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STEM AND STEAM EDUCATION IN 1st DECADE: A BIBLIOMETRIC ANALYSIS (2014-2025)

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Abstract

STEM and STEAM education has become a strategic learning approach in addressing global challenges in the Industrial Revolution 4.0 and Society 5.0 era, focusing on developing 21st-century skills, such as creativity, critical thinking, problem-solving and collaboration. This study used bibliometric analysis of 535 articles from the Scopus database published between 2014 and 2025 to explore research trends, dominant keywords, geographical contributions, and author and institutional impact. Data analysis conducted with RStudio, VOSviewer, and Excel identified four main clusters: skills development, educational approaches, utilization of STEM in various fields, and use of learning-based tools such as AR and VR. STEM and STEAM education effectively increased student engagement and built cross-disciplinary skills. However, challenges such as gaps in technology access and teacher training still need to be addressed. These results provide important insights for curriculum development, teacher professional training and education policies supporting technology-based learning transformation

Keywords: Bibliometric Analysis; STEM Education; STEAM Education

1. Introduction

STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) education have undergone significant evolution in response to global demands for a multidisciplinary workforce over the past decades (Deák & Kumar, 2024; Kang, 2019; Zhan et al., 2022). Rapid digital transformation and the need for innovation have driven educational reforms in various countries to adopt more integrated and holistic learning approaches (Bitar & Davidovich, 2024; Oke & Fernandes, 2020). These approaches aim to create a generation capable of thriving in the era of the Fourth Industrial Revolution and progressing towards Society 5.0, characterized by technological advancement, innovation, and global complexity.

In the early 21st century, STEM-based education initiatives began to gain momentum, particularly in developed countries such as the United States. In Southeast Asia, including Indonesia, STEM and STEAM education started to gain traction during the first decade of the century. National programs like *Educate to Innovate*, launched in 2009, aimed to improve STEM literacy among students and prepare them for an increasingly technology-driven labour market (Ahmed, 2016; Atkinson & Mayo, 2010). STEM education emerged as a learning paradigm integrating the four key disciplines—science, technology, engineering, and mathematics—into interconnected, project-based learning approaches (Felder, 2021). Governments and educational institutions began incorporating this approach into curricula through project-based learning, robotics competitions, and using digital technologies in classrooms (Pou et al., 2022).

The STEM concept later evolved into STEAM with the addition of the arts component, emphasizing the importance of creativity, design, and innovative thinking in learning (Boy, 2013). This evolution from STEM to STEAM marked a paradigmatic shift in understanding interdisciplinarity and the role of creativity in developing competencies in science and technology (Psycharis, 2017). Integrating arts into STEM enriches students' learning experiences and fosters critical thinking, creativity, and problem-solving skills (Shelley & Kiray, 2018). STEAM, which stands for Science, Technology, Engineering, Arts, and Mathematics, was developed as an approach as early as 2006 but was first formally introduced in 2010 (Yakman, 2010). Its implementation also enables students to develop creativity and emotional connections to learning. Digital art projects, technology-based cultural exhibitions, and cross-disciplinary collaboration are practical examples of STEAM implementation in schools (Leavy et al., 2023; Wu, 2023).

Technological advancement and artificial intelligence have brought new dimensions to STEAM education. According to a comprehensive study (Birt & Cowling, 2017), immersive technologies like virtual reality (VR) and augmented reality (AR) in STEAM learning enhance student engagement, critical thinking, and problem-solving skills, aligning with the needs of a new generation of learners. Additionally, Henriksen (2017) notes that integrating the arts in STEAM improves design thinking skills, fostering creative problem-solving capabilities.

Implementing STEM and STEAM education presents benefits and challenges, particularly in developing countries. Technology access gaps, inadequate teacher training, and insufficient infrastructure are significant barriers (Bati & Workneh, 2021). For instance, rural areas with limited access to modern educational resources often restrict students' opportunities to engage in STEM and STEAM learning. Thus, policy support, infrastructure improvement, and teacher training programs are crucial elements for successful implementation. In alignment with this, a UNESCO report (2023) shows a positive correlation between education budget allocation and learning quality improvement. Countries that prioritize significant portions of their budgets for education, including STEAM development, exhibit improvements in national innovation indexes.

Given the importance of STEM and STEAM in shaping the future of education and the workforce, a comprehensive understanding of research developments in these fields is highly relevant, especially in education (Belbase et al., 2022; Jafarov & Nadirsoy, 2024). Bibliometric analysis can provide valuable insights into how these fields have evolved, areas that have received significant attention, and gaps that require further research. Furthermore, the findings from this study are expected to offer valuable perspectives for educators, policymakers, and researchers regarding the utilization of STEM and STEAM in education. These insights could have significant implications for curriculum reform, teacher professional development, and the design of learning environments that prepare students to face future challenges.

2. Method

This study employs a bibliometric method to generate quantitative data on Science, Technology, Engineering, and Mathematics (STEM) and Science, Technology, Engineering, Arts, and Mathematics (STEAM). Bibliometrics is a field of research that utilizes quantitative and statistical methods to analyze and measure information in scientific publications and other sources (Chen et al., 2018; Donthu et al., 2021).

The protocol used is based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which comprises four stages: identification, screening, eligibility, and inclusion (Moher et al., 2009). Data collection begins with identification, screening, eligibility, and inclusion (Hajjaji et al., 2021). Identification involves inputting keywords relevant to the research theme. Researchers used keywords such as “STEM education,” “STEM learning,” “STEM approach,” “STEM integration,” “Science Technology, Engineering Mathematics,” and “STEM implementation” in the Scopus database alongside corresponding keywords for STEAM. This initial search yielded 1,292 publications for STEAM and 9,881 for STEM.

Next, the data were checked for duplicates, revealing 59 duplicate entries. As a result, 11,114 publications were carried forward to the next stage. The screening process then selected publications from the first stage based on the following criteria: (1) publications in the form of articles or conference papers; (2) publications in English; (3) publications in the field of mathematics education; and (4) publications from the period 2014–2025. After this screening process, 10,103 articles were excluded, leaving 151 STEAM-related and 919 STEM-related publications that met the criteria for the subsequent eligibility phase.

In the eligibility phase, 550 of the 1,070 publications from the previous stage met the inclusion criteria. To qualify for inclusion, the titles and abstracts of these publications had to contain terms related to STEM Education or STEAM Education explicitly. Figure 1 illustrates the data collection process and its stages.

