table 2. Top 10 highly cited sources of publication

S	Journal	No.	%
1.	International Journal of Science Education	146	5.52
2.	Research in Science Education	119	4.83
3.	International Journal of Science and Mathematics Education	118	4.79
4.	International Journal of Technology and Design Education	108	4.38
5.	Journal of Research in Science Teaching	99	4.03
6.	Journal of Chemical Education	88	3.58
7.	Journal of Science Education and Technology	79	3.20
8.	Journal of Baltic Science Education	79	3.20
9.	Science Education	77	3.12
10.	International Journal of Stem Education	77	3.12

4.2 Citations

4.2.1 Article Citation

Citations are a commonly used metric for assessing the quality of published documents. Our results indicate that there has been a significant increase in citations for STEM research in K-12 education. Our findings reveal that the article by Sahin and Yilmaz (2020) has the highest number of citations, with 138 according to the WSCC metrics. Another highly cited work, identified by the Web of Science, is the article by Phillips et al. (2019), which has received 124 citations, placing it in the top 1% of the academic field of Social Sciences. The third most cited article (Fauth et al., 2019) has obtained 121 citations. Table 3 provides a summary of the top 10 cited articles in STEM research for K-12 education.

Table 3. Top 10 highly cited articles of STEM research

Article	Article Title	SP	TC
(Sahin & Yilmaz, 2020)	The effect of Augmented Reality Technology on middle school students' achievements and attitudes towards science education	Computers & Education	138
(Phillips et al., 2019)	Engagement in science through citizen science: Moving beyond data collection	Science Education	124
(Fauth et al., 2019)	The effects of teacher competence on student outcomes in elementary science education: The mediating role of teaching quality.	Teaching and Teacher Education	121
(Orgill et al., 2019)	Introduction to Systems Thinking for the Chemistry Education Community.	Journal Of Chemical Education	110
(Lai et al., 2019)	An augmented reality-based learning approach to enhancing students' science reading performances from the perspective of the cognitive load theory.	British Journal of Educational Technology	96
(van den Hurk et al., 2019)	Interventions in education to prevent STEM pipeline leakage.	International Journal of Science Education	79
(York et al., 2019)	Applications of Systems Thinking in STEM Education.	Journal of Chemical Education	77
(Robinson et al., 2019)	Motivation in Transition: Development and Roles of Expectancy, Task Values, and Costs in	Journal of Educational Psychology	77

	Early College Engineering.		
(Calabrese Barton & Tan, 2019)	Designing for Rightful Presence in STEM: The Role of Making Present Practices.	Journal Of the Learning Sciences	74
(Raabe et al., 2019)	The Social Pipeline: How Friend Influence and Peer Exposure Widen the STEM Gender Gap.	Sociology of Education	73

SP=source of publication, TC=total of citations

4.2.3 Journal Citations

Journal citations are a reliable way to assess the quality of sources that publish research articles. An analysis conducted using Excel 365 shows that the *International Journal of Science Education* has the highest number of citations for its published articles (N=1,053), followed by the *Journal of Research in Science Teaching* with 935 citations. The *Journal of Science Education and Technology* ranks third with 927 citations. Table 4 provides more detailed information on the top 10 highly cited journals.

Table 4. Top 10 highly cited journals of STEM research

Ser	SP	TC
1	International Journal of Science Education	1053
2	Journal of Research in Science Teaching	935
3	Journal of Science Education and Technology	927
4	Science Education	916
5	International Journal of Stem Education	865
6	International Journal of Science and Mathematics Education	833
7	Research in Science Education	831
8	International Journal of Technology and Design Education	749
9	Computers & Education	747
10	Journal of Chemical Education	731

Ser=series number, SP=source of publication, TC=total of citation

To map the relationship between the number of published articles and the citations received by each journal, we extracted the Hirsch Index (H-index) using Bibexcel software. This index helps gauge the productivity and citation impact of the journals that publish STEM research in elementary education. The findings, which illustrate the correlation between publication frequency and citation metrics, are detailed in Table 5.

