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Review

A bibliometric exploration of research on STEM education and its role in fostering critical thinking (2004–2024)

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Abstract: Critical thinking is a metacognitive skill that has become inescapable for the 21st-century generation for handling complex real-life problems. This skill can be learned through tailored pedagogy and an integrated approach. STEM education is a forward-looking approach that can foster critical thinking, a core component of 21st-century skills, among students. This bibliometric analysis aimed to systematically map the research trends on STEM education and critical thinking over the last 20 years. Metadata were extracted from the Scopus and Web of Science databases over a period of 20 years, from 2004 to 2024. Inclusion criteria were the frequency and availability of studies on the keywords “STEM education” and “critical thinking” for synthesis. Unpublished articles, book chapters, conference papers, etc., were excluded. A final set of 69 (N = 69) eligible studies from Web of Science and 61 (N = 61) from Scopus was considered for bibliometric analysis. Parameters such as publication trends, research field categories, key term co-occurrence, countries contributing with link strength, most influential authors, bibliographic coupling, and top-ranked sources were studied using VOSviewer software. The major findings of this study are as follows: 1) Research on STEM education and critical thinking has exponentially increased since 2016. 2) Web of Science has comparatively richer metadata compared to Scopus. 3) The United States, China, and Australia predominantly produce research compared to Asian and European countries in this field. 4) Limited research collaboration has been done in STEM and critical thinking. 5) Educational innovation, creativity, and augmented reality are a few key terms that have future potential for research. This systematic literature review has developed insight into other highly significant and relevant terms, such as nanotechnology, the scientific process, active learning, educational innovation, and computational skills. The relationship between these terms and STEM education can be transformative.

Keywords: STEM, STEM education, critical thinking, 21st-century skills, bibliometric analysis

1. Introduction

1.1. STEM education and critical thinking

Critical thinking is defined as "the intellectually disciplined process of actively and skilfully conceptualising, applying, analysing, synthesising, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief and action" [1,2]. Critical thinking is the ability to engage in purposeful and self-regulatory judgment that is a prerequisite for process evaluation, data analysis, interpretation of a variety of data, and drawing of inference from the interpretation, as well as explanations of the considerations on which that judgment is based. Science, mathematics, engineering and technology disciplines in the 21st century have become key components for the scientific endeavour. This metacognitive process enhances the ability to think logically and produce logical scientific solutions to complex problems. Instruction in critical thinking enables individuals to develop a more complex understanding of the information they encounter in day-to-day real-life situations and enhance problem-solving and decision-making skills applicable to real-world contexts [3]. In the 21st century, due to advancements in computing and technology, there has been an exponential increase in complex knowledge. Hence, the problems people encounter are complex in nature and require HOT skills to resolve. Critical thinking skills nowadays are becoming an indispensable requisite for handling the challenges of a complex world and are becoming imperative for understanding and solving increasingly complex day-to-day problems across different aspects of life [4]. Higher-order thinking skills have now become a mandatory 21st-century skill that future generations need to develop to adapt accordingly [5]. Over the past many years, research on HOTS (higher-order thinking skills) has captured the attention of educators and policymakers from different countries. Educators worldwide acknowledge HOTS as essential for preparing students for competitive environments, emphasising skills like critical thinking and creativity. The World Economic Forum has also highlighted the need to develop and enhance human skills and capabilities through education and a practical approach toward work.

1.1.1. STEM education: An approach to skill development

The literature on STEM education highlights its multifaceted nature and potential to foster skill development through an interdisciplinary approach [6]. It provides a foundational understanding of STEM education, emphasising that it transcends traditional boundaries of science, technology, engineering, and mathematics, encompassing the behavioural and social sciences. This broad interpretation allows for a more comprehensive skill set to be developed, as STEM education is predicated on collaborative knowledge construction across various contexts, whether in schools or workplaces [6]. A literature review identified that this integrated approach fosters holistic understanding by allowing students to engage with STEM content as a cohesive whole. Bauer [7] highlighted the challenges educators face in implementing integrated strategies, underscoring their potential to enhance learning outcomes and foster deeper interest in STEM fields [7]. This research underscores the need for a comprehensive, integrated approach to STEM education that not only develops specific skills but also prepares students for the complexities of modern life. STEM education aims to foster interdisciplinary learning to develop skills for society and the workforce. Broadly, the term *STEM education* carries different connotations. It may refer to curriculum framework, teaching pedagogy, various learning approaches, and policies for economic and technological development. Critical thinking has been conceptualised as a construct comprising multidimensional competencies: analysis, evaluation, reasoning, and decision-making, while also being associated with HOTS. The literature also connects related constructs that reflect cognitive and applied dimensions within STEM learning. Recent debates on STEM education emphasised its role in cognitive skill development, yet a more critical lens raised the issues of technocratic bias, epistemological hierarchy, and unequal access. Voices have been raised on excluding feminist, decolonial, and socio-critical perspectives, favouring a specific group of knowledge. This study has its own limitations and, hence, does not advance any theoretical or critical framework. It maps key terms, “STEM education” and “critical thinking”, in indexed scholarly literature. Accordingly, the analysis is limited to bibliometric indicators such as keywords, titles, abstracts, and citation patterns. The relatively limited visibility of critical and equity-oriented perspectives in the findings reflects their marginal representation within the indexed dataset rather than their lack of theoretical importance. This highlights an important gap in the literature and points to the need for future research that incorporates more critical and inclusive perspectives.

1.1.2. Role of STEM in developing critical thinking skills

The integration of STEM into science teaching has been shown to significantly enhance students' critical and creative thinking skills. A meta-analysis of various studies revealed that STEM approaches foster higher-order thinking abilities, with an effect size of 0.798, indicating a strong positive impact on cognitive skills [8]. Many researchers attributed STEM education to skill development, which encourages the application of critical and analytical thinking and problem-solving skills in various situations. Rational, goal-oriented decision-making skills are also influenced by critical thinking. STEM education positively affects higher-order thinking and cognitive abilities, but specific effects on critical and creative thinking skills have not been conclusively addressed [9]. The current study aims to map the research (frequency) published on STEM education and critical thinking skills (HOTS), within the context of metacognition skills. As a first step, research on STEM education provides a detailed account of the field and its conceptualisation in the educational landscape.

