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Mapping the landscape: A bibliometric analysis of integrating STEM into science and mathematics classes

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Abstract

The integration of science, technology, engineering, and mathematics (STEM) into science and mathematics courses has gained prominence in global education due to its potential to foster interdisciplinary skills and innovation. The researchers in this study conducted a bibliometric analysis of 178 documents from the Scopus database (2004-2023) to examine research trends, key contributors, and international collaborations in STEM integration within science and mathematics education. The analysis identified a 10-fold increase in publications after 2014 (from 3 articles in 2014 to 30 in 2023), with the United States and the United Kingdom emerging as leading contributors. Findings revealed notable collaborative networks, impactful authors, and influential journals such as *Journal of Research in Science Teaching* and *International Journal of Science Education*. Additionally, keyword co-occurrence analysis uncovered thematic focuses on interdisciplinary learning, problem-solving, and critical thinking. This research emphasized the need for addressing gaps in culturally specific implementations of STEM education, such as in underrepresented regions like Africa and South America. The researchers recommended further examination of long-term student outcomes and the role of emerging technologies. This study provides insights to guide educators, policymakers, and researchers in optimizing STEM integration strategies, enhancing classroom practices across diverse educational contexts.

Keywords: STEM education, bibliometric analysis, science and mathematics integration, Scopus, interdisciplinary learning

INTRODUCTION

The purely educational modernization approach explains the inclusion of technology and engineering before science and mathematics in K-12 learning institutions science, technology, engineering, and mathematics (STEM) fields (Dijk, 2023). STEM is very instrumental in encouraging learners and at the same time bridging the social scientifically literate population gap (Badru & Owodunni, 2021; Hu et al., 2018). The use of hands-on activities to capture students' attention increases their perception of STEM subjects (Hu et al., 2018). According to Al Zahrani (2021), higher learner engagement resulted in enhanced academic achievement and improved data performance. STEM educators can promote students' STEM career interests because of the many rewarding career opportunities available by teaching science concepts and discoveries in stimulating ways. For instance, applying STEM principles to mathematics and science subjects offers students the opportunity to understand intricate concepts through everyday phenomena (Kushairi & Ahmi, 2021; Ninkov et al., 2022). Such integration goes beyond nurturing interest and appreciation for STEM subjects as learners are able to apply scientific principles to devise solutions for practical challenges (Donohue et al., 2021).

Moreover, the integration of STEM within these disciplines helps expand the understanding by the public of scientific research which paves the way for well-informed decisions (Leydesdorff & Hellsten, 2005).

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Contribution to the literature

- This study contributes to the existing literature by providing empirical evidence on the effectiveness of augmented reality (AR) technology in enhancing creative thinking skills among gifted students, an area that remains underexplored in science education research.
- By employing a rigorous quasi-experimental design and validating creative thinking assessments, the study offers a robust framework for future investigations into AR-based instructional strategies.
- The findings of this study extend the body of knowledge on technology-enhanced learning by demonstrating the substantial impact of AR on fostering higher-order cognitive skills in science education.
- This research not only underscores the pedagogical benefits of AR but also emphasizes the need for its integration into science curricula and teacher training programs, bridging the gap between technological innovation and effective classroom practice.

STEM education strives to foster confidence from successful engagements between scientists and the public (Al-Momani, 2021; Bickford et al., 2012; Malik et al., 2022). Clearly, it can be understood that the transformation STEM education seeking to ideal is harnessed for the advancement of science is the understanding that students get of the world in which they live tested for the greater good of mankind.

STEM remains a critical area of inquiry and teaching with the needed innovation publications soared from 0 in 2009 to 30 in 2023 according to Scopus data. Over the past decade, Phuong et al. (2023) observed an increased attention from educators, policymakers, and researchers regarding the factors that affect outcomes of STEM learning and student achievement. This includes pedagogy, curriculum, as well as the impact of technology and culture on students (Hamad et al., 2022). This emphasis also highlights the increasing importance of STEM education research in contemporary education and its relevance to advancing society.

The increase in interest toward the STEM disciplines results in additional academic studies being published each year, which indicates the need for systematic tools that assist in navigating literature (Hasanah, 2020). The use of bibliometrics, which is the application of mathematical and statistical approaches to the analysis of one or more fields of science, enables researchers to follow trends and focal points in publications, citations, and collaborations across different scientific disciplines (Dijk, 2023; Matta, 2020).

The increasing volume of available STEM literature illustrates the importance of bibliometric mapping, an emerging approach which facilitates the profound analysis of scientific domains (Aparicio et al., 2021). Using specialized software, researchers can determine the structure of particular sciences, study co-authorships, and discover thematic relations within the literature corpus (Karampelas, 2023; Phuong et al., 2023). Bibliometric tools analyze the data provided by authors, institutions, and countries, which aids in understanding the key units of scholarly research and crafting credible informed academic research strategies (Ninkov et al., 2022).

Research Rationale

Incorporating STEM education has gained attention recently, so has infusing STEM fundamentals into science and math syllabi. This stems from the need for basic exploration research in the following areas:

Educational significance

STEM education has certainly received international attention because it teaches interdisciplinary skills needed to resolve real-life issues. The infusion of STEM practices into science and math classes is crucial in developing the student's critical thinking, imagination, and problem-solving skills (Phuong et al., 2023). With the focus on these skills, students are prepared to be productive members of the economy and society and solve complex issues transcending borders.

Knowledge gap

Although there is a substantial focus on STEM education, no attempt has been made to carry out an extensive bibliometric analysis that integrates STEM into science and mathematics education. Such an analysis is needed with the aim of studying the research landscape mapping its trends, key players, and themes across the discipline (Matta, 2020). These hinders can be per the research rationale. Practical implications documenting the academic research landscape using bibliometric analysis reveals important gaps in the impact of various studies, collaborations, and emerging themes.

Mapping out the scientific landscape helps educators, policymakers, and curriculum designers develop STEM integration into classroom instructions (Aparicio et al., 2022; Ninkov et al., 2022). Moreover, it provides suggestions for aligning instructional methods to meet the STEM curriculum and industry standards.

Future research

This analysis will direct the future scholarly work by exploring the gaps and emerging themes in STEM integration. Through this, educators will be able to tackle the existing challenges in STEM integrative education and foster the development of culture-sensitive

responsive teaching models and practices (Karampelas, 2023). This also shows the increasing potential of interdisciplinary studies and the application of new technologies to STEM education research.

As a whole, this scientific work aspires to fill the gaps from different bodies of literature by compiling existing documents revolving around the integration of STEM into different scientific disciplines and mathematics classes. This systematically helps advance the goal of improving the attainability and inclusivity of quality STEM education in all countries.

Research Purpose

The purpose of this study is to undertake a comprehensive bibliometric analysis of research concerning the integration of STEM principles into science and mathematics classes within the framework of STEM education. This analysis aims to:

1. **Examine the current state of research:** Evaluate the quantity, trends, and distribution of publications related to the integration of STEM into science and mathematics classes over the past two decades (2004-2023), providing insights into the historical progression of this research field.
2. **Identify key research themes and topics:** Determine prevalent themes, concepts, and areas of focus within the field of STEM education, particularly those concerning the integration of STEM principles into science and mathematics curricula.
3. **Explore scholarly contribution:** Highlight leading authors, institutions, and countries contributing to research in this area. Additionally, analyze collaborations among researchers and institutions to understand the dynamics of scholarly networks within the field.
4. **Assessing impact and dissemination:** Analyze the impact and dissemination of research findings through citation analysis, co-citation patterns, and the examination of publication trends across influential journals and conferences. This objective aims to identify the most impactful studies and their contributions to the field.
5. **Provide insights for future research:** Offer valuable insights and recommendations to scholars interested in further exploring STEM integration within science and mathematics classes. These insights are intended to guide future research directions, highlight emergent trends, and address gaps in literature.