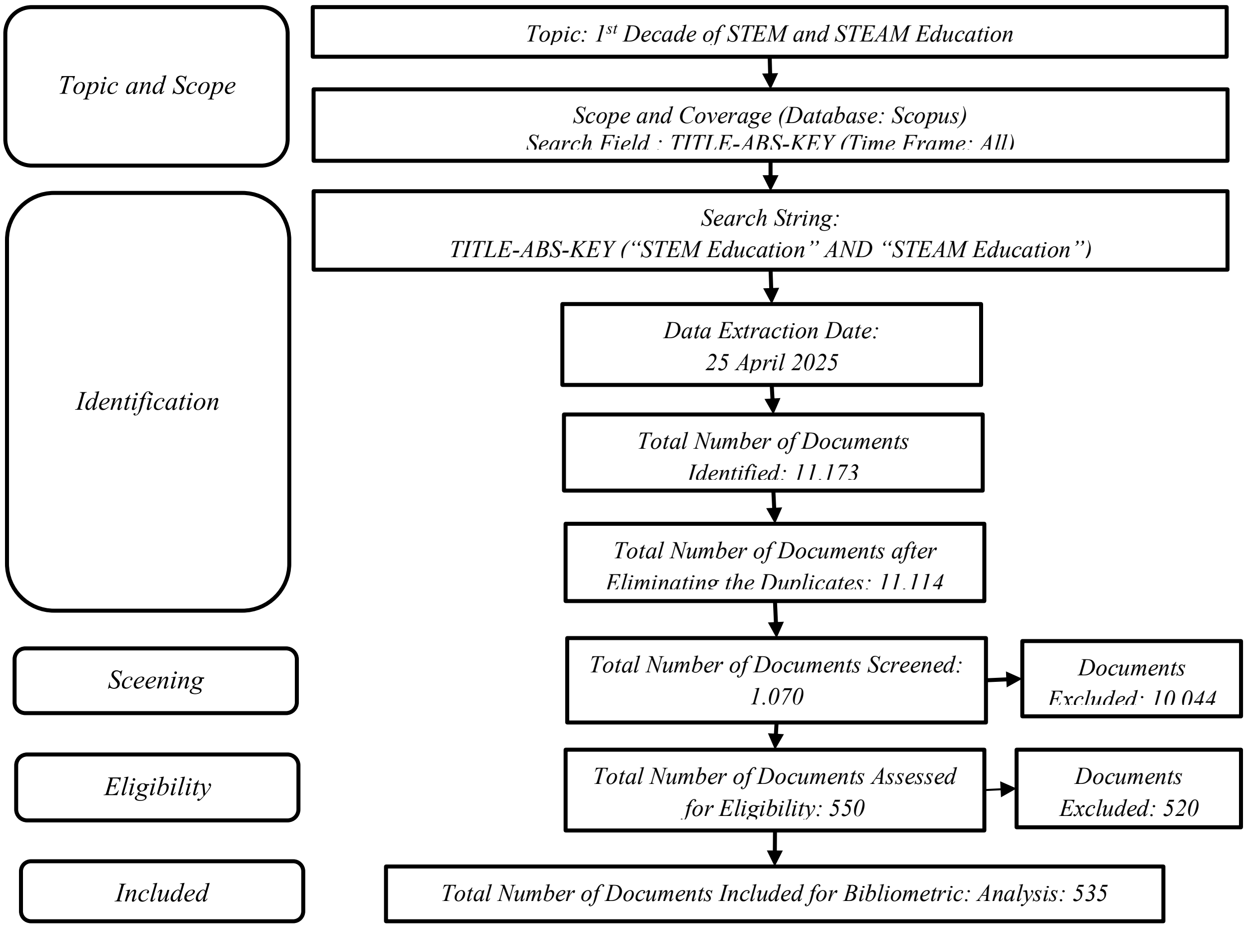

Figure 1. PRISMA flowchart of this writing

This study employs three bibliometric analysis tools: Ms. Excel, VOSviewer, and RStudio. RStudio is widely used to process bibliographic data from the available datasets. VOSviewer is utilized to create and visualize bibliometric networks, such as identifying recent research trends and analyzing the most frequently cited references within a specific theme (El Bied et al., 2024; van Eck & Waltman, 2019). Additionally, VOSviewer is used for bibliographic coupling. Ms. Excel complements the screening and visualization processes, particularly for tasks that are challenging to perform in RStudio and VOSviewer.

3. Results and Discussion

Table 1 provides an overview of the data collected, comprising 535 articles published over the last decade. This includes 262 journal articles with an average of 3.01 citations annually and 9,234 per document annually. Additionally, 1,503 keywords were identified from the analyzed data.

Figure 2 visualizes the annual distribution of the 535 articles published between 2014 and April 2025. The compound annual growth rate (CAGR) is 196.7%, indicating that STEM and STEAM have become increasingly popular research topics since 2016.

3.1 Analysis of Authors, Affiliations, and Influential Countries

The growth of articles in this field or topic is linked to authors, sources, and affiliations. Figure 3 represents the most relevant authors in this area. Huang is the most influential researcher, with nine published articles, followed by Lee and Ruangsiri, each with four articles. The top ten authors have published at least three articles each.

Figure 4 presents nine out of the top ten affiliations located in Asia. This prominence may be attributed to the progressive integration of educational technology in Asian institutions, where the latest educational technologies are being adopted and integrated into curricula to create modern and effective learning environments. Universitas Sebelas Maret is the only Indonesian university in the top ten affiliations contributing to this topic. Figure 5 shows that approximately 81 (15.1%) published article authors are affiliated with institutions in the USA.

Based on the visualization of Bradford's Law in Figure 6, three core journals are highly productive: Eurasia Journal of Mathematics, Lecture Notes in Computer, and International Journal of. These journals, represented by the grey block area in the graph, have produced approximately 40–70 articles each, with Eurasia Journal of Mathematics being the most productive. The graph exhibits a classic Bradford distribution, with a steep decline following the three core journals, succeeded by a long tail of numerous journals with low productivity. This highly concentrated distribution indicates that most literature in this research area is clustered within these three core journals. Therefore, focusing on these journals is an efficient approach to obtaining comprehensive coverage of the literature. This aligns with Bradford's Law, which describes the uneven distribution of scientific literature, where a few journals produce a significant proportion of total publications in a given field.

Table 1. Summary of the Review (Main Information)

Description	Results
Main Information About Data	
Timespan	2014:2025
Sources (Journals, Books, Etc)	121
Documents	535
Annual Growth Rate %	34.7
Document Average Age	3.01
Average Citations Per Doc	9.243
References	17702
Document Contents	
Keywords Plus (Id)	2043
Author's Keywords (De)	1503
Authors	
Authors	1722
Authors Of Single-Authored Docs	53
Authors Collaboration	
Single-Authored Docs	55
Co-Authors Per Doc	3.54
International Co-Authorships %	17.2
Document Types	
Article	262
Conference Paper	273