The fundamental principles of STEM include problem identification, solution design, application of science, technology, mathematics, and the rational verification of the answer. STEM education advocates learning by emphasising and encouraging students' innovation and transdisciplinary integration, which is essential for developing students for a global, competitive world. Despite the broad spectrum of metacognition, researchers agree on the very specific “critical thinking” skill. Figure 1, depicting “STEM education” research trends, shows a significant growth over the last 20 years. Studies have found that STEM education is strongly associated with higher-order thinking skills among students [10–13]. Various countries’ policies have advocated for the intervention of STEM in schools [14,15]. Globally, STEM education has gained prominence and is viewed as an essential ingredient for students’ overall growth and development, realising the need to prepare children for the upcoming challenges of a technological and innovation-driven world [16–19].

1.2. Research trends

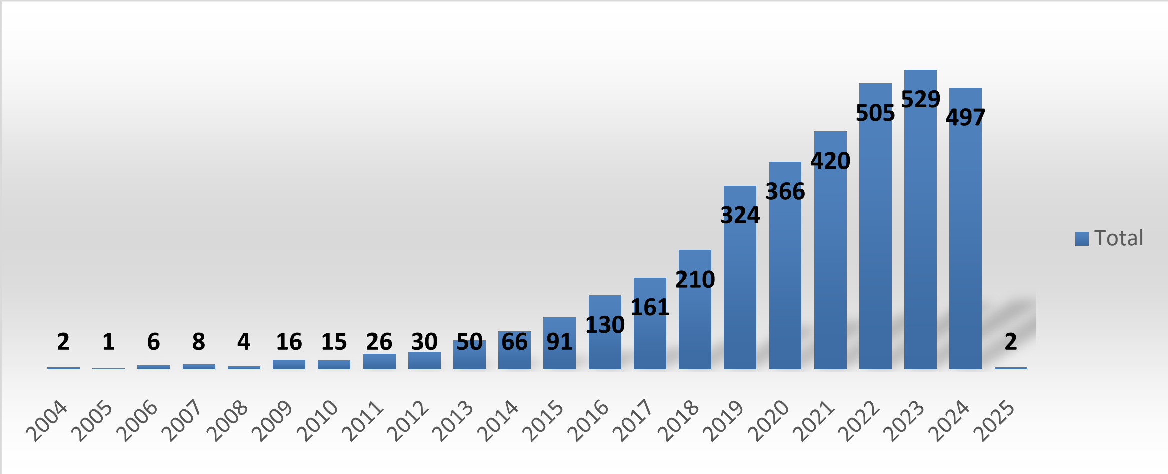

Figure 1. Number of publications over 20 years (2004–2024).

The bibliometric analysis technique is used in this systematic literature review, where researchers explore a broad spectrum of research with the key terms "STEM education" and "critical thinking". The analysis reveals the annual frequency of studies conducted on STEM education. This frequency reflects the evolution of research on the effects of STEM education on students' development of HOTS. Also, it highlights general trends in the field from different perspectives. A substantial number of studies show that the role of STEM in critical thinking has been fairly explored. This study will explore past research in the same area to further clarify the strength of the relationship between STEM education and critical thinking. For bibliometric exploration, various studies from the Scopus and Web of Science databases, published from 2014 to 2024, that examined the relationship between STEM education and critical thinking have been considered. By analysing published articles, this study aims to explore whether STEM education and critical thinking frequently co-occur.

1.3. Research contributions

This study offers a systematic overview of existing research trends in STEM education and critical thinking. Focusing on the last 20 years of research, identifying key publications and influential authors, will help establish a robust foundation for understanding how these domains have evolved over a period of time. By applying bibliometric analysis, the synergistic relationships among the key terms can be elucidated, uncovering notable trends in research output, such as the year and countries with the highest number of publications. This will shed light on how educational and social priorities have shaped the academic focus and provide a clear research gap for future research. This research can contribute to identifying and developing more nuanced designs that account for both qualitative and quantitative dimensions.

1.4. Research gaps

Despite the proven effect of STEM education in enhancing higher-order critical thinking skills among students, a significantly limited number of studies have systematically mapped literature to identify the trends, gaps, and emerging themes within the intersection of two keywords, “STEM education and “critical thinking”, in major academic databases. Also, an exploration of the literature to capture how discourse around STEM education and critical thinking has changed over time is also missing. In addition, geographical disparity in research output remains underexplored. Consequently, a systematic, temporally informed mapping of global research trends is needed to better understand existing knowledge structures and guide future empirical and theoretical research in STEM education and critical thinking.

1.5. Research questions

The following research questions will be addressed by this study:

1. What are the global research trends, from 2004 to 2024, addressing the relationship between critical thinking and STEM education?
2. How frequently have the keywords “STEM education” and “critical thinking” been used in the last 20 years in different databases?
3. What are recent emerging keywords and trends in this research area?
4. What is the geographical distribution and concentration of research output related to these keywords?
5. Which publications have been cited the most?
6. What is the current status of research on STEM education and critical thinking, and what future development trends can be identified within this field?
7. What are the potential key terms that may shape future directions of research in this field?

2. Methodology

2.1. Analytical framework: Bibliometric study

Bibliometric analysis is a technique used to systematically analyse the literature [20]. It is a quantitative approach to answering research questions through a systematic review of published literature. It identifies emerging trends and patterns in interdisciplinary research by revealing publication patterns, influential authors, collaboration networks, and emerging research directions in the field, trends in quality and citations, contributing countries, and co-occurrence and collaborative networks. This also unveils the limitations and challenges associated with the evolution of research through a systematic evaluation of relevant literature. Many bibliometric studies have been conducted across diverse disciplines and research areas, but research in STEM education remains comparatively limited. This highlights the need for more focused research and advanced investigations in STEM education and higher-order thinking skills, as these areas help promote 21st-century skills.

For bibliometric analysis, VOSviewer software supports text mining and visualisation to identify emerging trends, patterns, and dynamics in scientific research and innovation. The text-mining function of VOSviewer generates research maps by extracting key information from article titles, keywords, abstracts, citations, and other bibliographic data. This process enables the identification of current research gaps through a critical analysis of the literature and facilitates evidence-based decision-making. By employing parameters such as co-citation, bibliographic coupling, co-authorship, and keyword co-occurrence, a systematic evaluation of relevant research is achieved. Therefore, bibliometric analysis has been considered an appropriate strategy for systematically mapping research trends in STEM education and critical thinking over the past two decades. Using bibliometric parameters, the present study evaluates research performance to provide a comprehensive foundation for literature review. The framework for the research process is given in Figure 2.