By addressing these objectives, this study aims to bridge existing gaps in literature and contribute to the advancement of STEM education. The findings are expected to provide actionable insights for educators, policymakers, and researchers, fostering the development of effective and inclusive STEM integration strategies across diverse educational contexts.

Research Questions

Based on the study purpose outlined earlier, the following research questions are addressed:

1. **Trends in publications:** What is the overall trend in the number of publications related to the integration of STEM into science and mathematics classes within the field of STEM education from 2004 to 2023?
2. **Predominant themes and topics:** What are the predominant themes, keywords, and topics explored in research on the integration of STEM into science and mathematics classes?
3. **Scholarly landscape:** How has the scholarly landscape evolved over time in terms of authorship patterns, institutional affiliations, and geographic distribution of research on integrating STEM into science and mathematics classes?
4. **Key contributors:** Which authors, institutions, and countries have made significant contributions to research on integrating STEM into science and mathematics classes within STEM education? What are the characteristics of their collaborations?
5. **Citation patterns and impact:** What are the citation patterns and networks, and how do they influence research themes and future directions?
6. **Dissemination of research findings:** How are research findings disseminated across different publication outlets, such as journals and conferences, and what are the characteristics of these outlets?
7. **Emerging trends and gaps:** Are there any emerging trends, underrepresented areas, or gaps in literature that warrant further investigation in future research?

These research questions serve as guiding principles for bibliometric analysis, providing insights into the current state and potential future trajectories of research on the integration of STEM principles into science and mathematics classes. The findings aim to support educators, policymakers, and researchers in advancing STEM education practices worldwide.

Theoretical Framework: Integration of STEM into Science and Mathematics Classes

The theoretical framework provided helps to analyze integration of STEM principles with instruction of science and mathematics through key components, processes, and outcomes for educators, policymakers, and researchers regarding the planning, execution, and evaluation of STEM undertakings. As with any

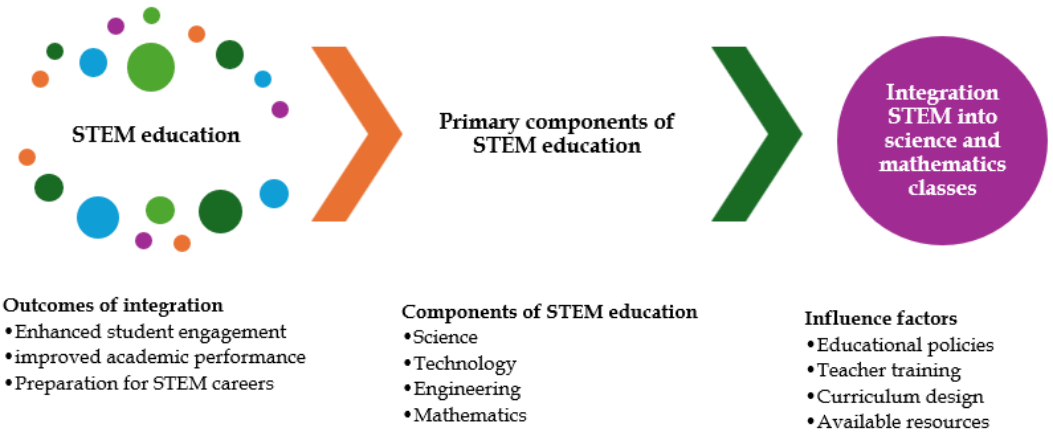

Figure 1. Integration of STEM into science and mathematics classes (Source: Authors' own elaboration)

educational concept, STEM serves as the main focal point–in this case, to equip learners with skills and knowledge that are interrelated across STEM disciplines. STEM advocates for the integration of these subjects to enhance holistic learning to equip students to tackle real-world problems and foster innovation. The primary components of STEM education include science, which advocates for learning and exploration through inquiry, technology which entails the application of tools, software, and digital resources for problem solving, engineering which encompasses the application of design thinking and active problem solving skills, and mathematics which focus on the application of reasoning and quantitative assessment in a broad range of areas. Together, these components provide unique perspectives and methodologies that form the foundation of STEM integration in education.

Integration involves infusing concepts, principles, and practices of STEM into existing science and mathematics curricula through interdisciplinary projects, hands-on activities, authentic problem-solving tasks, and group collaborative work. This method makes relevant connections between STEM fields and traditional content areas, as described by Honey et al. (2014). This integrative approach is affected by several factors, including government policies that support the school's STEM curriculum, teacher professional development programs, interdisciplinary curriculum mapping at the STEM program level, and funding and educational resources that equip schools with the necessary materials and technology. These components guarantee that the integration of STEM into education is viable and well-structured.

There are numerous educational advantages for integrating STEM into science and mathematics courses. Students show greater participation in STEM activities, demonstrating improved engagement and motivation. Their achievement in science and mathematics improves, as does their critical thinking and problem-solving abilities. Moreover, students are better prepared for careers in STEM fields because they acquire the appropriate knowledge, skills, and competencies necessary for their future professions. Integration of STEM is accompanied by a feedback loop that allows for evaluation, reflection, and improvement of integration efforts based on learners, educators, and other stakeholders' feedback. This iterative cycle guarantees that STEM approaches are refined progressively to meet specific educational requirements by tackling obstacles and leveraging successes to enhance results.

The framework has been developed based on strong theory, emphasizing educational theories like constructivism on learning where students actively participate, exploring and interacting with their surroundings to build knowledge; inquiry based education, which stimulate the study of galvanizing questions to better comprehend STEM topics; and project-based learning which uses real world interdisciplinary collaborative and creative challenges as projects to be solved. Also, as noted by Matta (2020), Aparicio et al. (2021), and Phuong et al. (2023), relevant studies and other evidence-based educational theories offer useful suggestions and effective practices for STEM integration. All in all, this theoretical framework depicts the systematic components of STEM integration, from concepts and practiced approaches to desired outcomes and guiding model to such efforts in educational contexts (**Figure 1**).

LITERATURE REVIEW

Employing Bibliometric Analysis in STEM

A range of scholars have incorporated bibliometric analysis tools, including Bibliometricx, BiblioShiny, RStudio, and VOSviewer, for STEM mapping within the last decade. Marín-Marín et al. (2021) pointed out that these instruments do much more than topic summarization. These tools discern patterns, highlight key concepts, and even provide an overview for the most active contributors in a given field. The more common approaches that these tools implement are bibliographic coupling, co-citation, co-authorship, citation network,

and concept association analysis. Collectively, these techniques provide valuable insights toward the modern understanding of scholarly communication and knowledge (Phuong et al., 2023).

Integration of STEM into Science and Mathematics

A surge of focus on incorporating STEM into science and mathematics classes at the K-12 level and as well as within STEM education frameworks can be seen. For example, Sugimoto and Thelwall (2013) assessed the impact of TED Talks using a variety of bibliometric indicators. They concluded that while TED Talks have had amazing reach, the greater portion of their audience is made up of non-academics. Science and technology presentations were, however, highly impactful. These studies have worked to prove that better communication techniques can be beneficial in promoting education and public participation in STEM fields.

Rauchfleisch and Schäfer (2018) investigated the development of research on scholarly communication through citation network analysis.

Evidence of an integrated internal framework in the field was noted which shows that interdisciplinary connections are valuable for advancing integrated areas of research. In the same way, Chen et al. (2022) provided a visualization of the global literature on the infusion of STEM into climate change education and discussed the rapid growth and evolution of this area of research primarily contributed by developed countries. This illustrates the wide applicability of bibliometric methods to analyze how new subject areas are integrated into STEM education.

von Zahn et al. (2022) discussed the ever-increasing volume of STEM educational research, stressing interdisciplinary collaboration and geographic variation in the implementation of solutions. This study synthesized the fragmented literature and classified the research themes into four dominant categories: career pathways, pedagogy, empirical outcomes, and equity in education. The authors described the qualitative differences within nations regarding the policies and practices enacted for STEM education and their social, cultural, and economic contexts. This highlights the need to pay attention to contextual differences in STEM education integration.