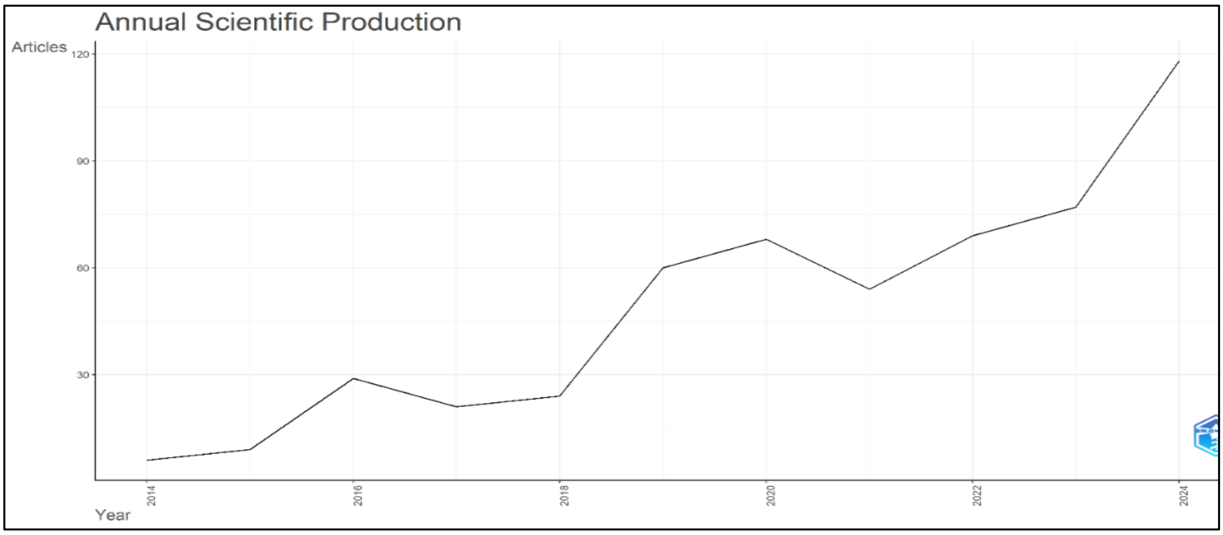

Figure 2. Document growth by year

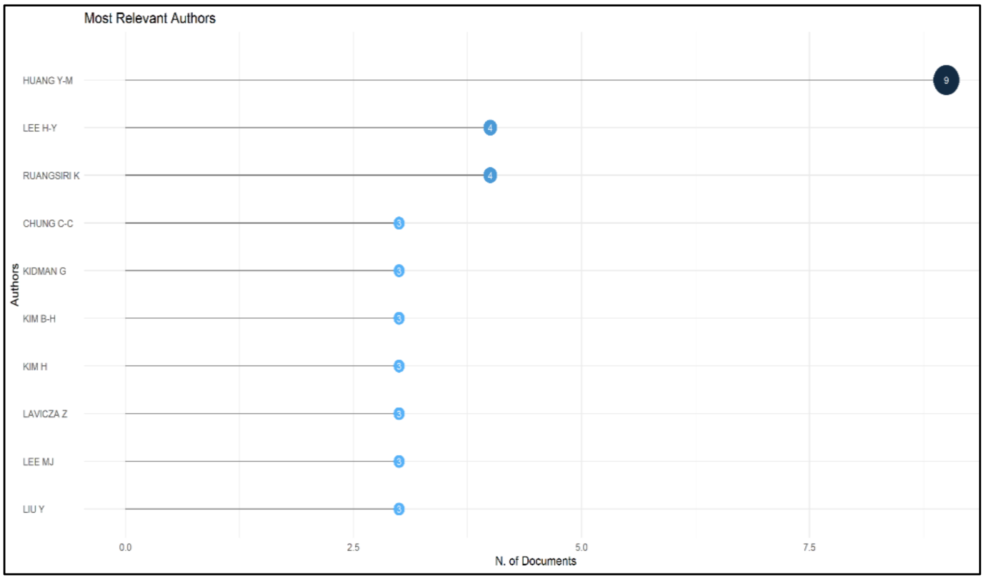

Figure 3. Most relevant authors in STEM and STEAM literatur

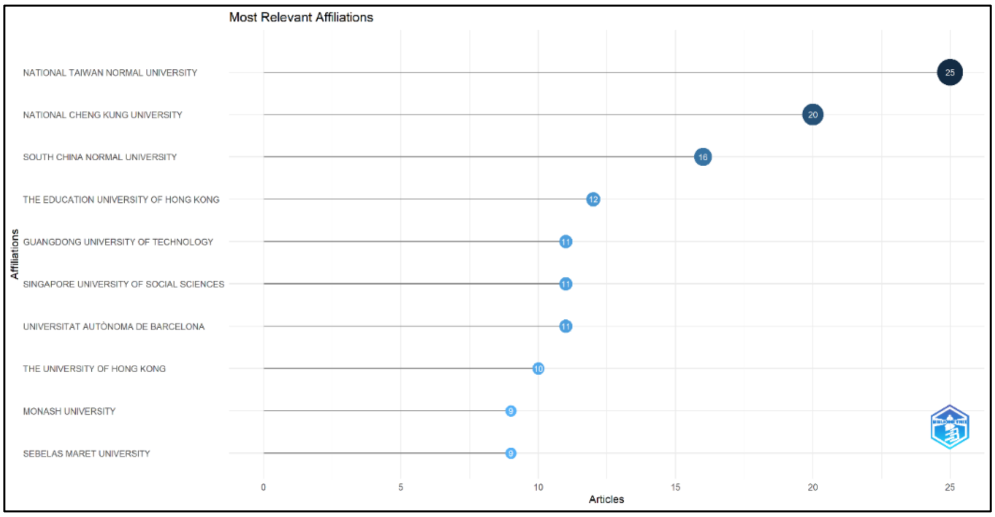

Figure 4. Most relative affiliations

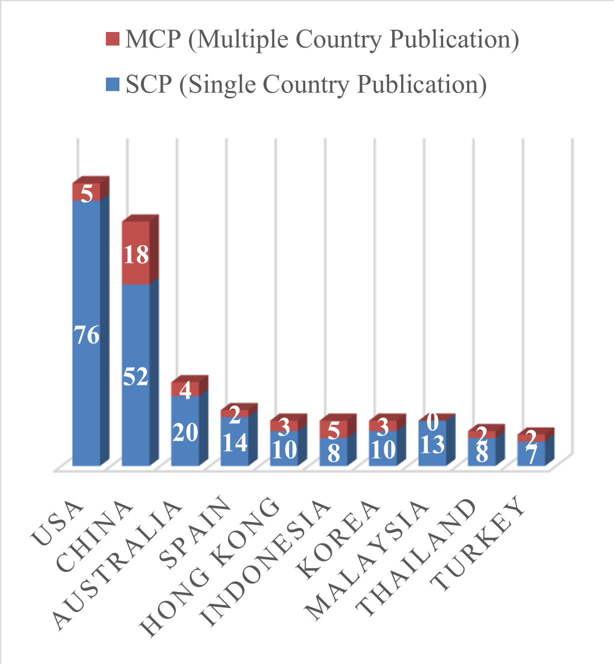

Figure 5. Most relevant countries

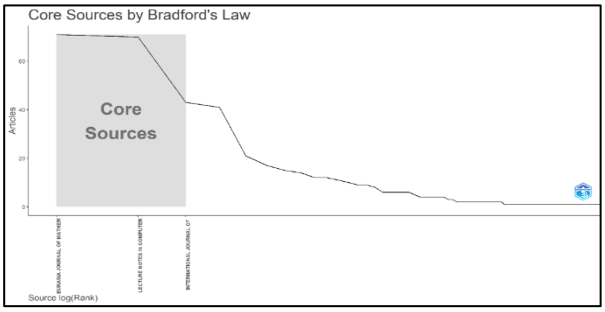

Figure 6. Bradford's Law

3.2 Citation Analysis

Citation analysis identifies relationships between documents. This stage provides citation analysis based on documents, references, sources, and the impact of sources and authors. Table 2 presents the most frequently cited articles in STEM and STEAM literature. Regarding citation analysis, Table 3 discusses the most frequently cited local references and their citation counts. Tables 4 and 5 represent authors and sources in the form of journals, respectively, highlighting their impact on STEM and STEAM literature.

This study does not identify a reference that significantly dominates most available literature, except for the reference by Bybee R.W., titled *The Case for STEM Education: Challenges and Opportunities*, published in 2013. Table 4 also does not indicate any author with a substantial impact on the STEM and STEAM literature body.

Regarding the impact of literature sources, *Eurasia: Journal of Mathematics, Science, and Technology Education* emerges as this topic's most relevant journal source.

Table 2. Top ten citied global documents

Paper	DOI	Total Citations	TC per Year	Normalized TC
Sintema Ej, 2020, Eurasia J Math Sci Technol Education	10.29333/EJMSTE/7893	308	61.6	28.1505376
English Ld, 2017, Int J Sci Math Education	10.1007/s10763-017-9802-x	213	26.625	7.46744574
Eguchi A, 2016, Rob Autom System	10.1016/j.robot.2015.05.013	164	18.2222222	6.47956403
Maass K, 2019, Zdm Math Education	10.1007/s11858-019-01100-5	148	24.6666667	9.83388704
Shahali Ehm, 2017, Eurasia J Math Sci Technol Education	10.12973/eurasia.2017.00667a	141	17.625	4.94323873
Park H, 2016, Eurasia J Math Sci Technol Education	10.12973/eurasia.2016.1531a	116	12.8888889	4.58310627
Holmes K, 2018, Int J Sci Math Education	10.1007/s10763-016-9793-z	113	16.1428571	4.55798319
Toma Rb, 2018, Eurasia J Math Sci Technol Education	10.29333/ejmste/83676	107	15.2857143	4.31596639
Han S, 2015, Eurasia J Math Sci Technol Education	10.12973/eurasia.2015.1306a	102	10.2	5.27586207
Rinke Cr, 2016, Sch Sci Mathhematics	10.1111/ssm.12185	89	9.88888889	3.51634877

Table 3. Top ten most locally citied references

Cited References	Citations
Bybee R.W., The Case For Stem Education: Challenges And Opportunities, (2013)	27
Next Generation Science Standards: For States, By States, (2013)	24
A Framework For K-12 Science Education: Practices, Crosscutting Concepts, And Core Ideas, (2012)	22
Stem Integration In K-12 Education: Status, Prospects, And An Agenda For Research, (2014)	20
Successful K-12 Stem Education: Identifying Effective Approaches In Science, Technology, Engineering, And Mathematics, (2011)	16
Breiner J.M., Harkness S.S., Johnson C.C., Koehler C.M., What Is Stem? A Discussion About Conceptions Of Stem In Education And Partnerships, School Science And Mathematics, 112, 1, Pp. 3-11, (2012)	14
Honey M., Pearson G., Schweingruber H., Stem Integration In K-12 Education: Status, Prospects, And An Agenda For Research, (2014)	13
Lave J., Wenger E., Situated Learning: Legitimate Peripheral Participation, (1991)	11
Cohen J., Statistical Power Analysis For The Behavioral Sciences, (1988)	10
Common Core State Standards For Mathematics, (2010)	9