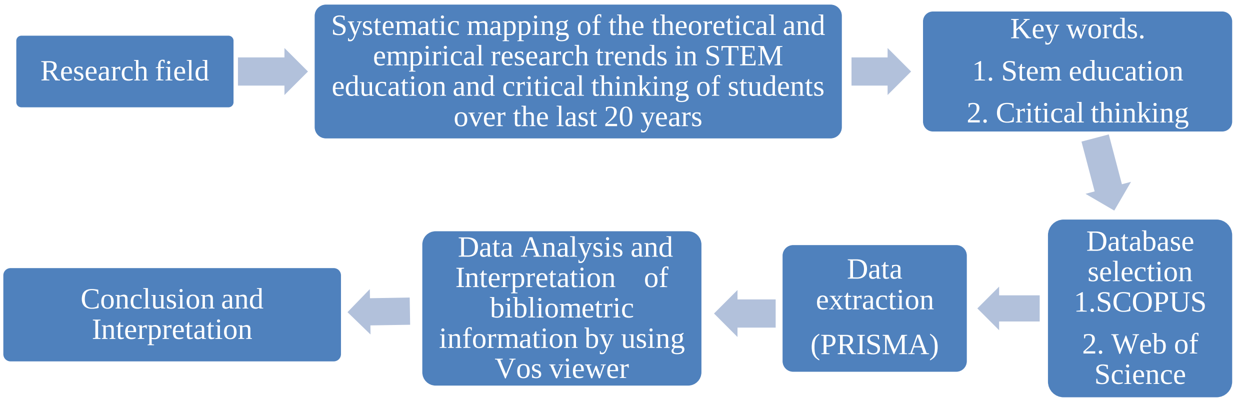

Figure 2. Framework for the research process.

2.2. Data source

For bibliometric analysis, various available databases were considered. After considering the research area and research performance, including the quantity (frequency) of research and citation impact, a list of suitable works was compiled from sources such as Scopus and Web of Science, as well as official partners including Wiley, SAGE, MDPI, The Royal Society, Cambridge University Press, Springer Nature, and ERIC. Inclusion and exclusion criteria used for selection were the frequency and accessibility of the relevant database for studies on the keywords “STEM education” and “critical thinking”. The Scopus, Web of Science, and ERIC databases provided sufficient coverage of research on these terms. Given the aim of the current research, the Web of Science (WoS) and Scopus databases were selected, whereas ERIC was excluded due to compatibility constraints with the chosen bibliometric tool. This is one limitation of the study.

2.3. Search criteria for Scopus/WoS

For the current study, Scopus and WoS were the two internationally recognised databases selected to extract reliable and valid data. Publications were searched in Scopus and WoS separately for the following screening criteria: 1) Research publications related to education and the science education field. 2) Theme related to only two key terms: “STEM education” and “critical thinking”. The search strategy was confined to specific terms to maintain conceptual precision, which may limit the inclusion of studies using alternative descriptors. 3) Only articles published in the last 20 years (2004–2024) were considered.

Metadata were extracted from Scopus and Web of Science (WoS) separately using predefined screening criteria.

2.3.1. Search string

Data were extracted by using the following structured Boolean search strings adapted to the Web of Science and Scopus databases:

1. WoS search string: KEYTERM ("stem education" "Critical thinking") Time span = 2004–2024, Language = English, Document type = Articles
2. Scopus search string: KEY ("stem education" "Critical thinking"), Pub year = 2004–2024, Language = English, DOCTYPE =" ar".

Inclusion and exclusion criteria for both databases: Only published research articles in the English language and relevant to the key terms "STEM education" and "critical thinking" published between 2004 and 2024 were included. Conference proceedings, book chapters, review notes, and unpublished articles were excluded. After the screening, 69 documents from Web of Science and 61 from Scopus were considered for the study. The clean dataset was exported in a compatible format and analysed using VOSviewer.

2.3.2. Screening and selection procedure

The selection process followed a structured screening procedure:

1. Initial identification of records from both databases
2. Removal of duplicate entries
3. Screening of titles and abstracts for relevance
4. Full-text eligibility assessment
5. Final inclusion for bibliometric analysis

The screening process was conducted systematically using predefined criteria to ensure consistency and reliability in data selection.

2.3.3. Data analysis and visualisation

1. Keyword co-occurrence: This is used to detect prevalent keywords in studies.
2. Citation link strength of country-wise publications
3. Most influential authors and researchers
4. Bibliographic coupling
5. Citations and total link strength to extract the data of top-ranked sources

2.3.4. Threshold selection

Threshold values were set for the size of the dataset to ensure significant and relevant visualisation, thereby avoiding excessive network fragmentation. The threshold limit for bibliometric analysis was set to a minimum of two occurrences.

For the citation threshold, a minimum of one citation was set to avoid significant data loss. By retaining all significant data, a meaningful visualisation was assured. These decisions were made to balance analytical inclusiveness and network clarity.

2.4. Methodological scope and limitations

As a bibliometric study, the analysis was limited to metadata elements and did not involve full-text conceptual or theoretical interpretation. Therefore, findings should be interpreted as patterns of scholarly representation rather than causal or empirical relationships. The exclusion of ERIC and the limited use of specific search terms may limit the dataset's comprehensiveness. These limitations are acknowledged and suggest directions for future research using complementary methodological approaches.

2.5. WoS document selection criteria

Data obtained from the WoS database includes only published research and reviewed articles on the key terms “STEM education” and “critical thinking”. Table 1 provides an overview of the different WoS research field categories that have emerged. Only the “education educational research” and “education scientific disciplines” (education-specific) categories were considered for the bibliometric analysis. As shown in Table 1, a total of 1251 documents were eligible for final analyses. Out of these, only education-centric documents were considered for the study: those whose scope fit either pure education or “science education”. After title and abstract screening, 69 were found eligible and were included in the study. Figure 3 shows the PRISMA 2020 flow diagram for the systematic review of the WOS database.

Table 1. WoS: different categories of research fields.

S.no	Web of Science categories	Record count	% of 69
1	Education educational research	32	55.33%
2	Education scientific disciplines	21	36.66%
3	Environmental sciences	7	11.67%
4	Green sustainable science technology	7	11.67%
5	Multidisciplinary science	2	5%

Note: Different categories were created by the VOSviewer software using data from the Web of Science database from 2004 to 2024.