STEM Integration in Other Learning Areas

Germany was the setting of Kessler et al.'s (2019) study regarding the incorporation of STEM into science and mathematics classes, noting particularly the secondary school's integration of a dominant learned society for the advancement of that particular discipline within the German-speaking world. The findings of the study showed that indeed the research in STEM education has been of immense and great concern within that region, especially with the infrastructural developments that have been made in the region. The study illustrates the mannerized and organized strivings which have been made in Germany regarding the improvement of STEM education. This effort is laudable, but much still needs to be done through systematic and institutional endeavors in order to make real progress in STEM education.

The integration of STEM in different regions has had a positive effect on students and teachers and continues to be a center of focus for many researchers. Mahzri and Al-Shehri (2023) discovered that a training session for secondary school mathematics teachers enhanced cohesive thinking and collaborative abilities with the help of the students. Al-Titi and Al-Omari (2022) noted change in Jordanian eighth graders' understanding of environmental concepts through multi-skill objectives after teaching them STEM-based units. Abboushi and Shana (2022) in Palestine reported changes in teamwork, thinking, and overall student attitudes as positive outcomes after implementing STEM approaches. Almutairi (2023) found that middle school students' 21st century skills were developed as a result of STEM enrichment programs. In Saudi Arabia, Al Zahrani (2021) recorded expanded academic performance and creative thinking amongst 9th graders after the implementation of STEM education in their schools. In a different part of the world, Hebebci and Usta (2022) showed in Turkey that Integrated STEM practices had a positive impact on problem-solving, scientific creativity, and critical thinking of grade 8 students, extending the positive impacts of STEM education beyond the Middle East.

Literature Gaps

Although some studies have started using bibliometric research in STEM education, there is still a lack of research on the integration of STEM within science and mathematics classes.

The existing literature indicates that there are not many bibliometric studies which have explored this subject deeply within the wider scope of STEM education. Furthermore, most of the research focuses on developed countries, and there is limited understanding of STEM education integration in underserved areas and contexts.

In the last decade, scholars began creating maps of specific topics or fields of study using various bibliometric analysis tools like Bibliometrics, BiblioShiny, RStudio, and VOSviewer. These tools overview the frameworks of interdisciplinary cooperation and competition, pinpoint emerging patterns, underscore major themes, and monitor leading scholars (Marín-Marín et al., 2021). Common methodologies adopted through these tools are bibliographic coupling, co-citation analysis, co-authorship analysis, citation network analysis, and

concept association analysis. All of these together provide important perspectives on the phenomena and processes concerning scholarly communication and the knowledge evolution (Phuong et al., 2023).

Research also shows that there is an increasing focus on incorporating STEM into science and mathematics classes and in the context of STEM education. For example, Sugimoto and Thelwall (2013) studied the readership influence of TED Talks from different bibliometric perspectives. Their results indicated that TED Talks were quite popular, especially in non-academic circles, and particularly science and technology presentations had a strong influence.

As Rauchfleisch and Schäfer (2018), the studies explored and showcased the effectiveness of strategic communication and its impact in STEM education along with educational engagement outreach for broader public involvement. Through citation network analysis, they focused on the scholarly communication research's evolution. They revealed a cohesive internal structure within the field which was much more interdisciplinary than hyper-specialized thanks to the external networks that enabled the subdomains to be level advanced.

Current Study

This study intends to fill these gaps by looking at STEM education scholarship concerning the application of STEM principles into science and mathematics instruction and classes. Furthermore, this research scans Scopus metadata from 2004 to 2023 and performs bibliometric analysis to examine the current trends, major contributors, and new areas of focus for comprehensive STEM education. The findings are bound to benefit educators, policymakers, and researchers, in terms of supported knowledge and the effective adoption of approaches for STEM education, implementations worldwide. This study uses VOSviewer to analyze co-authorship citation and thematic change over time in order to determine the direction of growth for the interdisciplinary area.

METHODOLOGY

Bibliometric analysis, a systematic and quantitative research method, was employed in this study to identify key studies, authors, journals, and trends related to the integration of STEM into science and mathematics classes within STEM education. This approach is essential for revealing the current state of research, highlighting significant contributors and publications, and mapping the connections between topics within the field. By doing so, it allows researchers to assess the strengths, limitations, and gaps in literature.

Data Collection

The researchers utilized the Scopus database to conduct a comprehensive search of peer-reviewed articles published between 2004 and 2023. Advanced search options were employed, focusing on keywords related to STEM integration in science and mathematics classes. The following criteria were applied:

- Articles were restricted to English-language, peer-reviewed publications.
- The search was confined to the social sciences to ensure relevance to educational contexts.
- A total of 178 relevant studies were identified for analysis.

Data Processing

The selected articles were downloaded from Scopus in CSV and BibTeX formats and subsequently converted into a TAB-delimited file. This file was uploaded into VOSviewer software for analysis. VOSviewer is a widely recognized tool in bibliometric research, offering advanced visualization capabilities. Unlike other tools such as R, VOSviewer emphasizes the graphical representation of bibliometric networks, enabling researchers to analyze:

- Co-authorship networks.
- Citation and co-citation patterns.
- Trends and associations between topics.

Analysis Techniques

The researchers employed various analytical techniques to extract meaningful insights, including:

1. **General statistics**: Yearly publication trends, prolific journals, authors, and institutions.
2. **Co-authorship analysis**: Patterns of collaboration among authors and institutions.
3. **Thematic analysis**: Identification of emerging themes and gaps in literature.
4. **Visualization**: Mapping co-occurrence networks, co-authorship relationships, and citation connections to uncover significant patterns.

The results of the bibliometric analysis provide quantitative insights into the evolution of research on the integration of STEM into science and mathematics classes, highlighting areas of strength and opportunities for further exploration.

RESULTS

The bibliometric analysis identified 178 articles related to the integration of STEM into science and mathematics classes published between 2004 and 2023. The distribution of these publications, as shown in **Figure 2**, highlights trends, patterns, and potential gaps in the research landscape.

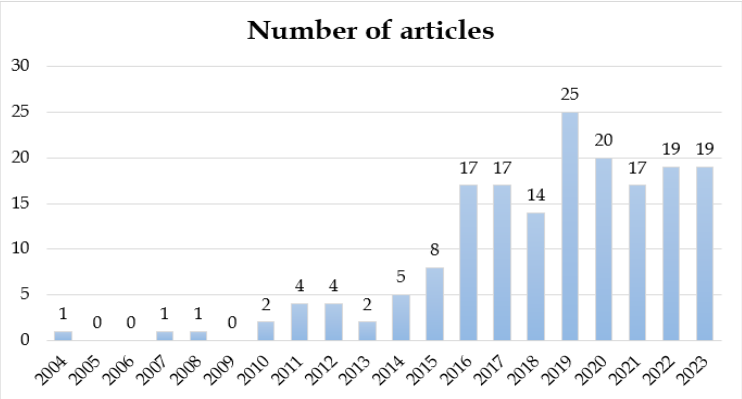

Figure 2. Distribution of studies according to years (Source: Authors' own elaboration)

1. **Yearly trends:** The number of articles published fluctuated significantly during this period. Notably:

   a. No articles were published in 2005, 2006, and 2009, suggesting limited research focus or activity during these years.

   b. From 2010 onward, there was a consistent upward trend in publication numbers, indicating a growing interest in the topic.

2. **Dynamics of growth:** There was a noticeable surge in the number of articles published during certain years, especially after 2015. This growth corresponds with the widespread attempt to integrate STEM into pedagogical frameworks which deepens the appreciation towards STEM education within teaching frameworks in recent years.

3. **Equilibrium state:** With interruptions, there seems to be an equilibrium state from 2015 to 2023 where research activities capture the moderate to high range in the number of publications. This suggests persistent scholarly engagement and sustained attention and funding towards research on integration of STEM into education.