Table 5. Top 10 journals with different metrics

h-index	Unit	TC	TP	JIF & Quartile
18	Journal of Science Education and Technology	927	79	4.4 (Q1)
17	Journal of Research in Science Teaching	935	99	4.6 (Q1)
17	Science Education	916	77	4.3 (Q1)
16	International Journal of Science Education	1053	146	2.3 (Q3)
16	International Journal of Stem Education	865	77	6.7 (Q1)
16	Computers & Education	747	31	12 (Q1)
15	International Journal of Science and Mathematics Education	833	118	2.2 (Q3)
14	Research In Science Education	831	119	2.3 (Q3)
14	International Journal of Technology and Design Education	749	108	3.1 (Q3)
14	Journal of Chemical Education	731	88	3 (Q3)

h-index= Hirch Index, TP=total of publications, TC=total of citations, JIF-Journal Impact Factor (as per Journal Citation Report, 2022)

Table 5 illustrates an interesting pattern: some journals, although publishing fewer articles, have managed to attain higher H-indices. For instance, Computers & Education, with only 31 articles published, achieved an H-index of 16, placing it as the fourth highest among the journals analyzed. Similarly, the Journal of Science Education and Technology published 79 articles and obtained the highest H-index of 18. In addition, Science Education published 77 articles and secured the second-highest H-index with a score of 17.

Countries and Institutions

VOSviewer outputs reveal that scholars from 90 countries have explored STEM research in K-12 education. Detailed information is available in Supplementary Material B. Table 6 highlights the top 10 countries in terms of citations and number of published documents. Furthermore, a figure illustrates the countries that have published at least 20 articles on STEM education in the K-12 context, visually depicting the geographic distribution of this research.

Table 6. Countries performance indicators in terms of total of publications and citations

Country	TP	TC
USA	1149	9014
China	219	1646
Australia	155	1228
Turkey	146	1057
England	144	1135
Germany	130	1311

Taiwan	99	1024
Spain	93	513
Sweden	88	698
Israel	81	635
Canada	74	541

TP=total of publication, TC=total of citations

The results indicate that the USA is the leading country in this research field, with 1,149 articles, accounting for 43.44% of the total global output. Furthermore, the USA has the highest number of citations, with 9,014 citations, representing approximately 48% of the total citations among the top 10 contributing countries. China comes in second place in terms of both the number of published documents and citation count. Australia ranks third in terms of the number of articles published, but fourth in citation count. Meanwhile, Germany holds the third position in terms of citation numbers.

4.3. Collaboration across authors, countries and institutions

The results indicate that 71 authors have published a minimum of five articles involving collaboration. Table 7 provides a summary of the top 10 authors who have been the most productive in terms of both the quantity and quality of their collaborative articles. Additionally, the analysis highlights authors who have established significant networks of international collaborations. Leading the way is S. Selcen Guzey with 12 collaborative articles, which have accumulated 86 citations. Close behind are Feng-Kuang Chiang and Gerhard Sonnert, each with 11 collaborative articles, receiving 63 and 111 citations respectively.

Table 7. Top influential authors of STEM research in k-12 education

S	Author	TP	TC
1	Guzey, S. Selcen	12	86
2	Chiang, Feng-Kuang	11	63
3	Sonnert, Gerhard	11	111
4	Ng, Oi-Lam	9	97
5	Sadler, Philip M.	9	109
6	So, Winnie Wing Mui	9	100
7	Bogner, Franz X.	8	89
8	Erduran, Sibel	8	80
9	Hwang, Gwo-Jen	8	112
10	Lin, Kuen-Yi	8	142

S=series number, TP=total of publications, TC=total of citations

Table 8 highlights the institutions with the field. Michigan State University is the leading institution, with 47 collaborative articles and 692 citations. Purdue University closely follows with 45 articles and 427 citations, while National Taiwan Normal University ranks third with 41 articles and 393 citations. For more detailed information on the collaboration metrics of the top 10 institutions, please refer to Table 8.

Table 8. The most productive institutions of STM research in K-12 education

Institution	TP	TC
Michigan State University	47	692
Purdue University	45	427
Nationall Taiwan Normal University	41	393
Beijing Normal University	32	288
University of Illinois	30	229
North Carolina State University	29	245
Arizona State University	28	177
Education University of Hong Kong	28	234
UCL	28	322
Vanderbilt University	28	239