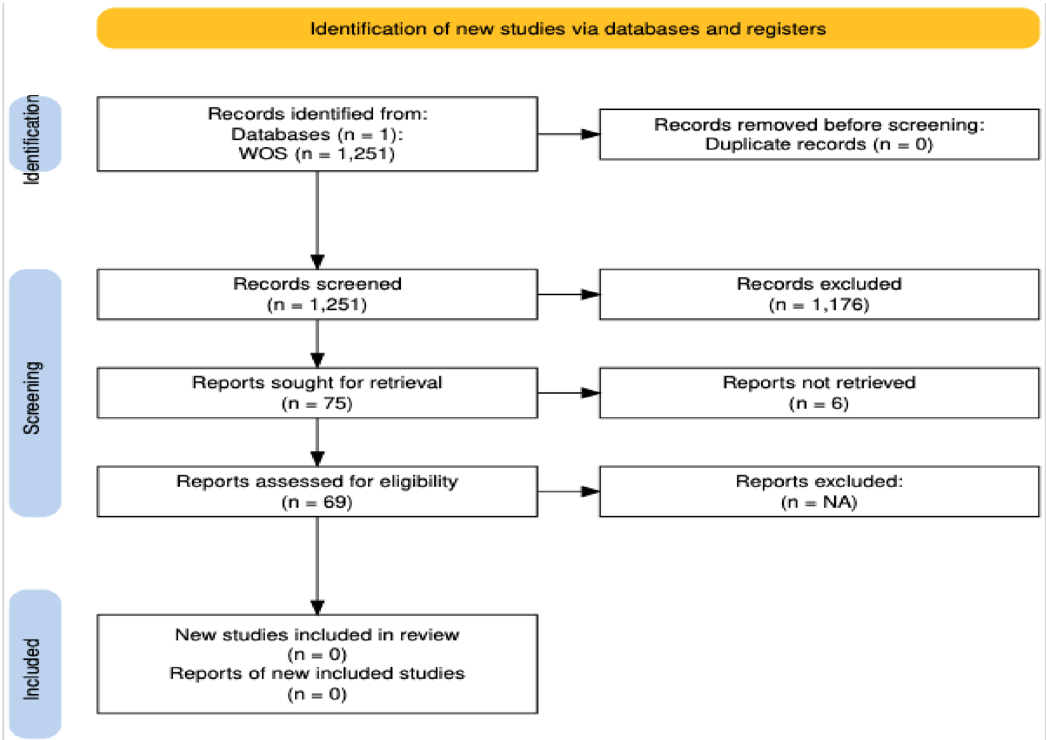

Figure 3. PRISMA 2020 flow diagram for the WoS database.

2.6. Scopus document selection criteria

In Scopus, the search was conducted using the keywords "STEM education" and "critical thinking". A total of 102 published articles passed the search criteria. After title and abstract screening, 61 were considered for final analysis. Figure 4 shows the PRISMA 2020 flow diagram for the systematic review of the Scopus database.

Table 2. Scopus: Different categories of research fields.

S.no	Scopus categories Documents_	Record count (102)
1	Social sciences	32
2	Engineering	21
3	Computer science	17
4	Physics and astronomy	8
5	Mathematics	7
6	Psychology	5
7	Decision science	4
8	Medicine	3
10	Agricultural and biological sciences	2
11	Health professions	2
15	Environmental science	1

Note: Different categories were generated by the VOSviewer software using data from the Scopus database from 2004 to 2024.

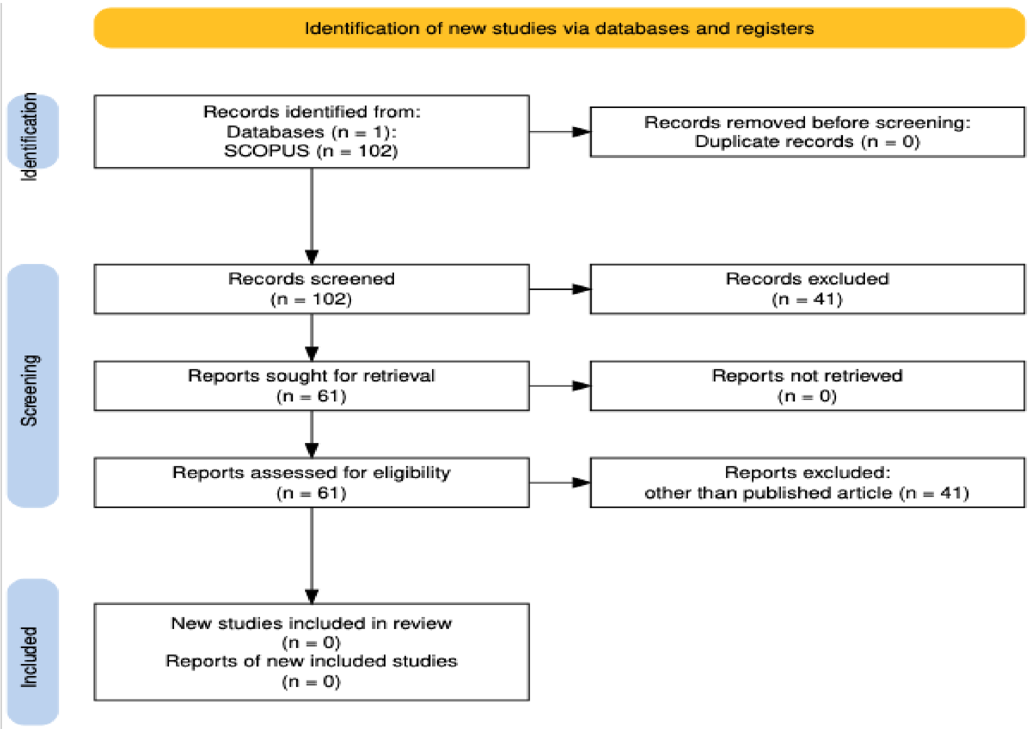

Figure 4. PRISMA 2020 flow diagram for the Scopus database.

3. Analysis

For analysis, publication trends and bibliometric techniques were used in this research.

All bibliometric information was obtained (e.g., publication years, final publication year, document types, researcher profiles, authors, citation topics, Web of Science index, affiliations, publication titles, countries/regions, publishers, research areas, open access) from the WoS and Scopus databases by using the function "analyse search result". Further, data were analysed using VOSviewer, which generated a graphical representation of the research field's structure and characteristics.