4. **Consolidated evaluation:** Throughout the period under consideration, 178 articles were uploaded which can be regarded as a significant corpus of literature discussing the integration of STEM into science and mathematics education. This shows the nature of the examined topic in context of education and STEM-discipline research.

5. **Unique avenues for further investigation:** Though the increase in publications shows an increased interest in the subject, there remains scope for further exploration, particularly in neglected areas. Filling these gaps can advance understanding and improve policies for STEM integration.

From publication data, it is possible to see the changing trends of research regarding integration of STEM concepts into science and mathematics classes.

These trends mark areas of strength like higher scholarly engagement and also point towards opportunities in the areas that require further investigative attention to fill the gaps in literature.

Contribution by Nations

Figure 3, **Figure 4**, and **Figure 5** present a breakdown of the number of co-authorship links between partner countries in integrating STEM into science and mathematics classes within STEM education. A total of 36 countries were analyzed, revealing five clusters of collaboration based on co-authorship networks.

1. **Primary collaborators:** The United States takes the top spot as the primary collaborator, recording 109 co-authorship links which mark a significant level of global collaboration in this area. This strong engagement illustrates how the United States is at the forefront of STEM integration research on a worldwide scale.

   Other important contributors are Taiwan with 10 links, Indonesia with 9 links, and Malaysia with 9 links, all of which indicate their important participation toward collaborative research in this area.

2. **Additional contributors:** Australia, South Korea, Canada, South Africa, Turkey, and Austria are also known to participate in international collaborations, thereby showcasing a wider range of geographical representation.

3. **International collaboration overview:** The network visualizations in **Figure 3**, **Figure 4**, and **Figure 5** present an elaborate picture of international collaboration, where many countries are contributing toward STEM education research. The co-authorship networks illustrate the collaborative nature of STEM integration research focused on incorporating STEM into sciences and mathematics classes around the globe.

4. **Insights from figures**

   a. **Figure 3** displays the international collaboration network, illustrating connections between key partner countries.

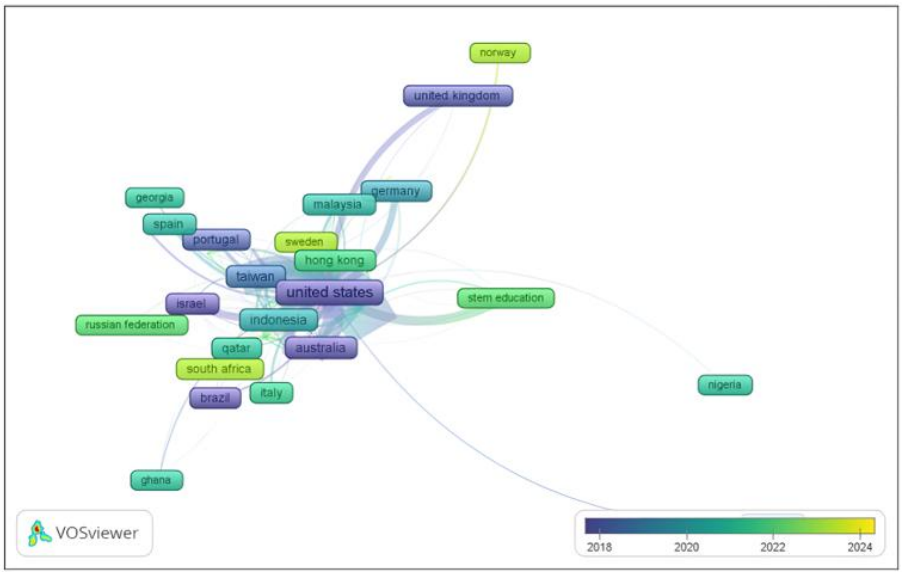

Figure 3. Visualizing international collaboration: A network analysis of partner countries in integrating STEM into science and mathematics classes within STEM education (Source: Authors' own elaboration, using VOSviewer 1.6.19)

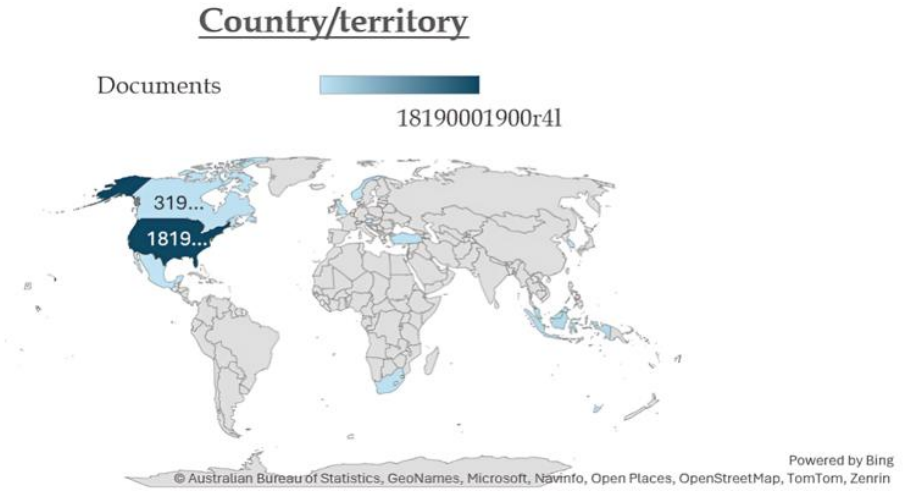

Figure 4. Co-authorization map according to countries (Source: Authors' own elaboration, using VOSviewer 1.6.19)

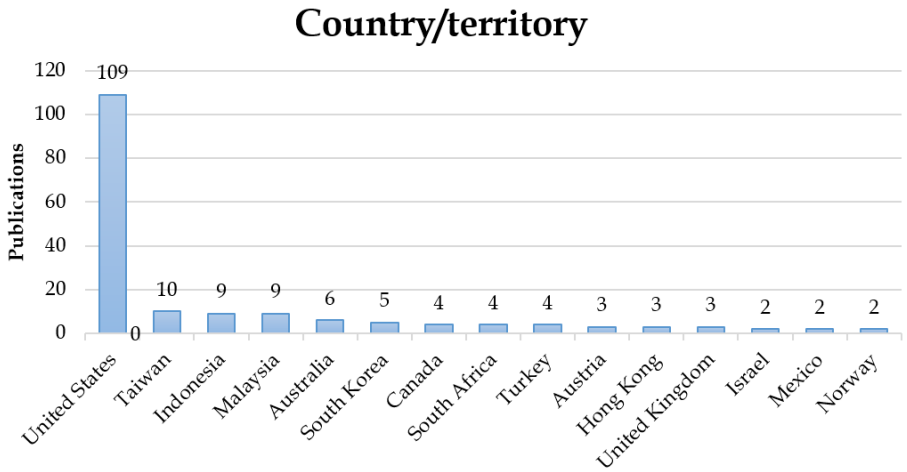

Figure 5. Number of publications by country/territory (Source: Authors' own elaboration)

b. **Figure 4** shows a co-authorship map based on geographical distribution, further emphasizing the United States' dominant role in research collaborations.

c. **Figure 5** provides a bar chart summarizing the number of publications per country, reinforcing the United States' leading position, followed by Taiwan, Indonesia, and Malaysia.

Table 1. Top 10 most productive affiliations published on integration STEM into science and mathematics classes in STEM education

No	Affiliation	Country	Documents	Citations
1	Universiti Kebangsaan Malaysia	Malaysia	6	42
2	Purdue University	United States	6	14
3	University of Kansas	United States	6	20
4	Texas A&M University	United States	6	18
5	Michigan State University	United States	6	72
6	Vanderbilt University	United States	5	34
7	University of Virginia	United States	5	10
8	National Taiwan Normal University	Taiwan	5	11
9	SRI International	United States	4	22
10	The University of Alabama in Huntsville	United States	4	15

Table 2. Top 10 most productive authors published on integration STEM into science and mathematics classes in STEM education

No	Author	Institutions	Country	Documents	Citations
1	Capraro, R. M.	Texas A&M University	United States	6	619
2	Biswas, G.	Vanderbilt University	United States	6	615
3	Capraro, M. M.	Texas A&M University	United States	5	619
4	Love, T. S.	University of Maryland Eastern Shore	United States	5	118
5	Ault, M.	University of Kansas	United States	3	72
6	Barroso, L. R.	Michigan Technological University	United States	3	34
7	Basu, S.	Vanderbilt University	United States	3	10
8	Bolyard, J.	West Virginia University	United States	3	11
9	Bulgren, J.	University of Georgia	United States	3	22
10	Carmen, C.	University of Alabama	United States	3	15

The data reflects a well-established international effort to advance the integration of STEM into science and mathematics classes. The active involvement of countries from different regions highlights the collaborative nature of this research area and underscores the global commitment to improving STEM education.