TP=total of publications, TC=total of citations

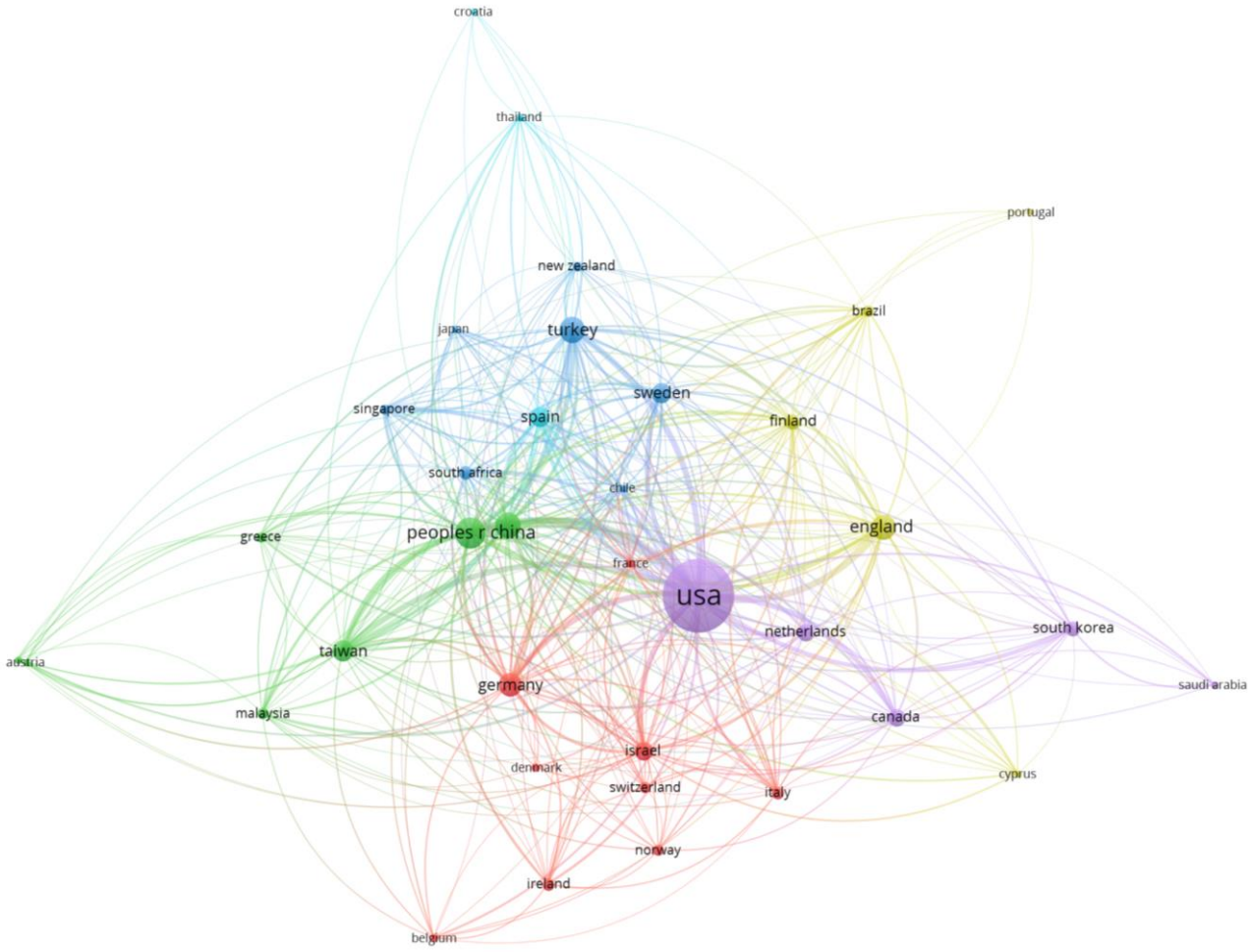

Figure 2. Visualization of country performance of STEM research with minimum 10 articles

The results show that 36 countries have participated in collaborations involving at least 10 articles on STEM in K-12 education. The USA tops the list, contributing to a significant number of documents (N=1,029). China follows with 204 documents, and Australia with 127, demonstrating their significant roles in global research collaboration. It is also worth noting that 95 articles were published as single-authored, suggesting a combination of collaborative and independent research efforts in this field. Figure 2 presents a visualization of the collaboration network among these countries, offering a graphical representation of the international collaborative landscape in STEM education research in K-12 education.