Table 4. Authors' impact

Author	H_index	G_index	M_index	TC	NP	PY_start
Lee Mj	3	3	0.5	46	3	2019
Maiorca C	3	3	0.6	94	3	2020
Nersesian E	3	3	0.5	46	3	2019
Roberts T	3	3	0.6	79	3	2020
Saat Rm	3	3	0.27272727	78	3	2014
Spryszynski A	3	3	0.5	46	3	2019
Abdinejad M	2	2	0.5	14	2	2021
Ahmad Nj	2	2	0.4	12	2	2020
Albarracín L	2	2	0.33333333	27	2	2019
Almukhambetova A	2	2	1	29	2	2023

H-index = an author has an h-index of 'h' when they have h papers that have been cited h times at least, G-Index = is where the top G articles have together received G citations, M-index = is the H-index divided by the number of years that an author has been active, Tc = Total Citation, Np = Number of papers, Py_Start = publication year start

3.3 Network Analysis

3.3.1 Bibliographic Coupling

Citation mapping of 535 articles was conducted using the bibliographic coupling technique in VOSviewer software. VOSviewer allows three types of bibliographic coupling analyses: journals, publications, and authors. Based on van Eck and Waltman (2019), this study designated the analysis unit as "documents" and employed the "fractional analysis" method for bibliographic coupling.

According to Perianes-Rodriguez et al. (2016), in fractional analysis, each reference cited in a publication is assigned equal influence in bibliographic coupling analysis, as each reference is considered equally representative of the respective publication.

In this study, the minimum citation threshold for an article was set at 5, and the minimum clustering threshold was set at 25 to enable a more comprehensive identification process. This analysis identified 166 out of 535 articles as influential to the topic.

Table 5. Sources' impact

Source	h_index	g_index	m_index	TC	NP	PY_start
Eurasia Journal Of Mathematics, Science And Technology Education	21	40	1.909	1720	71	2014
International Journal Of Science And Mathematics Education	18	31	2.25	1027	43	2017
School Science And Mathematics	10	17	1.111	307	21	2016
Lecture Notes In Computer Science (Including Subseries Lecture Notes In Artificial Intelligence And Lecture Notes In Bioinformatics)	8	10	0.727	180	70	2014
Zdm - Mathematics Education	7	17	1.167	320	17	2019

Source	h_index	g_index	m_index	TC	NP	PY_start
International Journal Of Education In Mathematics, Science And Technology	6	11	0.857	129	11	2018
Mathematics	6	9	1.2	111	15	2020
Communications In Computer And Information Science	4	7	0.4	69	41	2015
Isec 2016 - Proceedings Of The 6th Ieee Integrated Stem Education Conference	4	6	0.444	46	12	2016
Isec 2017 - Proceedings Of The 7th Ieee Integrated Stem Education Conference	4	6	0.5	47	6	2017

Note: H-index = an author has an h-index of 'h' when they have h papers that have been cited h times at least, G-Index = is where the top G articles have together received G citations, M-index = is the H-index divided by the number of years that an author has been active, Tc = Total Citation, Np = Number of papers, Py_Start = publication year start

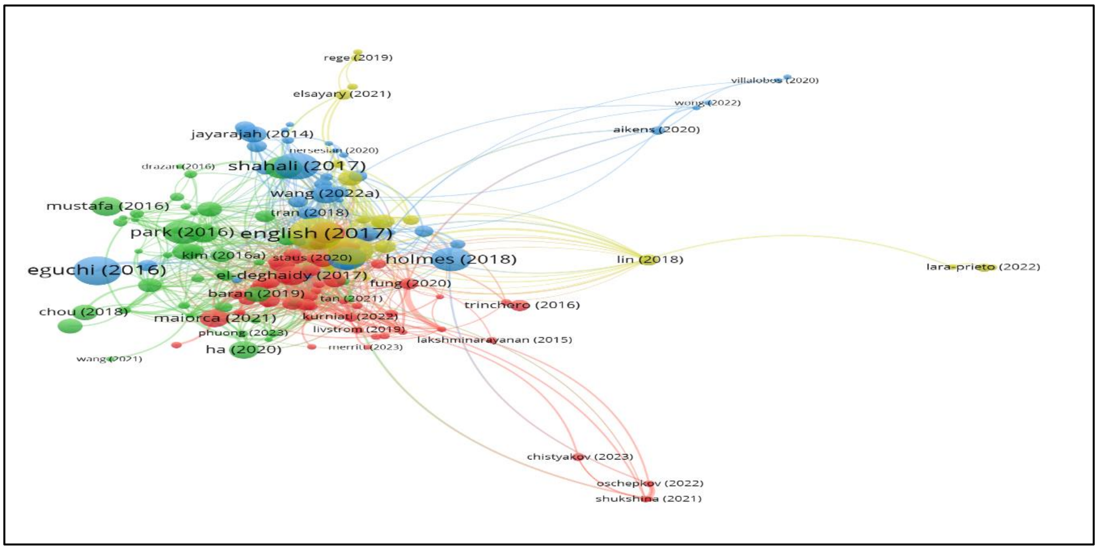

Figure 7. Bibliographic coupling of 535 STEM and STEAM Education articles

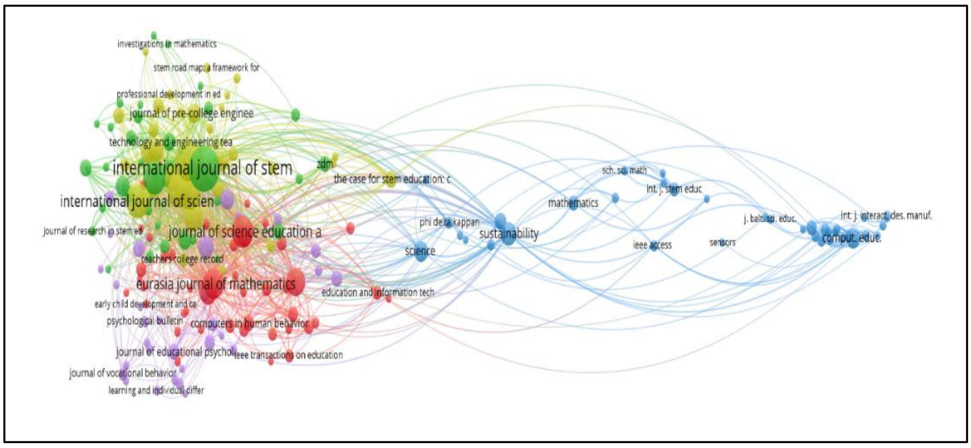

Figure 8. Co-citation of jurnals

Figure 7 provides a visual interpretation of the bibliographic coupling analysis generated using VOSviewer, identifying four clusters: "Cluster 1" (red) comprises 57 articles; "Cluster 2" (green) includes 45 articles; "Cluster 3" (blue) contains 39 articles; and "Cluster 4" (yellow) consists of 25 articles.

3.3.2 Co-Citation Analysis

In the next stage, a co-citation analysis was conducted using document sources to visualize the network among journals publishing articles related to STEM and STEAM. Co-citation analysis illustrates the relationships or interconnections between articles and research topics (Kim & McMillan, 2008). The coloured networks in Figure 8 represent these connections.

In this study, the minimum citation threshold for an article was set at 10, resulting in 182 articles distributed across five clusters. The visualization in Figure 8 also facilitates exploring relationships among the journals. Generally, journals nearby exhibit more substantial connections, while the lines indicate stronger co-citation relationships.

3.3.3 Co-Authorship Analysis

Figure 9 represents the results of the co-authorship analysis using authors as the unit of analysis. The same parameters were applied when using countries as the unit of analysis, resulting in 16 articles distributed across three clusters.