3.1. Publication trends on "STEM education" and "critical thinking" over the past 20 years

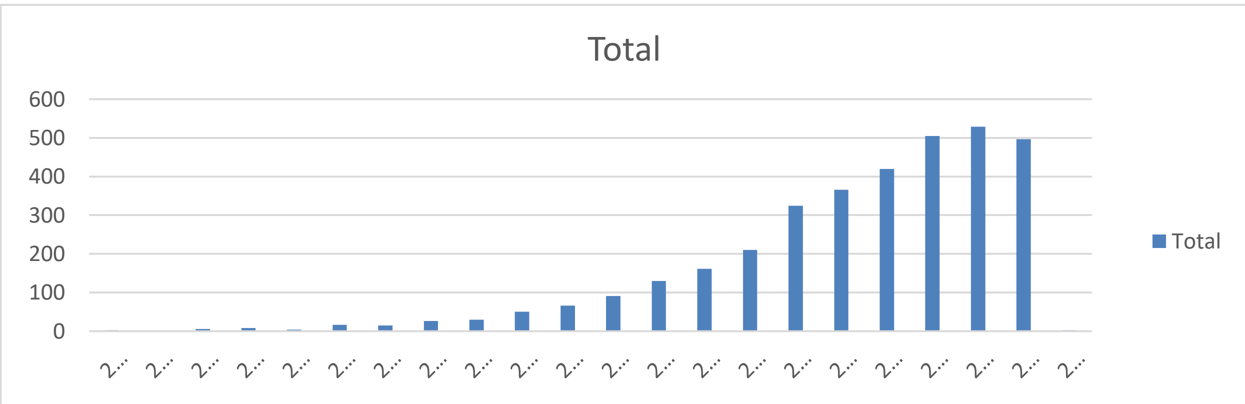

Figure 5. Frequency of research on STEM education.

The databases revealed a clear developmental trajectory, as shown in Figure 5. Data indicate an exponential increase in research studies on “STEM education” from 2009 to 2023. There is a decreasing trend in 2024, as data are considered only up to October. From 2004 to 2008, no research was conducted on STEM education.

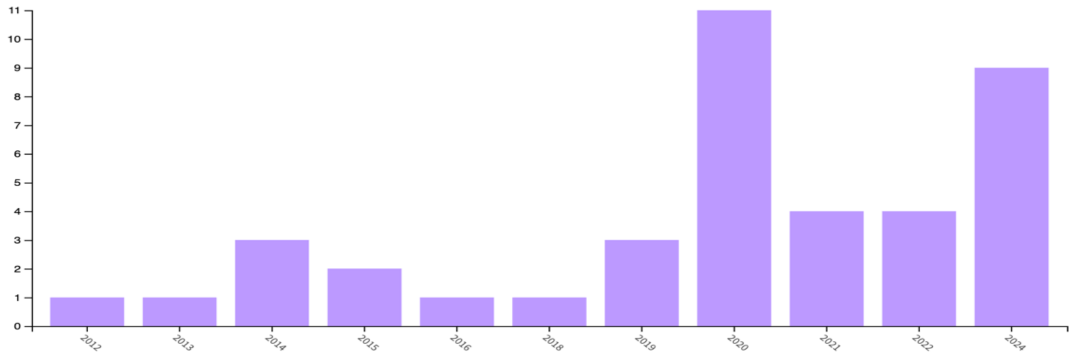

Figure 6. WoS publications (frequency/year) on STEM education and critical thinking.

Figure 6 illustrates the frequency of publications on “STEM education” and “critical thinking” over the past two decades. The graph highlights the years 2014, 2019, 2020, 2021, 2022, and 2024 as highly productive years, indicating significant researcher engagement in the area. In contrast, the years 2004–2007 can be considered as a dormant phase, during which very few studies were published, indicating that the field had not yet gained significant research attention. From 2018 to 2024, a notable upward trend emerges, with a consistent increase in research output.

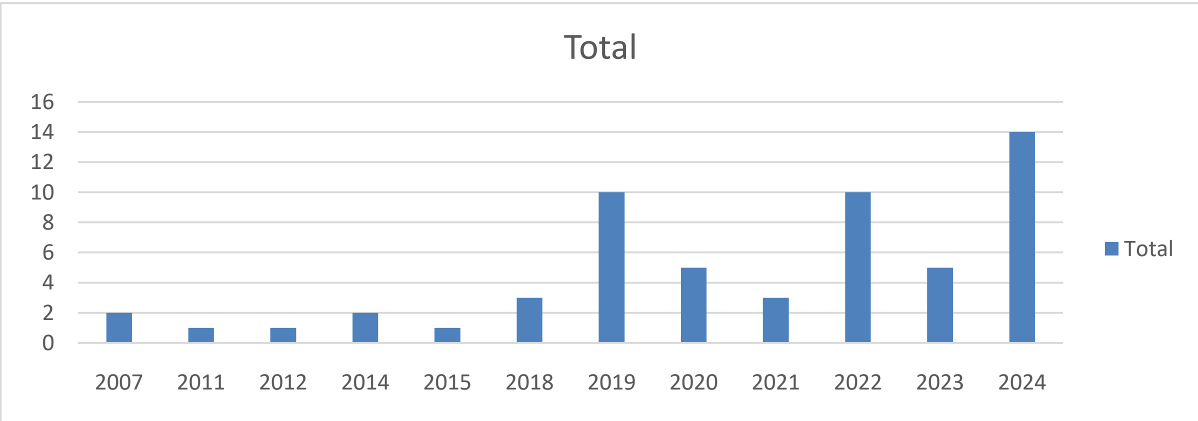

Figure 7. Scopus publications (frequency/year) on STEM education and critical thinking.

Figure 7 illustrates the growth of research publications on STEM education and critical thinking, particularly within the fields of education and science education. An upward unsteady trajectory can be seen from 2018 onwards, culminating in a peak in 2024. An unexpected decline during 2020–2021 is observed, reflecting disruptions in global research activity. Remarkably, the Scopus database recorded the highest publication frequency in 2024. It can be inferred that the recognition of “critical thinking” and “STEM education” as essential terms in the 21st century was globally acknowledged.

3.2. Keywords: Bibliometric mapping of emerging themes

In this study, keyword co-occurrence was used to identify and explore emerging keywords and trends in the research area of STEM education and critical thinking. In Figure 8, the co-occurrence of key terms is shown by coloured dots, whereas the relatedness between two keywords is shown by the coloured curves, which connect the key terms. The most frequently researched keywords from WoS and Scopus are represented in the co-occurrence network visualisation in Figure 8.