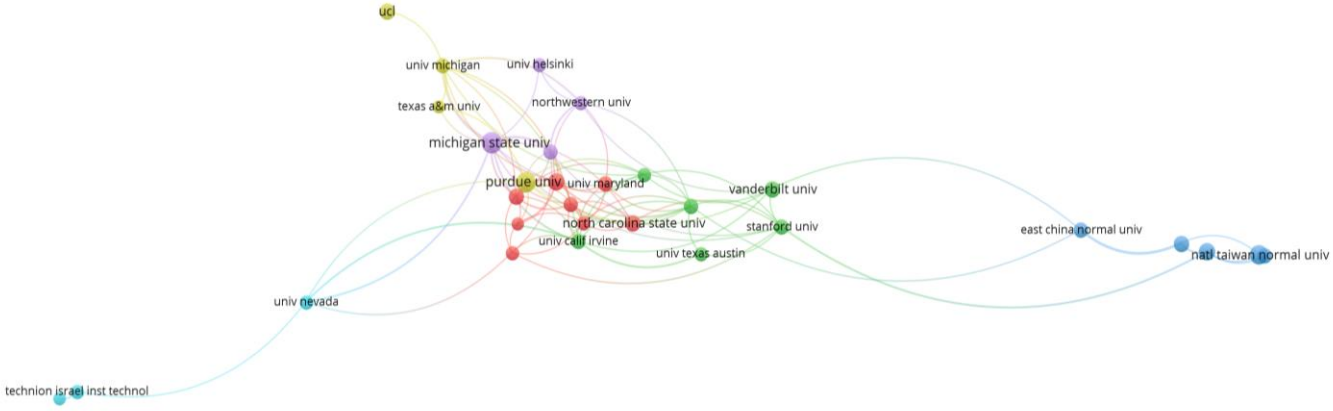

Figure 2 Visualization of institutions' performance of STEM research with minimum 10 articles

4.5. Word co-occurrence

We used word co-occurrence analysis to identify the most popular research topics in K-12 STEM education. By setting a threshold of at least 50 occurrences, we found 47 frequently used words. According to the results from VOSviewer, the word "science" was used the most, appearing 521 times, followed by "education" mentioned 418 times. The word "student" was the third most frequently used, appearing 397 times. Table 9 and Figure 3 provide details on the top 10 most commonly used words, while Figure 4 shows a visualization of the 47 keywords used by authors in VOSviewer. This analysis offers a clear understanding of the main themes and terminology in current STEM education research in K-12 settings.

Table 9. Word-co-occurrence of STEM research in k-12 education

Keyword	Frequency
SCIENCE	521
EDUCATION	418
STUDENTS	397
ACHIEVEMENT	296
KNOWLEDGE	284
MATHEMATICS	236
SCHOOL	227
TECHNOLOGY	176
TEACHERS	175
GENDER	157