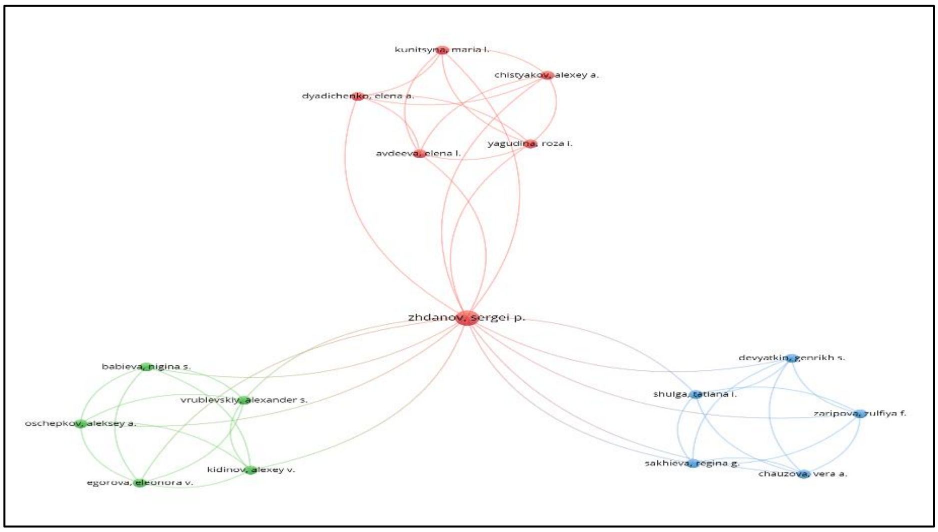

Figure 9. Co-authorship by author

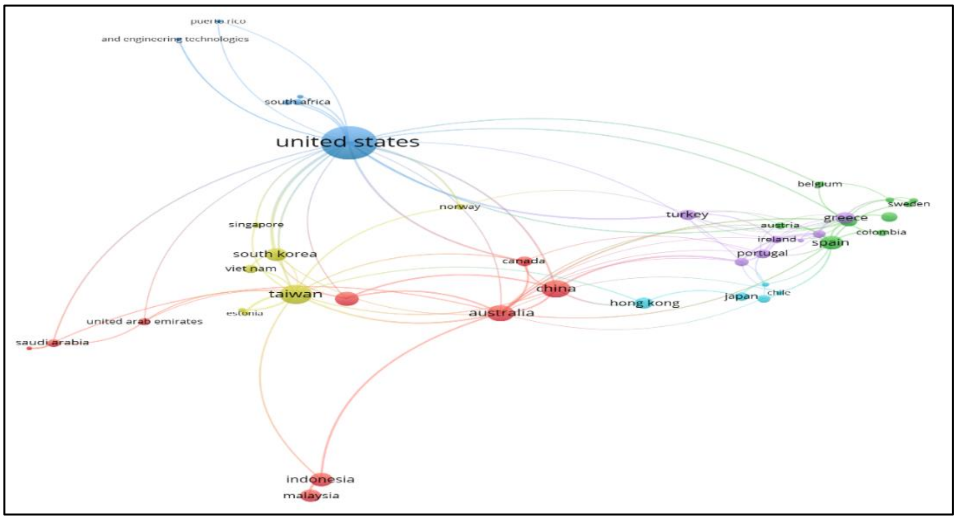

Figure 10. Co-authorship by countries

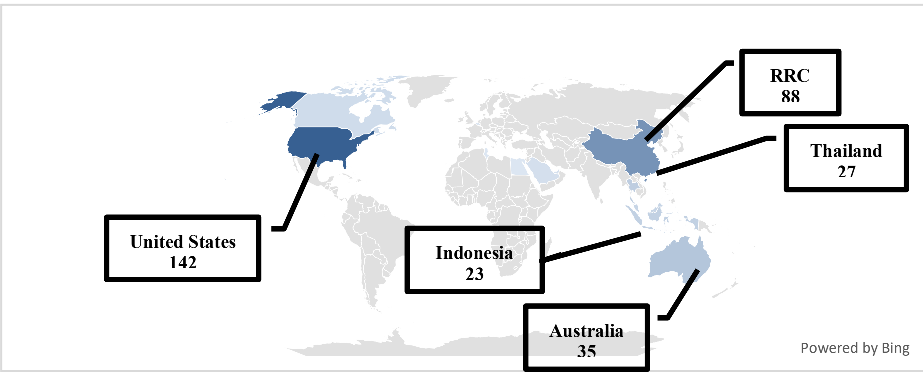

Figure 11. Geographical Distribution

The next step involves further exploration by analyzing co-authorship using fractional counting. The purpose of fractional counting is to minimize the influence of articles with multiple authors. In this research, co-authorship analysis was also conducted using countries as units of analysis. The minimum number of documents from a country and the minimum number of citations for an article were set to 1, and the minimum clustering was set to 5 to enable more comprehensive identification. The parameters used resulted in 46 articles grouped into six clusters, as visualized in Figure 10.

Figure 10 illustrates the collaborative network between countries in the context of STEM and STEAM Education research. The United States demonstrates numerous connections with other countries, with precisely 25 connections. This phenomenon indicates that the United States excels in the number of publications and shows a significant level of collaboration compared to other countries.

The collection of publications encompasses contributions from 42 distinct countries. Figure 11 demonstrates that the United States primarily produces publications, with 142 documents specifically addressing STEM and STEAM Education topics. In comparison, the Republic of China ranks second with 88 publications. The data reveals publication contributions across continents, highlighting global engagement in this topic. Specifically, the continents of Asia and America dominate with 346 publications, accounting for approximately 65% of all documents related to STEM and STEAM Education.

3.3.4 Cartography Analysis

In this research, a cartography analysis was conducted to categorize research themes based on the keywords from the articles. Figure 12 presents the visual results of the cartography analysis using VOSviewer. Co-occurrence was selected as the analysis method, and all keywords were chosen as the unit of analysis. The minimum occurrence threshold for a keyword was set to 10, and the minimum clustering was set to 5 to enable more comprehensive identification. From this analysis, 49 articles were grouped into four main clusters. These four clusters are represented in “red”, “blue”, “yellow”, and “green” colours.

Table 6 below presents the keywords, number of occurrences, and the link strength. The link strength measures the power of the connection between items. The three most frequently occurring keywords are STEM Education, STEM, and Students. Using the co-occurrence method, the cartography analysis enables us to finalize the clusters and identify the key themes of the most frequently published STEM or STEAM Education articles. The first cluster relates to expanded skills with various subthemes. However, the most general theme is associated with STEAM Education, focusing on developing students' skills. The second cluster identifies the divisibility of themes generally related to educational approaches. In the third cluster, articles are grouped based on using STEM Education in various fields. Finally, the fourth cluster focuses on implementation in learning, using media or learning approaches and methods that can encourage the optimal application of STEM and STEAM.