3.2.1. WoS keyword co-occurrence

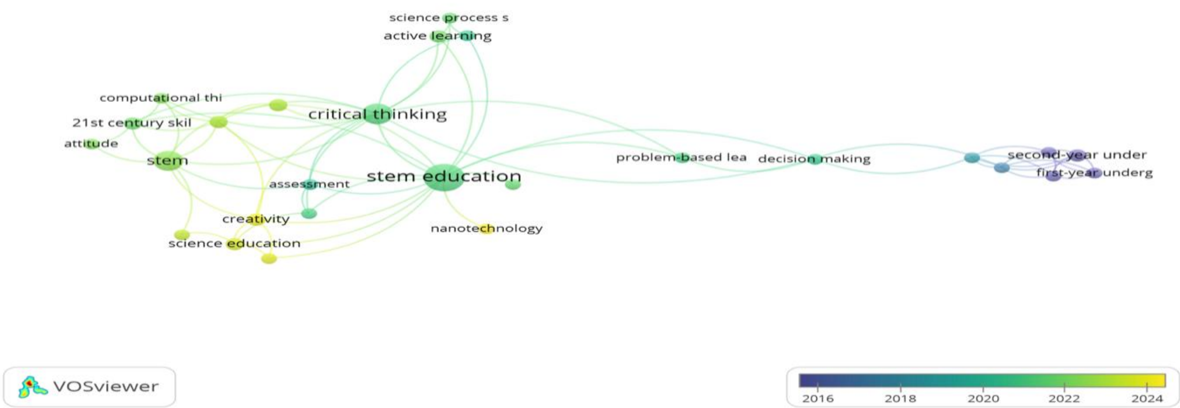

Figure 8. Co-occurrence cluster map of keywords of research obtained in Web of Science within the field of STEM education and critical thinking (online version of the map for more details). The colours of the nodes represent the year of publication, thereby illustrating the temporal distribution of research output within the network.

Out of 27 key terms that co-occurred, five clusters were formed. Each cluster produced by the VOS clustering technique includes a threshold limit of 1 as the minimum number of co-occurrences specified by this parameter.

Cluster 1: Key terms include science education, creativity, assessment, pedagogy, SDGoals, and equity. This indicates the role of science education and its pedagogy in developing SDG goals by developing creativity and assessment skills.
Cluster 2: Key terms include STEM, attitude, 21st century skills, thinking skills, higher education, computational thinking, and critical thinking. This reveals that the cognitive–analytical dimension of critical thinking is the most dominant, as evidenced by its strong connections to keywords such as computational thinking, 21st-century skills, and attitude. This suggests that critical thinking is primarily framed as an analytical and skill-based construct in STEM education research.
Cluster 3: Key terms include science processing skills and active learning. This highlights the importance of science processing skills for active learning, which in turn contributes to various OECD and SDG goals [21,22].
Cluster 4: Key terms include problem-based learning, decision making, inquiry-based discovery learning, laboratory instruction, second-year graduates, and first-year graduates. This, as shown in

Figure 2, highlights the importance of the above-mentioned skills for higher education.
Cluster 5: Key terms include STEM education and nanotechnology. The co-occurrence of both key terms highlights the need for further studies in the field of nanotechnology.

The map shows thematic clusters, showing how frequently keywords co-occur, thereby helping to identify other dominant themes, research linkages, and emerging trends. The 69 selected research documents from WoS contained 419 co-occurring keywords, whereas 268 total "authors' keywords" co-occurred. After considering all key terms, 27 terms co-occurred twice. In the keyword co-occurrence network, the thematic web of research on key terms "STEM education" and "critical thinking" is represented, indicating their strong co-occurrence and conceptual prominence within the literature. The thematic web of key terms such as "computational thinking" and "21st-century skill" represents the cognitive–analytical dimension of critical thinking as the most dominant, as evidenced by their strong connections. This suggests that critical thinking is primarily framed as an analytical, skill-based construct in STEM education research.

Furthermore, the presence of terms such as creativity, science education, and assessment in closely linked clusters reflects the integration of critical thinking within broader higher-order thinking skills (HOTS) frameworks. These associations indicate that critical thinking is frequently studied alongside other advanced cognitive competencies rather than as an isolated construct.

3.2.2. Scopus keyword co-occurrence

Out of the 195 identified key terms, only 17 met the threshold of two co-occurrences, indicating that only a relatively small subset of terms demonstrated meaningful relational significance within the dataset.

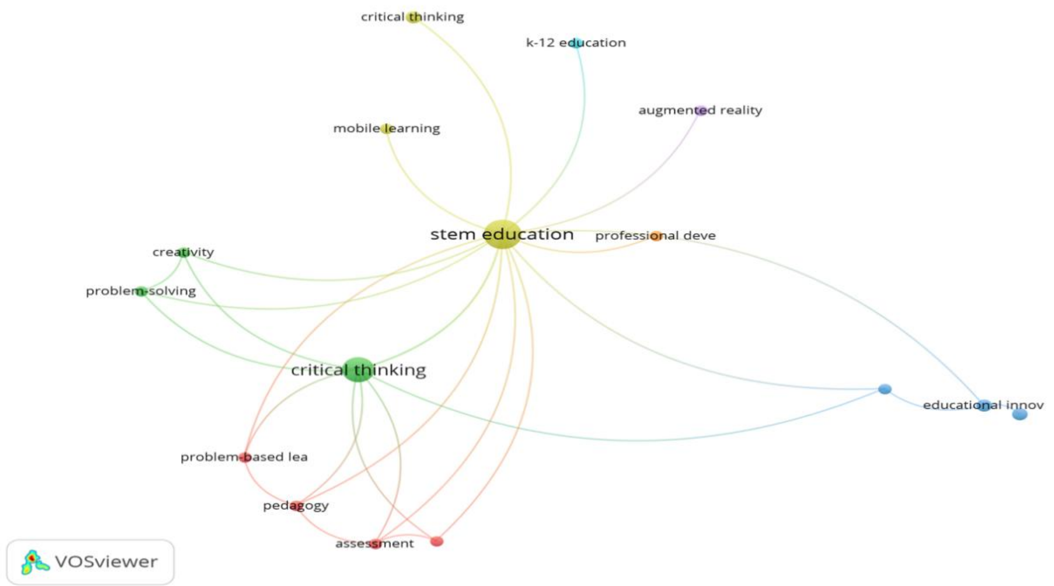

Figure 9. Co-occurrence cluster map of keywords in Web of Science within the field of STEM education and critical thinking. Online version for more details (Author key terms co-occurring in the Scopus database).