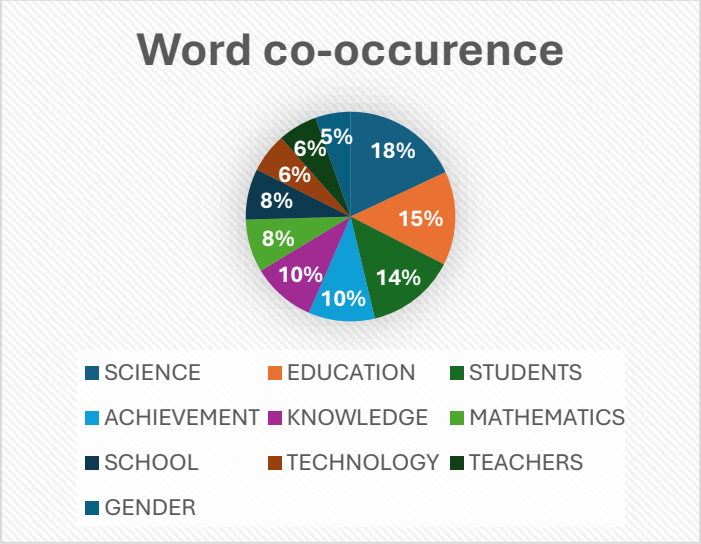

Figure 3. Word-co-occurrence of STEM research in k-12 education

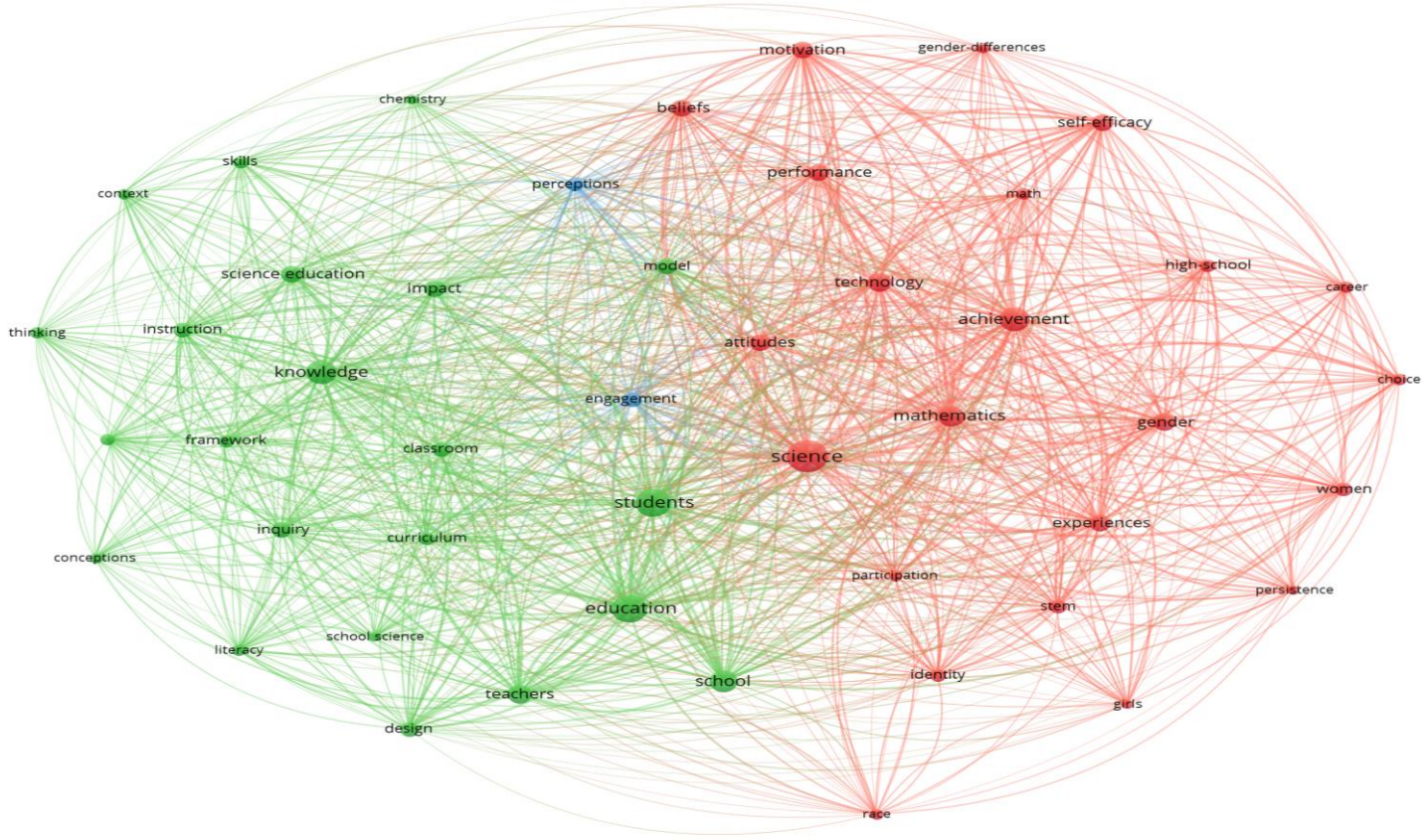

Figure 4. Visualization of Word-co-occurrence of STEM research in k-12 education

5. Discussion

The findings from our analysis of STEM education publications from 2019 to 2023 reveal significant trends and contributions that have shaped the landscape of educational research in this domain. During the studied period, the volume of publications has markedly increased, rising from 409 in 2019 to 730 in 2023, representing a growth of 56%. This upsurge highlights a growing interest in STEM education, likely driven by global economic demands for STEM skills, technological advancements, and pedagogical shifts towards more integrative approaches to science and mathematics education. The upward trajectory of STEM research is consistent with previous studies (Jamali et al., 2023; Muhammad & Triansyah, 2023; Zheng et al., 2022). These studies have shown that STEM research has been increasing over the years and has been addressing various pedagogical issues.