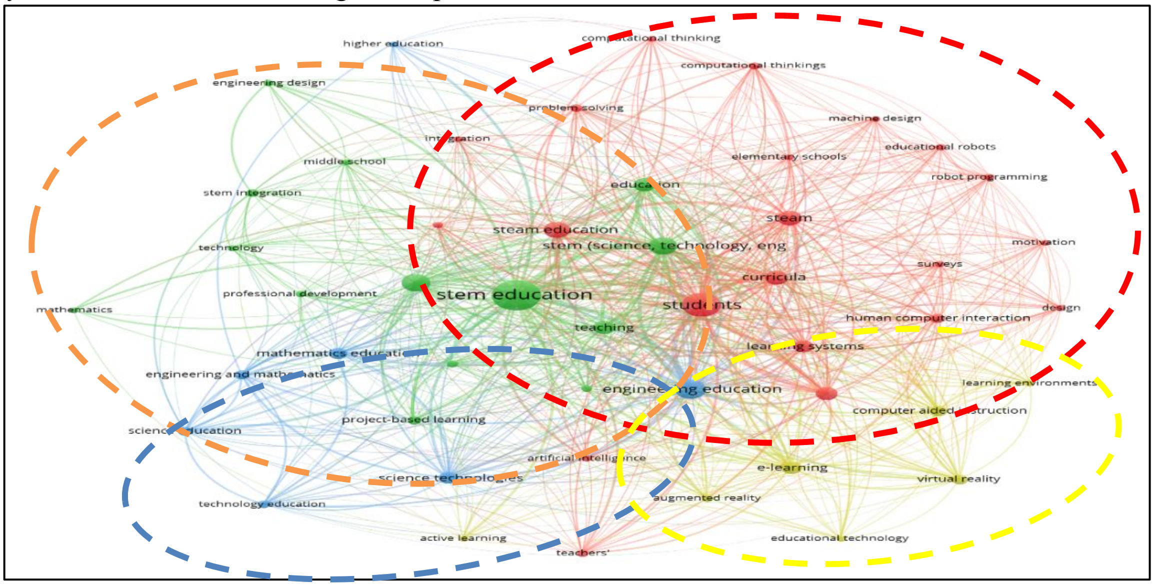

Figure 12. Keyword co-occurrence

Table 6. Keywords and the number of occurrences along with the link strength

No	Keyword	Occurrences	Total link strength
Cluster 1 (red): Skills'			
1	Computational thinking*	27	26
2	Problem Solving	18	17
3	Motivation	10	10
4	Robot Programming	14	14
Cluster 2 (green): Education Approaches			
1	Education	55	55
2	Engineering design	12	11
3	Mathematics	10	8
4	Technology	11	11
5	Middle School	10	9
6	Teaching and Learning	12	12
Cluster 3 (blue): STEM Education			
1	Engineering and Mathematics	25	25
2	Engineering Education	105	105
3	Higher Education	10	9
4	Mathematics Education	38	37
5	Science Education	28	27
6	Science Technologies	43	43
7	Technology Education	19	19
Cluster 4 (yellow): Immersive Learning Tools			
1	Augmented Reality	10	10
2	E-learning	48	48
3	Virtual Reality	30	30
4	Computer Aided Instruction	35	35

3.4 Content Analysis based on Research Streams

3.4.1 Cluster 1: Skills'

STEM and STEAM education has become essential in developing 21st-century skills relevant to modern society's needs. In the first decade of implementation, this educational approach has successfully enhanced skills such as computational thinking, problem solving, motivation, creativity, and collaboration through technology-based approaches and pedagogical innovations.

In the context of computational thinking, Barana et al. (2020) highlight using animated graphics to support students' understanding of STEM concepts, particularly in enhancing analytical and systematic thinking skills. This technology enables students to comprehend algorithmic flow through intuitive visual means. Additionally, Eguchi (2014), through the RoboCupJunior robotics competition, demonstrates how robotics-based technology can serve as an engaging learning medium where students learn programming logic while developing technology-based solutions.

Creativity is a key aspect of STEAM education, which integrates arts to foster innovative solutions to real-world problems. Hattori et al. (2024) developed a creativity-based methodology that enables students to explore flexible project design. O'Byrne et al. (2018) emphasize the importance of creating learning spaces that support divergent thinking. This research indicates that creativity is not merely an additional element but the core of holistic learning. However, its implementation still faces challenges, such as insufficient specialized educator training.

Problem-solving has also received substantial attention as a core skill in STEM education. Evans et al. (2021) describe how non-routine mathematical problem-solving can enhance student creativity, while Fung et al. (2022) utilize project-based learning to promote effective collaboration and communication. This research underscores the importance of interdisciplinary approaches in addressing complex challenges, particularly in 21st-century education.

On the other hand, student motivation has also become a primary topic in STEM and STEAM education. Alali and Wardat (2024) found that flipped classrooms can significantly increase student engagement, particularly in complex STEM subjects. Chou and Shih (2020) demonstrate how 3D-based digital design can enhance students' spatial visualization skills while strengthening their confidence in solving technology-based problems.

Over this decade, STEM and STEAM education has demonstrated the effectiveness of technology-based approaches, such as robotics, augmented reality, and digital games, in building student skills. However, despite promising results, further research is needed to bridge educational access gaps and ensure these methods are adopted across various contexts. STEM and STEAM education aims to enhance technical skills and shape students as holistic learners prepared to face the Fourth Industrial Revolution.

3.4.2 Cluster 2: Education Approaches

STEAM education, particularly STEM, has demonstrated significant potential in preparing students to face 21st-century challenges. This educational approach builds knowledge by integrating elements such as education, engineering design, mathematics, technology, middle school instruction, and teaching and learning methodologies. It develops skills relevant to modern world requirements. However, to ensure its sustainability and effectiveness, greater attention must be directed toward teacher training, inclusive curriculum development, and enhanced technological accessibility across various educational contexts. Antunes and Trigo (2024) emphasize the importance of technology integration in STEM learning, utilizing digital simulations and practical experiments to increase student engagement. This approach helps students connect theory with real-world applications, strengthening their analytical and problem-solving capabilities.

In the educational aspect, cross-disciplinary education has emerged as a crucial element. Nugraha et al. (2024) emphasize that integrating various disciplines enables students to solve complex problems innovatively. Through this approach, students develop a deeper understanding of scientific principles and the ability to recognize interdisciplinary connections in addressing real-world challenges. Furthermore, through the connection between theory and practice, as Shahali et al. (2017) discussed, design-based projects provide students with direct experience in applying engineering concepts to real situations. These projects enhance analytical skills and foster student creativity in finding innovative solutions to industrial challenges.

The mathematics component in STEM has also become a primary focus. Khalil et al. (2024) highlight teachers' challenges in teaching mathematics, particularly within the STEM context. This research found that project-based learning methods can enhance students' understanding of complex mathematical concepts, especially in practical applications related to technology and science. Beyond mathematics, the role of technology is inseparable from STEM education transformation, particularly during the COVID-19 pandemic. Accordingly, Alangari (2022) argues that online learning accelerated technology adoption in education, although challenges such as access disparities and technological infrastructure readiness remain obstacles. Technology has proven to support student engagement in STEM learning, though further strategies are needed to ensure its sustainability and inclusivity.

At the Middle School level, Martínez et al. (2024) highlight the success of project-based approaches in building critical thinking skills and student collaboration from an early age. These projects enable students to learn in more engaging and applicable ways, providing a strong foundation for STEM learning at higher levels. Furthermore, in the teaching and learning aspect, teacher training and developing relevant teaching strategies become key to STEM education success. Wahyuni et al. (2024) explain the importance of balance in STEM teaching approaches, emphasizing that teachers must be supported with adequate resources and training to create interactive and practical learning environments. This is crucial to ensure that STEM learning focuses on content and holistic student skill development.

3.4.3 Cluster 3: STEM Education

The STEM education cluster focuses on developing skills and literacy relevant to the modern era, emphasizing innovative cross-disciplinary approaches. Nguyen et al. (2024) explain the potential of board games as transformative tools in STEM learning, which can enhance student engagement and facilitate understanding of fundamental STEM concepts. Furthermore, Revák et al. (2024) provide insights into systematic STEM teaching methods and activities for early childhood education, offering practical guidance for educators in creating interactive learning environments.

Regarding data literacy and critical thinking, Schreiter et al. (2024) highlight the importance of data-driven STEM learning in K-12 education. This research demonstrates that teacher variables and their educational background significantly influence the success of statistical literacy instruction in STEM education. Meanwhile, Ariza and Olatunde-Aiyedun (2024) contribute to the discussion with their analysis of pre-service and in-service teacher readiness to support sustainable STEAM education, emphasizing the need for relevant and continuous professional development.

Additionally, Ortiz-Laso et al. (2023) complement the discussion by exploring how STEAM projects can support teachers' professional growth by exploiting mathematical competencies. This indicates that project-based learning can enhance teachers' skills holistically and sustainably. These studies demonstrate that STEM Education is a highly effective approach to preparing students for global challenges. Using innovative tools such as board games, data-driven learning, and socially-based projects, STEM education can create relevant, engaging, and transformative learning environments across all educational levels.

3.4.4 Cluster 4: Immersive Learning Tools

Immersive Learning Tools, including Augmented Reality (AR), Virtual Reality (VR), and E-Learning platforms, have significantly transformed STEM and STEAM education. These technologies provide interactive learning experiences, enabling students to comprehend complex concepts through realistic simulations. For instance, VR has been utilized to visualize data in 3D coordinate systems, substantially assisting students in understanding spatial and geometric concepts.

Gamification, Artificial Intelligence (AI), and Virtual Reality (VR) have emerged as primary elements in STEM education innovation. Moral-Sánchez et al. (2022) demonstrate that gamification, through elements such as challenges and rewards, can enhance student motivation while strengthening their engagement in learning. Through an enjoyable and relevant approach, gamification helps students understand abstract concepts such as geometry and bridges the gap between theory and practical applications. The potential of gamification lies in its ability to integrate gaming elements with real-world contexts, making STEM learning more engaging and meaningful.