Out of 17 key terms that co-occurred, seven clusters were formed. Each cluster produced by the VOS clustering technique includes a threshold limit of 1 as the minimum number of co-occurrences specified by this parameter.

Cluster 1: Key terms include problem-based teaching, pedagogy, assessment, and computational thinking. This cluster comprises problem-based teaching, pedagogy, assessment, computational thinking, and critical thinking, reflecting a significant orientation in educational research toward pedagogical innovation and assessment, as well as the advancement of complex cognitive competencies. The interplay of computational and critical thinking within problem-based pedagogies underscores the demand for learners who can navigate complexity with both analytical precision and reflective judgment, aligning educational practice with the broader imperatives of 21st-century learning [23].

Cluster 2: Key terms include problem-solving, creativity, STEM education, and critical thinking. This tightly interrelated cluster signifies a set that collectively contributes to the development of HOTS and needs to be prioritised in the current education system. This highly interconnected illustration of key terms identifies a paradigm shift, positioning STEM education as a platform for cultivating higher-order skills among students.

Cluster 3: Key terms include creative thinking, educational innovation, professional development, STEM education, and critical thinking. This cluster again reflects the same web, in which STEM education is key to other cognitive skills. The co-occurrence of these constructs is encouraging and welcoming.

Cluster 4: Key terms include STEM education and augmented reality. Such a clustering signifies an emergent research trajectory that integrates advanced digital technologies with science, technology, engineering, and mathematics learning. This also signifies that augmented reality is beginning to attract researchers' attention, as it can serve as an add-on to STEM education.

Cluster 5: Key terms include STEM education and mobile learning. This highlights the growing integration of digital, portable technologies into science, technology, engineering, and mathematics teaching and learning. It also reflects the alignment and coordination between STEM pedagogical goals in education and the technological affordances of mobility, pointing to innovative pathways for future education.

Cluster 6: Key terms include STEM education and critical thinking skills. STEM education provides a context that demands inquiry, analysis, and innovation, while critical thinking equips learners to evaluate evidence, question assumptions, and make reasoned judgments. The co-occurrence of these terms highlights a dual aim of STEM education: first, to develop both disciplinary expertise and, second, the critical thinking skills necessary for 21st-century workforce readiness.

Cluster 7: Key terms include STEM education and K-12 education. This suggests that integrating STEM at the school level is viewed as essential for preparing learners with the cognitive, technical, and creative skills required for future workforce participation.

The keyword co-occurrence network generated using VOSviewer highlights the thematic organisation of research on STEM education and critical thinking. STEM education at the centre connects multiple thematic strands, reflecting its integrative function across diverse research domains. Apart from the “cognitive-analytical dimension” of critical thinking, the “instructional and applied dimension” can also be assessed through a distinct pedagogical cluster linking “problem-based learning”, “pedagogy”, and “assessment”. Hence, it can be inferred that the development of critical thinking is closely connected to teaching strategies, educational framework, foundational learning stages, and evaluation mechanisms within STEM education.

Additionally, emerging technology-oriented themes such as “mobile learning” and “augmented reality” appear as peripheral yet connected nodes, indicating a growing research interest in leveraging digital tools to enhance critical thinking within STEM contexts. Similarly, professional development and educational innovation form another cluster, emphasising the role of teacher training and systemic educational reforms in fostering critical-thinking competencies.

Within the network structure, relatively weak link strengths among diverse connections indicate a fragmented and developing research landscape. Moreover, the absence of metacognitive and dispositional dimensions of critical thinking indicates a prioritisation of observable cognitive and instructional aspects over reflective and attitudinal components. The co-occurrence network of the SCOPUS database indicates that critical thinking and STEM education are primarily framed within cognitive, pedagogical, and emerging technological contexts, while deeper reflective and dispositional dimensions remain unexplored.

Overall, both Web of Science and Scopus co-occurrence networks consistently indicate that critical thinking in STEM education is predominantly framed through cognitive and pedagogical dimensions. However, while the Web of Science dataset reflects a relatively more structured and interconnected thematic landscape with stronger emphasis on higher-order thinking and inquiry-based learning, the Scopus dataset presents a more fragmented and emerging network, with greater inclusion of technological and innovation-oriented themes such as mobile learning and augmented reality. In both cases, the metacognitive and dispositional dimensions of critical thinking remain notably underrepresented, highlighting a shared conceptual gap in the existing literature.

3.3. Geographical concentration of research output based on citation link strength

Citations: Item relatedness as measured by citation links. Relatedness of the items is determined by the number of times each work cites the other. In this study, a minimum of one citation was considered; 59 of 69 studies met this threshold. For each of the 59 documents, the number of citation links was calculated. Documents with the largest number of links were selected. Tables 4 and 5 provide an overview of the countries with a higher number of citations.

3.3.1. WoS database analysis

Out of 24 countries that contributed to research on STEM education and critical thinking, a total of 19 countries met the threshold and were included in the analysis. For each of the 19 countries, the total strength of the citation links is given in Table 3. Countries with the highest total link strength were selected.

Table 3. Citation link strength of country-wise publications based on the WoS database.

S.No	Country	Documents	Citations	Total link strength
1	USA	28	507	4
2	People's Republic of China	14	143	1
3	Australia	6	75	2
4	Russia	1	41	0

5	Taiwan	4	36	6
6	Turkey	4	36	2
7	Malaysia	1	12	0
8	Vietnam	1	12	0
9	England	1	8	0
10	Lithuania	1	7	0
11	Israel	1	5	0
12	Saudi Arabia	1	5	0
13	Turkiye	3	3	1
14	Germany	1	3	0
15	Austria	1	2	0
16	Jordan	1	2	0
17	United Arab Emirates	1	2	0
18	Ghana	1	1	0
19	India	1	1	0

The United States exhibits the highest total link strength (4), being identified as the most productive country in research on STEM education and critical thinking. The USA also shows stronger global research connectivity. While Taiwan contributes less to research, its link strength is quite high. An examination of country-level publication outputs reveals that only a limited number of countries contribute to this field. Among them, the United States (28 publications) and China (14 publications) dominate the research landscape, while contributions from other countries remain minimal or negligible. This citation link analysis highlights the need for broader international collaboration and diversified contributions to advance a more global understanding of the relationship between STEM education and critical thinking.

3.3.2. Scopus database analysis

Table 4. Citation link strength of country-wise publications.