Contribution by Institutions

Table 1 presents the top 10 institutions with the most published articles on integrating STEM into science and mathematics classes within STEM education. The analysis reveals that these institutions are predominantly located in developed countries, underscoring their significant role in advancing this field of research.

1. **Geographic distribution**

   a. **The United States** accounts for most affiliations, with six institutions represented in the top 10 list.

   b. **Malaysia** and **Taiwan** each have one institution included, reflecting their growing contributions to the research landscape.

2. **Notable contributions**

   a. Among these institutions, **Michigan State University** stands out with the highest number of citations (72), indicating the significant impact of its research on the field.

   b. Other highly cited institutions include **Universiti Kebangsaan Malaysia** (42) and **Vanderbilt University** (34), highlighting their contributions to STEM integration research.

3. **Insights from the data**

   a. The articles produced by these institutions have collectively garnered substantial attention, reinforcing the importance of their research in shaping STEM education practices.

   b. The presence of institutions from Malaysia and Taiwan emphasizes the international dimension of STEM integration research, complementing the dominant contributions from the United States.

Summary of Findings

The study underscores the importance of primary institutions in the research problem of STEM integration. For example, Michigan State University and Universiti Kebangsaan Malaysia have performed noteworthy work given the citation numbers. The information also demonstrates the prevalence of these USA-based institutions while still highlighting the case of Malaysia and Taiwan, indicating the increasing international interest in STEM education.

Contribution by Authors

Table 2 presents the top 10 authors with the highest number of published articles on the integration of STEM into science and mathematics classes within STEM

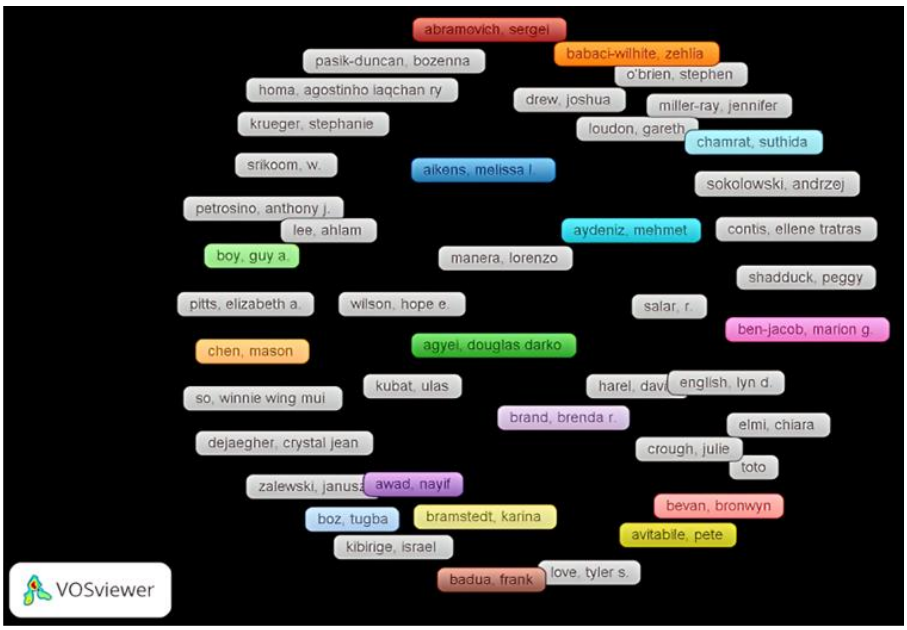

Figure 6. Authors' citation network map (Source: Authors' own elaboration, using VOSviewer 1.6.19)

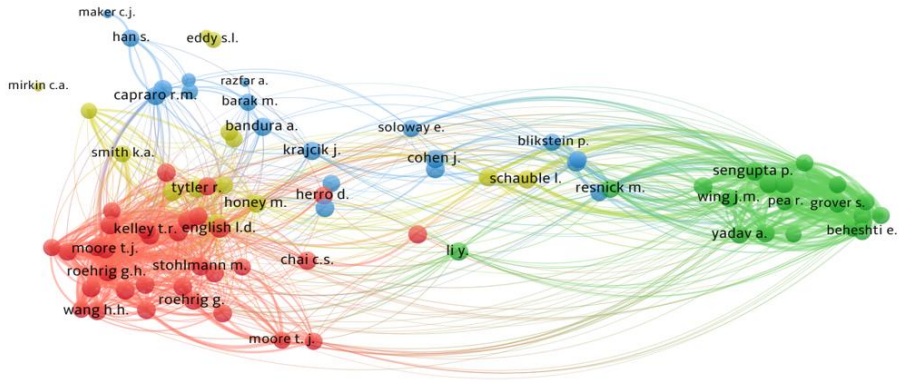

Figure 7. Authors' co-citation map (Source: Authors' own elaboration, using VOSviewer 1.6.19)

education. These authors have significantly shaped the research landscape through their contributions.

1. **Leading contributors**

   a. **Capraro, R. M.** and **Biswas, G.**, both from the United States, lead with six articles each, demonstrating their substantial involvement in advancing STEM education research.

   b. Notably, **Capraro, R. M.** and **Capraro, M. M.** achieved the highest number of citations, with **619 citations each** in the Scopus database, highlighting the widespread impact of their work.

2. **Other notable authors**

   a. **Love, T. S.** follows closely with five articles and **118 citations**, showcasing significant contributions to integrating STEM into science and mathematics curricula.

   b. Additional contributors, such as **Ault, M.**, **Barroso, L. R.**, and **Bolyard, J.**, have also made meaningful contributions, with their articles receiving noteworthy attention within the field.

3. **Co-authorship and citation networks**

   a. A **co-authorship analysis** identified a cluster of **11 articles**, highlighting collaborative research efforts within the field.

   b. A **citation network map** (Figure 6) was constructed, focusing on articles with at least 30 citations out of the 178 documents analyzed. This map, organized into **eight clusters**, serves as a visual representation of influential research within STEM education.

4. **Co-citation analysis**

   a. To further identify central contributors, a **co-citation analysis** was conducted, using a minimum threshold of 20 citations. This analysis revealed three main clusters among the 28 researchers meeting this criterion.

   b. Figure 7 illustrates these co-citation clusters, with prominent contributions from **Osborne et al. (2003)**, **Besley et al. (2015)**, and **Scheufele (2022)**, who were identified as the most influential researchers in the field.

Table 3. Top 10 journals by productivity and citations

No	Journal Name	Publications	Citations
1	Public Understanding of Science	12	215
2	Journal of Integration STEM into Science and Mathematics Classes	10	182
3	International Journal of Science Education, Part B	9	176
4	Frontiers in Communication	8	144
5	Journal of Microbiology and Biology Education	7	120
6	Journal of Research in Science Teaching	7	210
7	International Journal of Science Education	6	108
8	Integration STEM into Science and Mathematics Classes	6	102
9	Science and Education	5	98
10	Frontiers in Education	5	96

Summary of Findings

The analysis underscores the impact of major authors like Capraro, R. M., Biswas, G., and Love, T. S., who have pioneered the integration of STEM. Collaborative research networks and co-citation analysis also illustrate the connectedness of various researchers in the development of STEM education.