Meanwhile, Zhao (2024) highlights the role of Artificial Intelligence (AI) in creating personalized and adaptive learning experiences. AI analyzes student data in real time to adjust learning materials according to individual needs, enhancing learning effectiveness. Through integration with technologies such as Augmented Reality (AR) and Virtual Reality (VR), AI expands learning potential to become more interactive and inclusive. However, AI implementation still faces significant challenges, such as data privacy and technological infrastructure requirements, necessitating further attention to support its widespread adoption.

Research conducted by Smith et al. (2023) explores the use of smartphone-based Virtual Reality (VR) as an affordable STEM learning tool. This technology helps students visualize mathematical concepts such as three-dimensional coordinate systems in an accessible and effective manner. By utilizing readily available devices such as smartphones, VR offers significant opportunities to enhance the accessibility of advanced technology across various educational environments. This approach strengthens students' understanding of the subject matter and increases their engagement in the learning process.

Overall, Immersive Learning Tools present substantial potential for enhancing STEM education. These technologies can create more inclusive, personalized, and effective learning experiences with proper development and collaborative solutions to address cost and infrastructure constraints.

4. Conclusions

STEM and STEAM approaches have significantly contributed to education by focusing on developing 21st-century skills, such as creativity, critical thinking, and problem-solving abilities. Technologies like AR and VR have demonstrated their capacity to enhance student engagement in learning, strengthen their conceptual understanding, and enable more innovative teaching approaches. Nevertheless, implementing this educational framework faces challenges, particularly in developing countries, which encounter obstacles in accessing technology and providing adequate teacher training.

The geographical distribution indicates that the United States and Asia dominate contributions to STEM and STEAM-related publications. The United States exerts substantial influence in document volume and international collaboration, while China holds the second position in publication quantity. In Indonesia, Sebelas Maret University has emerged as one of the leading institutions in this research, reflecting national contribution to global discourse. Furthermore, bibliometric analysis reveals that core journals such as the Eurasia Journal of Mathematics, Science and Technology Education have become this field's most productive and relevant literature sources.

Implementing STEM and STEAM has also expanded the scope of project-based learning, positively connecting theory with practice. Using immersive learning tools, such as gamification and AI, presents significant opportunities to enhance educational accessibility and effectiveness, particularly in resource-constrained regions. This research provides educators, policymakers, and researchers with relevant insights to redesign curricula that support educational transformation in the Fourth Industrial Revolution era.

Greater investment in technological infrastructure and teacher training is essential to enhancing the effectiveness of STEM and STEAM education, particularly in developing nations. Governments and educational institutions are expected to provide sustainable policy support to expand technology access, enhance teacher capacity, and promote project-based curriculum development. Furthermore, cross-national and interdisciplinary collaboration must be strengthened to ensure more inclusive and relevant adoption of educational technology.

Recommendations for future research suggest exploring emerging themes, such as the application of AI for adaptive learning, the integration of sustainability in STEM education, and interdisciplinary approaches addressing global issues. Moreover, collaboration among educational sectors, industry, and the government is crucial for creating an innovative educational ecosystem responsive to labour market demands. Further research is necessary to address access disparities and ensure equitable implementation of STEM and STEAM approaches worldwide.

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References

Ahmed, H. O. K. (2016). *Strategic Future Directions for Developing STEM Education in Higher Education in Egypt as a Driver of Innovation Economy* (Vol. 7, Issue 8). Online. www.iiste.org

Alali, R., & Wardat, Y. (2024). Enhancing student motivation and achievement in science classrooms through STEM education. *STEM Education*, *4*(3), 183–198. https://doi.org/10.3934/steme.2024012

Alangari, T. S. (2022). Online STEM education during COVID-19 period: A systematic review of perceptions in higher education. *Eurasia Journal of Mathematics, Science and Technology Education*, *18*(5). https://doi.org/10.29333/ejmste/11986

Antunes, M., & Trigo, A. (2024). Scientific Whispers: Mapping Innovative Pedagogies in STEAM and Programming Education. *OpenAccess Series in Informatics*, *122*. https://doi.org/10.4230/OASIcs.ICPEC.2024.8

Ariza, J. Á., & Olatunde-Aiyedun, T. G. (2024). A systematic literature review on STEAM pre- and in-service teacher education for sustainability: Are teachers ready? *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(9). https://doi.org/10.29333/ejmste/14982

Atkinson, R. D., & Mayo, M. (2010). *Fresh Approaches to Science,Technology, Engineering and Mathematics (STEM) Education*. https://ssrn.com/abstract=1722822Electronicco pyavailableat:https://ssrn.com/abstract=172282 2

Barana, A., Conte, A., Fissore, C., Floris, F., Marchisio, M., & Sacchet, M. (2020). The Creation of Animated Graphs to Develop Computational Thinking and Support STEM Education. *Communications in Computer and Information Science*, *1125 CCIS*, 189–204. https://doi.org/10.1007/978-3-030-41258-6_14

Bati, T. B., & Workneh, A. W. (2021). Evaluating integrated use of information technologies in secondary schools of Ethiopia using design-reality gap analysis: A school-level study. *Electronic Journal of Information Systems in Developing Countries*, *87*(1). https://doi.org/10.1002/isd2.12148

Belbase, S., Mainali, B. R., Kasemsukpipat, W., Tairab, H., Gochoo, M., & Jarrah, A. (2022). At the dawn of science, technology, engineering, arts, and mathematics (STEAM) education: prospects, priorities, processes, and problems. *International Journal of Mathematical Education in Science and Technology*, *53*(11), 2919–2955. https://doi.org/10.1080/0020739X.2021.19229 43

Birt, J., & Cowling, M. (2017). Toward Future "Mixed Reality" Learning Spaces for STEAM Education. In *International Journal of Innovation in Science and Mathematics Education* (Vol. 25, Issue 4). www.oculusvr.com/

Bitar, N., & Davidovich, N. (2024). Transforming Pedagogy: The Digital Revolution in Higher

Education. *Education Sciences*, *14*(8). https://doi.org/10.3390/educsci14080811

Boy, G. A. (2013). From STEM to STEAM: Toward a human-centred education, creativity & learning thinking. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/2501907.2501934

Chen, X., Xie, H., Wang, F. L., Liu, Z., Xu, J., & Hao, T. (2018). A bibliometric analysis of natural language processing in medical research. *BMC Medical Informatics and Decision Making*, *18*. https://doi.org/10.1186/s12911-018-0594-x

Chou, P. N., & Shih, R. C. (2020). 3D Digital Design to Support Elementary School Students' Spatial Visualization Skills: A Preliminary Analysis. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *12555 LNCS*, 71–76. https://doi.org/10.1007/978-3-030-63885-6_8

Deák, C., & Kumar, B. (2024). A Systematic Review of STEAM Education's Role in Nurturing Digital Competencies for Sustainable Innovations. In *Education Sciences* (Vol. 14, Issue 3). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/educsci14030226

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Eguchi, A. (2014). Educational Robotics for Promoting 21st Century Skills. *Journal of Automation, Mobile Robotics and Intelligent Systems*, 5–11. https://doi.org/10.14313/jamris_1-2014/1

El Bied, S., Ros Mcdonnell, L., de-la-Fuente-Aragón, M. V., & Ros Mcdonnell, D. (2024). A Comprehensive Bibliometric Analysis of Real Estate Research Trends. *International Journal of Financial Studies*, *12*(3). https://doi.org/10.3390/ijfs12030095

Evans, T., Klymchuk, S., Murphy, P. E. L., Novak, J., Stephens, J., & Thomas, M. (2021). Non-routine mathematical problem-solving: creativity, engagement, and intuition of STEM tertiary students. *STEM Education*, *1*(4), 256–278. https://doi.org/10.3934/steme.2021017

Felder, R. M. (2021). STEM education: A tale of two paradigms. *Journal of Food Science Education*, *20*(1), 8–15. https://doi.org/10.1111/1541-4329.12219

Fung, C. H., Poon, K. K., & Ng, S. P. (2022). Fostering student teachers' 21st century skills by using flipped learning by teaching in STEM education. *Eurasia Journal of Mathematics, Science and Technology Education*, *18*(12). https://doi.org/10.29333/EJMSTE/12728

Hajjaji, Y., Boulila, W., Farah, I. R., Romdhani, I., & Hussain, A. (2021). Big data and IoT-based applications in smart environments: A systematic review. In *Computer Science Review* (Vol. 39). Elsevier Ireland Ltd. https://doi.org/10.1016/j.cosrev.2020.100318

Hattori, T., Hayashi, T., Hattori, M., Imai, Y., Ohno, A., & Tanaka, T. (2024). Methodology for Creativity Oriented STEM Education Based on ETT Theory. In *J:COM HorutoHall*.