The *International Journal of Science Education* is widely recognized as a prominent outlet for STEM research, underscoring its significant role in the academic community. Other journalss such as *Research in Science Education* and the *International Journal of Science and Mathematics Education* are also esteemed for their extensive publication and citation records, which highlight their commitment to rigorous research methodologies and the exploration of effective teaching strategies in science and mathematics. Additionally, *Computers & Education*, a

leading journal in educational technology and ranked number one in the Education & Educational Research category, as well as the *International Journal of STEM Education*, a specialized journal in STEM education, are recognized as highly influential publication outlets. This demonstrates the importance of publishing pivotal research in specialized journals dedicated to science and mathematics education, as well as top-tier journals in educational technology. The analysis of word co-occurrence reveals that "science" and "mathematics" are among the most frequently used keywords, emphasizing the strong emphasis on these disciplines. Therefore, journals specializing in the teaching and learning of science and mathematics play a crucial role in disseminating research aimed at enhancing educational practices in these fields. This strategic alignment between the scopes of the journals and the content of the research ensures that findings are presented to audiences who can directly utilize this knowledge to advance educational outcomes in science and mathematics education.

The top highly cited articles highlight key research areas in K-12 STEM education, specifically focusing on gender disparities, the impact of peer influence on STEM interest, and the critical need for inclusivity among marginalized groups. The most frequently cited papers explore pedagogical advancements like problem-based learning and the use of augmented reality to enhance student engagement and comprehension. Moreover, these papers emphasize the importance of addressing motivational aspects and overcoming systemic obstacles to create fair STEM educational environments. Collectively, these themes advocate for a comprehensive strategy to improve STEM education by integrating social context, educational technologies, and equity-centered strategies, thereby fostering an inclusive and stimulating learning environment for all students.

Citation data sheds light on the impact of specific research themes, particularly those that utilize augmented reality and investigate the effects of teacher competence on student outcomes. The prominence of these topics indicates a strong interest within the community in how innovative technologies and effective teaching enhance student engagement and learning outcomes in STEM fields. The high citation rates of articles in these areas highlight their relevance and potential to influence educational practices and policies. It should be noted that research demonstrates that the longer an article has been published, the more likely it is to receive citations (Araújo et al., 2012). Since our dataset covers a five-year period (2019-2023), articles need at least a two-year period (Araújo et al., 2012) to be recognized as highly cited articles in the field of study. Upon reviewing the highly cited articles, it is evident that 9 out of 10 articles were published in 2019, with only one article from 2020 topping the list. This exceptional article, which received a high surge of citations, can be attributed to its publication venue, Computers & Education, a leading journal in the field of Education & Educational Research ranked number 1 in its category. Research shows that authors tend to cite more works published in reputable journals with a high impact factor compared to those from less impactful journals (Zhang & Poucke, 2017). Another factor that influences citations is the tendency for leading authors in a field of study to be cited more frequently than unknown authors, resulting in bias in citation metrics (Mohsen, 2021).

The geographical analysis of STEM education publications reveals that the United States is a leader both in terms of volume and impact, contributing to nearly half of the global citations in this field. This finding aligns with the research conducted by Jamali et al. (2023), which confirms the USA's prominence in STEM education research. It is evident that this dominance is a result of significant investments made by U.S. institutions in STEM education, which play a crucial role in global educational research. On the other hand, contributions from countries like China, Germany, and others highlight the global relevance of STEM education research, emphasizing its importance across different educational systems. The variation in publication output across countries can be attributed to various factors such as the number of institutions, concentration of scholars, and the level of available research funding. As noted by Rahman and Fukui (2003), countries with greater resources tend to produce more research outputs. Consequently, countries like the USA, China, and England, with higher capita and more extensive educational infrastructure, dominate in STEM research publications. In contrast, countries with smaller capita face challenges like fewer institutions and a limited number of researchers, which may hinder their ability to make significant contributions to the global STEM education research landscape.

Collaborative networks among authors and institutions in STEM education research demonstrate a strong pattern of cooperation, indicating that the multifaceted challenges of STEM education require multidisciplinary approaches and collective scholarly efforts. The high rates of collaboration, especially among top-publishing authors and leading institutions, likely represent strategic partnerships. These collaborations leverage diverse expertise, combining knowledge from various fields to enhance the depth and breadth of research. Such a collaborative trend not only improves the quality and impact of research outputs but also facilitates the integration of different perspectives and methodologies, ultimately driving innovation and progress in STEM education. This pattern underscores the importance of collaborative frameworks that bridge disciplinary and institutional boundaries to effectively address complex educational challenges.