Contribution by Journals

The evaluation of peer-reviewed journals which published works on the integration of STEM into math and science teaching and STEM education reveals the most influential journals in the discipline. **Table 3** shows the 10 journals who, within the specified period, published the largest number of papers in the topic under consideration.

1. **Key journals and publication frequency**

   a. Journals such as *Public Understanding of Science*, *Journal of Integration STEM into Science and Mathematics Classes*, and *International Journal of Science Education, Part B: Communication and Public Engagement* published the highest number of articles.

   b. Other active journals include *Frontiers in Communication*, *Journal of Microbiology and Biology Education*, *Integration STEM into Science and Mathematics Classes*, *Journal of Research in Science Teaching*, *International Journal of Science Education*, *Science and Education*, and *Frontiers in Education*.

2. **Citation impact**

   a. Journals like *Journal of Research in Science Teaching*, *Public Understanding of Science*, and *Journal of Integration STEM into Science and Mathematics Classes* stand out for their significant citation impact, reflecting the influence of their published articles within the academic community.

3. **Publishing organizations**

   a. The analysis identified 77 publishing organizations that have released articles on STEM integration in science and mathematics classes. By setting a threshold of at least one published article and 10 citations per source, 21 journals met the inclusion criteria.

4. **Bibliographic network analysis**

   a. Using VOSviewer software, a bibliographic matching map (**Figure 8**) was generated to visualize the relationships between journals in terms of bibliographic links.

   b. The analysis identified 21 journals grouped into five clusters. Journals with the strongest bibliographic link strengths include:

   - *International Journal of Science Education, Part B*
   - *Journal of Research in Science Teaching*
   - *Integration of STEM into science and mathematics classes*
   - *Public Understanding of Science*
   - *Journal of Integration STEM into Science and Mathematics Classes*

Summary of Findings

This analysis emphasizes the central role of specific journals in advancing research on STEM integration in education. Journals like *Public Understanding of Science* and *Journal of Integration STEM into Science and Mathematics Classes* not only publish a significant number of articles but also contribute highly influential research, as reflected in their citation impact. The bibliographic network further highlights the interconnectedness of these journals, serving as a valuable resource for scholars seeking to explore the field.

Analysis of Keywords

Using VOSviewer software, a co-occurrence analysis was conducted to examine research keywords related to the integration of STEM into science and mathematics classes. This type of analysis identifies relationships between frequently used keywords, shedding light on prevailing themes and emerging topics in the field.

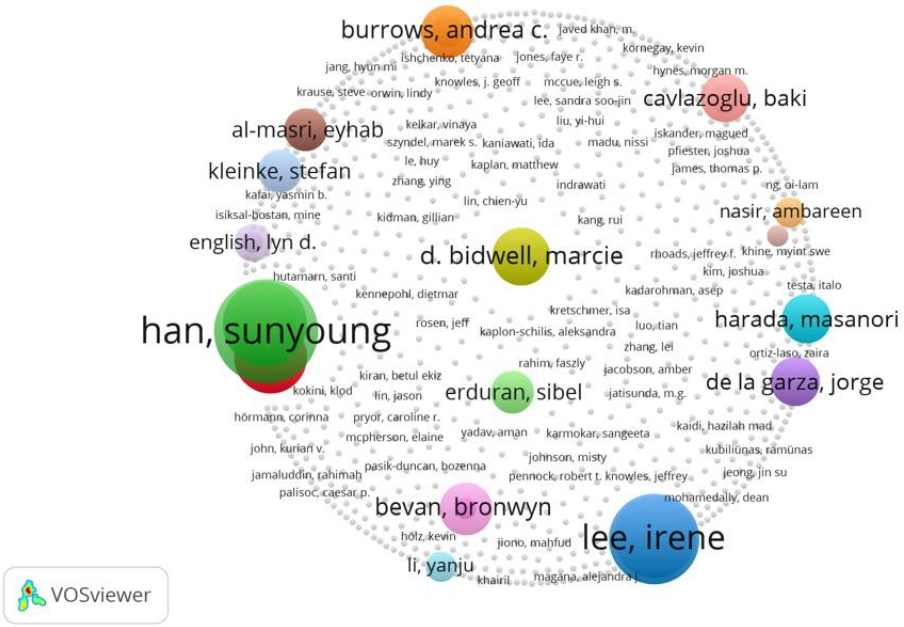

Figure 8. Authors' analysis according to bibliographic matching map (Source: Authors' own elaboration, using VOSviewer 1.6.19)

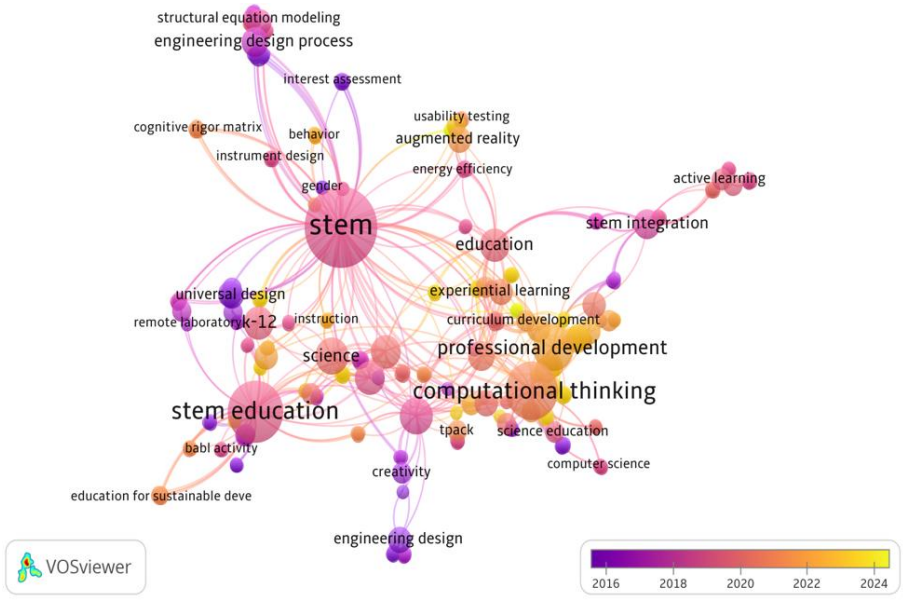

Figure 9. Co-occurrence analysis of index keywords on integration STEM into science and mathematics classes research in STEM education (Source: Authors' own elaboration, using VOSviewer 1.6.19)

1. **Scope of the analysis**

   a. A total of **689 unique keywords** were identified in the analysis, reflecting the diversity and breadth of research within this domain.

   b. Keywords included in the analysis encompassed all terms that appeared frequently across the dataset, offering a comprehensive overview of the research focus.

2. **Most frequently used keywords**

   a. The analysis highlights that the most used keywords are:

   - **Integration STEM into science and mathematics classes**
   - **Science education**
   - **Education**
   - **STEM**

   b. These keywords underscore the central focus of research on integrating STEM principles into educational practices, particularly within the disciplines of science and mathematics.

3. **Key insights from Figure 9**

   a. **Figure 9** illustrates the connections between keywords, forming clusters that represent distinct research areas.

b. The visual map suggests strong associations between the integration of STEM and broader topics such as **science education** and **STEM education**, highlighting the interdisciplinary nature of this research field.

c. Additional connections with terms like **collaboration**, **curriculum design**, and **teaching methods** reflect ongoing efforts to develop effective strategies for implementing STEM in classrooms.

4. **Emerging trends**

a. The keyword analysis reveals a growing emphasis on practical applications of STEM integration, such as:

- **Project-based learning**
- **Interdisciplinary teaching**
- **Technological advancements in education**

b. These trends highlight the evolution of research toward actionable methodologies that improve STEM education outcomes.

5. **Visual representation**

a. **Figure 7** shows the co-occurrence map generated by VOSviewer provides a detailed visualization of keyword relationships, illustrating how various research topics are interconnected.