Henriksen, D. (2017). Creating STEAM with Design Thinking: Beyond STEM and Arts Integration. *The STEAM Journal*, *3*(1), 1–11. https://doi.org/10.5642/steam.20170301.11

Jafarov, S., & Nadirsoy, F. (2024). The Essential Role of STEM in Shaping Future Workforce Leaders. *Pakistan Journal of Life and Social Sciences*, *22*(1), 6272–6281. https://doi.org/10.57239/PJLSS-2024-22.1.00463

Kang, N. H. (2019). A review of the effect of integrated STEM or STEAM (science, technology, engineering, arts, and mathematics) education in South Korea. In *Asia-Pacific Science Education* (Vol. 5, Issue 1, pp. 1–22). Brill Rodopi. https://doi.org/10.1186/s41029-019-0034-y

Khalil, I., Al Zahrani, A., Awaji, B., & Mohsen, M. (2024). Teachers' perceptions of teaching mathematics topics based on STEM educational philosophy: A sequential explanatory design. *STEM Education*, *4*(4), 421–444. https://doi.org/10.3934/steme.2024023

Kim, J., & McMillan, S. J. (2008). Evaluation of internet advertising research: A bibliometric analysis of citations from key sources. *Journal of Advertising*, *37*(1), 99–112. https://doi.org/10.2753/JOA0091-3367370108

Leavy, A., Dick, L., Meletiou-Mavrotheris, M., Paparistodemou, E., & Stylianou, E. (2023). The prevalence and use of emerging technologies in STEAM education: A systematic review of the literature. In *Journal of Computer Assisted Learning* (Vol. 39, Issue 4, pp. 1061–1082). John Wiley and Sons Inc. https://doi.org/10.1111/jcal.12806

Martínez, F. de J. R., Merchán, M. A. M., & Camacho-Tamayo, E. (2024). Teaching sequences based on the STEM approach for the development of inquiry in early childhood education: A systematic review. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(10). https://doi.org/10.29333/ejmste/15207

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P. C., … Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. In *PLoS Medicine* (Vol. 6, Issue 7). Public Library of Science. https://doi.org/10.1371/journal.pmed.1000097

Moral-Sánchez, S. N., Sánchez-Compaña, M. ª. T., & Romero, I. (2022). Geometry with a STEM and Gamification Approach: A Didactic Experience in Secondary Education. *Mathematics*, *10*(18). https://doi.org/10.3390/math10183252

Nguyen, T. T. K., Ngo, T. P. A., Pham, A. T., Nguyen, D. D., Cheng, P. H., & Nguyen, V. B. (2024). Let's play! Transforming STEM education with board games. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(8). https://doi.org/10.29333/ejmste/14920

Nugraha, M. G., Kidman, G., & Tan, H. (2024). Interdisciplinary STEM education foundational concepts: Implementation for knowledge creation. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(10). https://doi.org/10.29333/ejmste/15471

O'Byrne, W. I., Radakovic, N., Hunter-Doniger, T., Fox, M., Kern, R., & Parnell, S. (2018). Designing spaces for creativity and divergent thinking: Pre-service teachers creating stop motion animation on tablets. *International Journal of Education in Mathematics, Science and Technology*, *6*(2), 182–199. https://doi.org/10.18404/ijemst.408942

Oke, A., & Fernandes, F. A. P. (2020). Innovations in teaching and learning: Exploring the perceptions of the education sector on the 4th industrial revolution (4IR). *Journal of Open Innovation: Technology, Market, and Complexity*, *6*(2). https://doi.org/10.3390/JOITMC6020031

Ortiz-Laso, Z., Diego-Mantecón, J. M., Lavicza, Z., & Blanco, T. F. (2023). Teacher growth in exploiting mathematics competencies through STEAM projects. *ZDM - Mathematics Education*, *55*(7), 1283–1297. https://doi.org/10.1007/s11858-023-01528-w

Perianes-Rodriguez, A., Waltman, L., & van Eck, N. J. (2016). Constructing bibliometric networks: A comparison between full and fractional counting. *Journal of Informetrics*, *10*(4), 1178–1195. https://doi.org/10.1016/j.joi.2016.10.006

Pou, A. V., Canaleta, X., & Fonseca, D. (2022). Computational Thinking and Educational Robotics Integrated into Project-Based Learning. *Sensors*, *22*(10). https://doi.org/10.3390/s22103746

Psycharis, S. (2017). *STEAM in Education: A Literature Review on The Role of Computational Thinking, Engineering Epistemology and Computation Science. Computational STEAM Pedagogy (CSP)* (2nd ed., Vol. 4). The Royal Society. https://encr.pw/70un1

Revák, I. M., Csernoch, M., Szilágyi, K. C., Dávid, Á., Tóth, B. K., Malmos, E., Sütő, É., & Kurucz, D. (2024). A systematic review of STEM teaching-learning methods and activities in early childhood. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(8). https://doi.org/10.29333/ejmste/14779

Schreiter, S., Friedrich, A., Fuhr, H., Malone, S., Brünken, R., Kuhn, J., & Vogel, M. (2024). Teaching for statistical and data literacy in K-12 STEM education: a systematic review on teacher variables, teacher education, and impacts on classroom practice. *ZDM - Mathematics Education*, *56*(1), 31–45. https://doi.org/10.1007/s11858-023-01531-1

Shahali, E. H. M., Halim, L., Rasul, M. S., Osman, K., & Zulkifeli, M. A. (2017). STEM learning through engineering design: Impact on middle secondary students' interest towards STEM. *Eurasia Journal of Mathematics, Science and Technology Education*, *13*(5), 1189–1211. https://doi.org/10.12973/eurasia.2017.00667a

Shelley, M., & Kiray, S. A. (2018). *Research Highlights in STEM Education* (Dr. Mack Shelley & Dr. S. Ahmet Kiray, Eds.). ISRES. www.isres.org

Smith, J. R., Snapp, B., Madar, S., Brown, J. R., Fowler, J., Andersen, M., Porter, C. D., & Orban, C. (2023). A Smartphone-Based Virtual Reality Plotting System for STEM Education. *PRIMUS*, *33*(1), 1–15. https://doi.org/10.1080/10511970.2021.2006378

UNESCO. (2023). *Global Education Monitoring Report 2023: Technology in education: A tool on whose terms?* GEM Report UNESCO. https://doi.org/10.54676/UZQV8501

van Eck, N. J., & Waltman, L. (2019). *VOSviewer Manual*.

Wahyuni, S., Saputri, L., Yustinaningrum, B., Mandasari, L., Suaibah Nasution, S., & Rahmadhani, E. (2024). STEM in Mathematics Teaching and Learning: A Bibliometric Analysis. In *Communications on Applied Nonlinear Analysis* (Vol. 31, Issue 1).

Wu, Z. (2023). *Developing a Digital Solution Framework through a Digital Community of Practice System to Support Teachers' Implementation of STEAM*.

Yakman, G. (2010). *What is the point of STEAM?-A Brief Overview*. https://www.researchgate.net/publication/327449281

Zhan, Z., Shen, W., Xu, Z., Niu, S., & You, G. (2022). A bibliometric analysis of the global landscape on STEM education (2004-2021): towards global distribution, subject integration, and research trends. *Asia Pacific Journal of Innovation and Entrepreneurship*, *16*(2), 171–203. https://doi.org/10.1108/apjie-08-2022-0090

Zhao, Y. (2024). Integrated and Innovative Application of Artificial Intelligence and Big Data Technologies for STEM Education. *Applied Mathematics and Nonlinear Sciences*, *9*(1). https://doi.org/10.2478/amns-2024-2326