The analysis of keyword frequencies in STEM education research, with terms like "science," "education," and "students" being the most common, highlights the ongoing focus and concerns in the field. The prominent use of keywords like "achievement," "knowledge," and "technology" further emphasizes the persistent emphasis on enhancing educational outcomes and integrating innovative technologies into teaching practices. This thematic concentration not only reflects areas of sustained interest but also indicates potential gaps in the existing literature. These gaps present opportunities for future research to delve deeper into areas such as effective measurement of educational outcomes, the impact of technology on learning, and methods to improve student engagement and understanding in STEM subjects. Addressing these areas can provide valuable insights and practical guidance for educators and policymakers seeking to optimize STEM education strategies and tools.

6. Conclusion

The present study provides a comprehensive view of STEM research conducted in K-12 education through bibliometric analysis. By examining metrics related to citations and the productivity of authors, institutions, and countries, this research offers insights into how this field has been explored. Additionally, the study analyzes word co-occurrence to identify the most trending research themes. Our findings highlight the principal countries, authors, and institutions, and identify highly cited articles that reflect the most current research issues in K-12 STEM education.

Our geographical analysis suggests that advanced countries are at the forefront of examining research related to STEM education in schools. These countries demonstrate unparalleled efforts to invest in STEM education. Furthermore, there is a strong pattern of international collaboration, where strategic partnerships across authors and institutions utilize multidisciplinary approaches to effectively address complex educational challenges. Our results show that collaborating with highly international institutions leads to influential research outputs, with a high frequency of publications and an increase in highly cited documents. However, the dominance of advanced countries in STEM education research raises concerns about the accessibility of cutting-edge technologies and methodologies for researchers in less developed countries with limited resources. This imbalance emphasizes the importance of conducting research that addresses the technological challenges faced by resource-constrained nations. The existence of this gap suggests that many crucial issues specific to these contexts have not been explored, which could hinder global progress in STEM education and perpetuate inequalities in access to high-quality STEM learning opportunities.

The identification of key publication venues in the field can guide authors and researchers in deciding where to publish their research, increasing their visibility within the research community. Our keyword analysis shows a focus on integrating cutting-edge technologies to enhance teaching practices. This analysis provides researchers with a way to explore innovative teaching methodologies by staying updated on advances in artificial intelligence for teaching STEM in K-12 schools. The highly cited articles analyzed in our study highlight the latest issues in STEM education and the new research methodologies examined in these articles, further enhancing their visibility and impact among STEM researchers.

7. Limitations and Suggestions for Future Research

This study provides valuable insights into STEM education through bibliometric analysis, but it has several limitations that suggest avenues for future research. The data scope is limited to specific bibliometric databases, namely WSCC, potentially missing significant contributions from journals or conferences not indexed in these sources, such as Scopus and ERIC. To address this, future research could expand the array of databases used to provide a more comprehensive global perspective. Another issue is that the analysis is confined to publications in English, which excludes studies in other languages and limits the global comprehensiveness of the findings. Future studies should incorporate

publications from a diverse linguistic background to enhance the inclusivity and representativeness of the research.

The timeframe of the study may not fully capture the rapid developments in the evolving field of STEM education. Conducting a longitudinal analysis over a longer period could offer deeper insights into the trends and shifts in STEM education research, reflecting its dynamic nature. Additionally, the reliancerelying on bibliometric indicators such as citations and productivity does not always accurately reflect the quality or impact of the research. Future studies might focus on qualitative reviews of the content of highly cited and emerging papers to better understand conceptual advancements better. Moreover, examining the actual impact of scholarly work on educational practices and outcomes through case studies or meta-analyses could provide more practical insights. The study's focus on quantitative bibliometric indicators can overlook the interdisciplinary nature and practical application of STEM education research. Encouraging interdisciplinary approaches that integrate methods and theories from other fields can effectively address complex educational issues. As technology evolves, it is also crucial to explore the implications of new technologies like augmented reality and machine learning on STEM education, focusing on the opportunities and challenges they present.

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Appendices

Supplementary Materials A

Sources of pub 229.xlsx

Supplementary Materials B

Countries contribution and Cit.xlsx