Summary of Findings

The keyword analysis demonstrates the diverse and interconnected nature of research on STEM integration in science and mathematics classes. Frequently used keywords and their associations emphasize the central themes of the field while revealing emerging trends that offer directions for future research. The strong linkage between STEM integration and broader educational topics further highlights the significance of this research in shaping contemporary education practices.

DISCUSSION

This analysis aimed to carry out a thorough bibliometric evaluation of the assimilation of STEM into science and math classes in the context of STEM education through bibliographic data in the Scopus database from 2004 to 2023. This study is the first of its kind to competitively analyze existing research in this area, so it adds value to the literature by providing research insights, including collaboration activities in the domain. The study sought to map out the landscape of the subject area, employing analytical tools to help researchers track trends and discover key studies as well as important figures in the field.

The data demonstrated an increasing trend of volume in publications concerning the integration of STEM into various subjects, particularly in math and science classes as STEM education from the year 2014. Such an increase in scholarly attention is indicative of changes taking place in STEM education research. Most notably, the United States, the United Kingdom, Australia, Canada, and Germany formed the core of the cited literature, with the USA institutions outpacing their peers as the foremost publishing contributors.

This trend implies that scholars in developed regions seem to be particularly busy studying the implementation of STEM integration within science and mathematics classrooms across the STEM education continuum.

The study underscores the importance of articles as the preferred form of academic publication, serving as objective indicators of scientists' academic effectiveness and productivity. By identifying research content and direction through network clusters, this research provides valuable insights for scholars evaluating the current state of the field, guiding them toward new and original research directions.

The knowledge institutions of this nation have a significant impact in contributing to the production of knowledge. We encourage researchers from other parts of the world to follow the academic and scientific results published by these institutions and trust their publications will be of high quality. International collaboration analyses show Germany, the United States, Finland, Australia, Netherlands, Portugal, Austria, United Kingdom, Italy, and Ireland actively participated in collaborative STEM integration studies (**Figure 3**). Concerning corresponding authors, the United States dominated the list with six affiliations from the top ten, while Australia, Canada, Israel, and United Kingdom each contributed to one paper.

STEM education as well as integrating STEM into the mathematics and science curriculum was most heavily researched by developed countries. Most cited articles were also from developed countries where University of Wisconsin-Madison researchers are affiliated. Also, the analysis reveals that for Scopus database Osborne et al. (2003) takes the crown as the most cited researcher in the subject area. Kohen and Dori (2019), Besley et al. (2015) are some other authors that were highlighted as strongest citation links during citation network analysis.

Mercer-Mapstone and Kuchel (2017), along with Feinstein (2015), are also cited in other works. Osborne et al. (2003), Simis et al. (2016), Tatalovic (2009), Ishmuradova et al. (2023), and Besley et al. (2015) were the top cited researchers in the integration of STEM into science and mathematics classes. Co-citation analysis showed that Osborne et al. (2003) along with Besley et al. (2015), and Scheufele (2022) made the most contributions to this area of research. Co-citation analysis identifies links between two studies in case they are jointly cited in the same document, with frequent co-citations strengthening the relationship between these works. In

contrast, the analysis of the citation networks concentrates on the document relationships between direct citations where stronger links are indicated by greater citations.

This study corroborates previous work suggesting that adding STEM components to educational activities deepens the scope of studies and broadens their impact on research, teaching, and society. In contrast, Sugimoto and Thelwall (2013) pointed out crosses between disciplines; this study adds to the conversation about patterns of collaboration, key figures, and trends in the literature on science and mathematics education.

von Zahn et al. (2022) reported that publications on STEM education continue to dominate discussions while also highlighting the growing importance of interdisciplinary collaboration in enhancing the discipline.

This study maintained attention on the integration of STEM into science and math classes and investment in them from 2015 to 2023, depicting a relatively stable state of research activity.

Unlike the findings from Chen et al. (2022) which underscored the tendency to focus on contributions from developed countries and the importance of public understanding in climate change discussions, this study brings forward the United States, marking it as the top collaborator in STEM education research with 109 co-authorship links, showcasing remarkable international collaboration in STEM education research. Other contributing countries such as Taiwan, Indonesia, and Malaysia also actively participated in the collaborative research.

In the STEM integration in teaching and learning context, these findings are consistent with those of Mahzri and Al-Shehri (2023) who highlighted the fostering of comprehensive thinking and teamwork among educators. Al-Titi and Al-Omari (2022) also advocated for STEM integration in the teaching of important scientific skills, while Abboushi and Shana (2022) concentrated on the benefits of integration onto the students' critical thinking and collaboration activities.

This bibliometric research study brings forward important new information regarding the patterns, cooperation networks, and gaps in research concerning the integration of STEM into science and mathematics teaching globally. These results can be used by educators, decision makers, and researchers who are trying to improve STEM education.

In particular, the focus on problem-solving along with interdisciplinary collaboration, and the USA-led international collaborations show promising applications: educators can incorporate popular phenomena such as robotics into the teaching of science and mathematics, as required by the next generation science standards, while policymakers could promote international policy exchange partnerships such as those between the USA and Taiwan where STEM education teaching resources and funding are streamlined.

CONCLUSIONS

This bibliometric study provides valuable insights into global trends, collaboration networks, and key areas of focus in STEM education research. By identifying emerging patterns and influential contributors, this research highlights the escalating importance of integrating STEM principles into science and mathematics classes. It underscores the need for continued investment in STEM education to address the challenges of the 21st century.

Limitations

The investigation into the integration of STEM into the education system faces a set of challenges that may alter the range and depth of its results. They limit themselves to Scopus as a data source which may miss key publications that are indexed in other databases such as Web of Science or ERIC and, thus, reduce the breadth of the analysis. In addition, the use of VOSviewer for bibliometric analysis, although efficient, does not provide as many options as other instruments like Bibliometrix or Citespace, potentially leading to less nuanced data analysis. Furthermore, the study suffers from bibliometric biases since such information usually overrepresents highly cited, English-language journals, and diminishes findings from smaller, non-English publications, thus narrowing the scope of the research's geographic representation.

Recommendations for Future Research

Further work could broaden and inclusively the scope of studies focused on STEM education. Researchers need to combine databases beyond Scopus to include the Web of Science and ERIC for a more holistic analysis capturing a wider range of publications. It is also suggested that new technologies, such as artificial intelligence and machine learning, be explored for bibliometric analyses since they can enhance the processing and visualization of data which can lead to better findings. In addition, focusing more attention on regions that have received less attention, such as Africa and South America, would help diversify the global research landscape and promote a more balanced understanding of STEM inclusive within education globally.

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REFERENCES

Abboushi, M., & Shana, H. (2022). The effectiveness of applying the STEM approach in developing teamwork, critical thinking, and the attitudes towards it among primary school students in Palestine. *IUG Journal of Educational and Psychology Sciences, 30*(5), 268-292.

Al Zahrani, Y. (2021). Effectiveness of using STEM approach in solving mathematical verbal problems in mathematics subject on academic achievement and creative thinking in a sample of ninth grade students in Makkah. *Journal of Reading and Knowledge, 21*(232), 384-420.

Al-Momani, M. O. (2021). Vocational-education students' attitudes towards their academic specialization in Jordan. *Education and Self Development, 16*(3), 10-24. https://doi.org/10.26907/esd.16.3.03

Almutairi, N. (2023). The effectiveness of an enrichment teaching program based on STEM approach in developing the 21st skills of intermediate school students. *Journal of Educational and Psychological Sciences, 44*(7), 66-81. https://doi.org/10.26389/AJSRP.R070923

Al-Titi, I., & Al-Omari, W. (2022). The effectiveness of an educational unit based on the STEM integration approach in the acquisition of environmental concepts among eighth basic grade students. *Jordan Journal of Applied Science, 30*(2), Article 6.

Aparicio, G., Iturralde, T., & Maseda, A. (2021). A holistic bibliometric overview of the student engagement research field. *Journal of Further and Higher Education, 45*(4), 540-557. https://doi.org/10.1080/0309877X.2020.1795092

Badru, A. K., & Owodunni, S. A. (2021). Influence of mathematical language ability and parental supports on students' academic achievement in secondary school sciences (physics, chemistry, and biology) in Ogun State, Nigeria. *Education and Self Development, 16*(1), 10-20. https://doi.org/10.26907/esd16.1.03

Besley, J. C., Dudo, A., & Storksdieck, M. (2015). Scientists' views about communication training. *Journal of Research in Science Teaching, 52*(2), 199-220. https://doi.org/10.1002/tea.21186

Bickford, D., Posa, M. R. C., Qie, L., Campos-Arceiz, A., & Kudavidanage, E. P. (2012). Integration STEM into science and mathematics classes for biodiversity conservation. *Biological Conservation, 151*(1), 74-76. https://doi.org/10.1016/j.biocon.2011.12.016

Chen, D., Guo, Y., Wang, C., Xu, Y., & Zhang, H. (2022). Dispersion and disparity: Bibliometric and visualized analysis of research on climate change science communication. *International Journal of Environmental Research and Public Health, 19*, Article 15766. https://doi.org/10.3390/ijerph192315766

Dijk, A. V. (2023). *"Science is more fun when I see it in real life"-Changing secondary school students' attitudes towards science with a museum program* [Master's thesis, Utrecht University].

Donohue, K., VanDenburgh, K., Reck, C., & Buck, G. (2021). Integrating science communication into a large STEM classroom. *Journal of College Science Teaching, 51*(2), 46-50. https://doi.org/10.1080/0047231X.2021.12290548

Feinstein, N. W. (2015). Education, communication, and science in the public sphere. *Journal of Research in Science Teaching, 52*(2), 145-163. https://doi.org/10.1002/tea.21192

Hamad, S., Tairab, H., Wardat, Y., Rabbani, L., AlArabi, K., Yousif, M., Abu-Al-Aish, A., & Stoica, G. (2022). Understanding science teachers' implementations of integrated STEM: Teacher perceptions and practice. *Sustainability, 14*(6), Article 3594. https://doi.org/10.3390/su14063594

Hasanah, U. (2020). Key definitions of STEM education: Literature review. *Interdisciplinary Journal of Environmental and Science Education, 16*(3), Article e2217. https://doi.org/10.29333/ijese/8336

Hebebci, M. T., & Usta, E. (2022). The effects of integrated STEM education practices on problem-solving skills, scientific creativity, and critical thinking dispositions. *Participatory Educational Research, 9*(6), 358-379. https://doi.org/10.17275/per.22.143.9.6

Honey, M., Pearson, G., & Schweingruber, H. A. (Eds.). (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research* (Vol. 500). Washington, DC: National Academies Press.

Hu, S., Li, Z., Zhang, J., & Zhu, J. (2018). Engaging scientists in science communication: The effect of social proof and meaning. *Journal of Cleaner Production, 170*, 1044-1051. https://doi.org/10.1016/j.jclepro.2017.09.210

Ishmuradova, A. M., Svintsova, M. N., Kondakchian, N. A., Zaitseva, N. A., Sokolova, N. L., & Khairullina, E. R. (2023). A bibliometric overview of science communication research in STEM education. *Online Journal of Communication and Media Technologies, 13*(4), Article e202341. https://doi.org/10.30935/ojcmt/13415

Karampelas, K. (2023). Examining the relationship between TPACK and STEAM through a bibliometric study. *European Journal of Science and Mathematics Education, 11*(3), 488-498. https://doi.org/10.30935/scimath/12981

Kessler, S. H., Fähnrich, B., & Schäfer, M. S. (2019). Science communication research in the German-speaking countries: A content analysis of conference abstracts. *Studies in Communication Sciences, 19*(2), 243-251. https://doi.org/10.24434/j.scoms.2019.02.012

Kohen, Z., & Dori, Y. J. (2019). Toward narrowing the gap between science communication and science education disciplines. *Review of Education, 7*(3), 525-566. https://doi.org/10.1002/rev3.3136

Kushairi, N., & Ahmi, A. (2021). Flipped classroom in the second decade of the millennia: A bibliometrics analysis with Lotka's law. *Education and Information Technologies, 26*, 4401-4431. https://doi.org/10.1007/s10639-021-10457-8

Leydesdorff, L., & Hellsten, I. (2005). Metaphors and diaphorases in science communication. *Science Communication, 27*(1), 64-99. https://doi.org/10.1177/1075547005278346

Mahzri, I. M. M., & Al-Shehri, M. A. M. (2023). Proposed program based on the STEM approach in acquisition of secondary stage mathematics teachers' teaching excellence skills and its effect on their students' development of divergent thinking skills. *Humanities and Educational Sciences Journal*, (32), 139-177. https://doi.org/10.55074/hesj.vi32.759

Malik, D., Singh, P., & Dhiman, D. (2022). Science communication in India: Current trends and future vision. *Science Communication in India: Current Trends and Future Vision*. https://doi.org/10.2139/ssrn.4199480

Marín-Marín, J. A., Moreno-Guerrero, A. J., Dúo-Terrón, P., & López-Belmonte, J. (2021). STEAM in education: A bibliometric analysis of performance and co-words in Web of Science. *International Journal of STEM Education, 8*(1), Article 41. https://doi.org/10.1186/s40594-021-00296-x

Matta, G. (2020). Science communication as a preventative tool in the COVID-19 pandemic. *Humanities and Social Sciences Communications, 7*, Article 159. https://doi.org/10.1057/s41599-020-00645-1

Mercer-Mapstone, L., & Kuchel, L. (2017). Core skills for effective science communication: A teaching resource for undergraduate science education. *International Journal of Science Education, Part B, 7*(2), 181-201. https://doi.org/10.1080/21548455.2015.1113573

Ninkov, A., Frank, J. R., & Maggio, L. A. (2022). Bibliometrics: Methods for studying academic publishing. *Perspectives on Medical Education, 11*, 173-178. https://doi.org/10.1007/s40037-021-00695-4

Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. *International journal of science education, 25*(9), 1049-1079. https://doi.org/10.1080/0950069032000032199

Phuong, H. Y., Phan, Q. T., & Le, T. T. (2023). The effects of using analytical rubrics in peer and self-assessment on EFL students' writing proficiency: A Vietnamese contextual study. *Language Testing in Asia, 13*, Article 42. https://doi.org/10.1186/s40468-023-00256-y

Rauchfleisch, A., & Schäfer, M. S. (2018). Structure and development of science communication research. Co-citation analysis of a developing field. *Journal of Science Communication, 17*(3), Article A07. https://doi.org/10.22323/2.17030207

Scheufele, D. A. (2022). Thirty years of science–society interfaces: What's next?. *Public Understanding of Science, 31*(3), 297-304. https://doi.org/10.1177/09636625221075947

Simis, M. J., Madden, H., Cacciatore, M. A., & Yeo, S. K. (2016). The lure of rationality: Why does the deficit model persist in science communication?. *Public Understanding of Science, 25*(4), 400-414. https://doi.org/10.1177/0963662516629749

Sugimoto, C. R., Thelwall, M., Larivière, V., Tsou, A., Mongeon, P., & Macaluso, B. (2013). Scientists popularizing science: Characteristics and impact of TED talk presenters. *PloS One, 8*(4), Article e62403. https://doi.org/10.1371/journal.pone.0062403

Tatalovic, M. (2009). Science comics as tools for science education and communication: A brief, exploratory study. *Journal of Science Communication, 8*(4), Article A02. https://doi.org/10.22323/2.08040202

von Zahn, M., Bauer, K., Mihale-Wilson, C., Jagow, J., Speicher, M., & Hinz, O. (2022). *The smart green nudge: Reducing product returns through enriched digital footprints & causal machine learning* (No. 363). SAFE Working Paper. https://doi.org/10.2139/ssrn.4262656