S.No	Country	Documents	Citations	Total link strength
1	Portugal	1	1	0
2	New Zealand	1	2	0
3	Slovakia	1	2	0
4	Italy	1	3	0
5	Malaysia	2	3	0
6	(Camra), US	1	5	0
7	Mexico	3	8	0
8	India	3	11	0
9	United Kingdom	3	13	0
10	China	4	15	0
11	Qatar	3	17	0
12	Vietnam	1	18	0
13	Russian Federation	1	20	0

14	Turkey	4	23	0
15	Australia	4	31	0
16	Thailand	3	35	0
17	United States	19	41	0
18	Indonesia	5	113	0

Note: Countries with documents with 0 citations were not included in the study.

The Scopus data presented in Table 4 indicate that the United States (20 publications) is the most productive country in STEM education and critical thinking, followed by Indonesia (5 publications). While the United States demonstrates higher research output, Indonesia's relatively fewer publications have received comparatively higher citation counts, reflecting the strong quality and impact of these contributions. Overall, data suggest that only a limited number of countries are actively engaged in research on STEM education and critical thinking. Both databases rank the USA as the most contributing country, with the highest number of citations. Indonesia contributes less compared with the USA, whereas citations are highest.

3.4. Most influential authors and researchers

3.4.1. WoS database

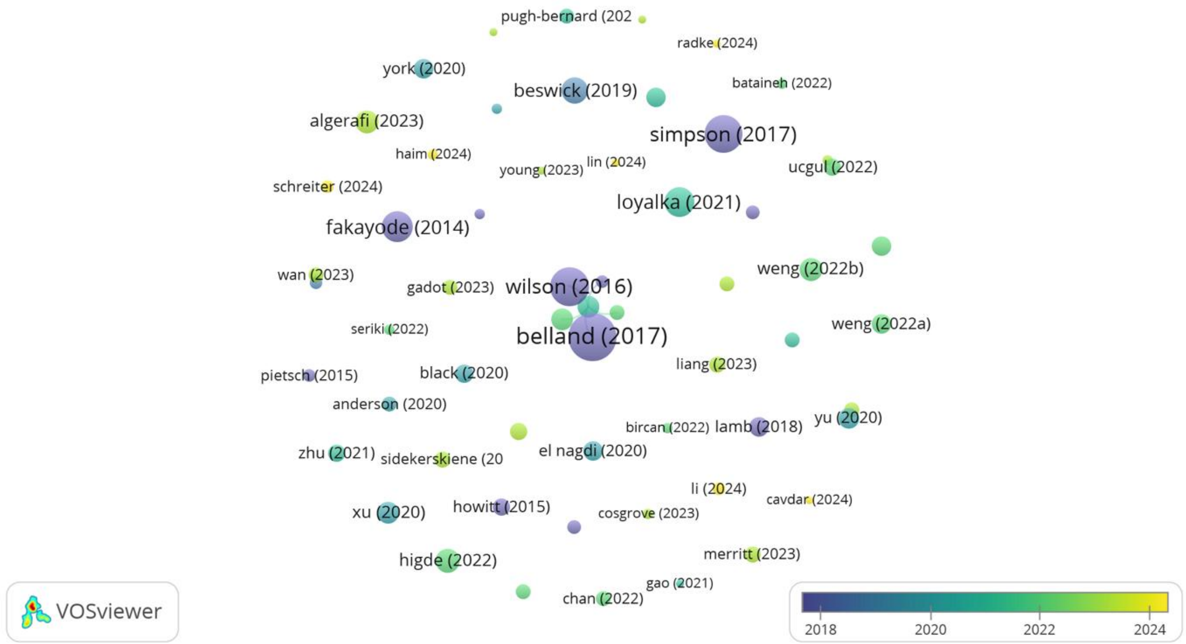

Figure 10. Most influential authors in the WoS database on STEM education and critical thinking. Details are available in the online version of the map.

As per Figure 10, the works with the highest number of citations are by Belland with 154 citations in 2017, Wilson (Wilson and Varma-Nelson 2016) with 86 citations, Simpson (2017) with 81 citations, Fakayode (2014) with 45 citations, and Loyalka (2021) with 41 citations.

3.4.2. Scopus database

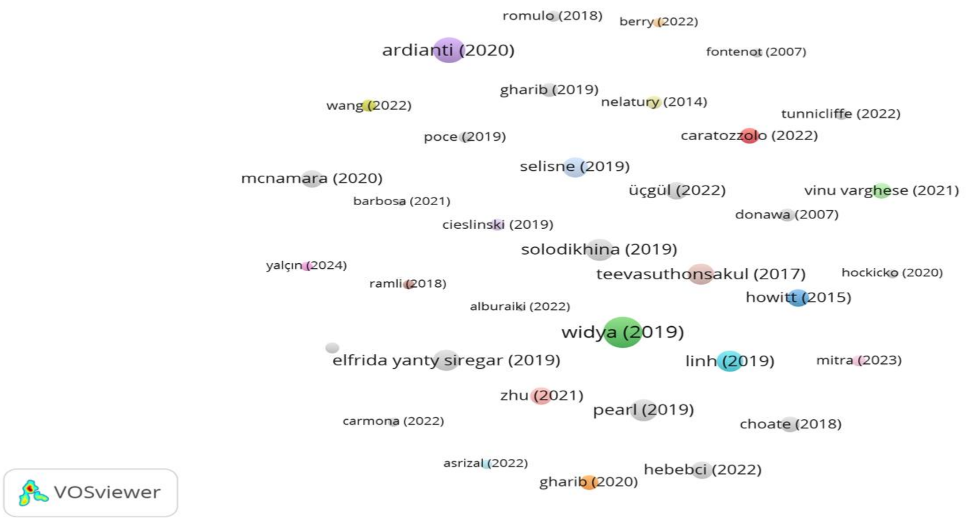

Figure 11. Scopus's most influential researchers on STEM education and critical thinking. Details are available in the online version of the map.

In the Scopus database, out of 61 documents, 36 met the threshold of a minimum of 1 citation per document. From those, the works with the highest number of links are by Widya (2019) with 49 citation links, Ardianti (2020) with 30 citations, Solod Ikhina (2019) with 20 citations, Pearl (2019) with 19 citations, and Linh (2019) with 18 citations, with "0" link strength. It is evident from Figures 10 and 11 that the Web of Science database has more cited research than the Scopus database.

3.5. Bibliographic coupling of the document

Bibliographic coupling strength is also called the Jaccard Index (Jaccard,1901), being defined by the number of items divided by the total number of items in the reference list of the two papers.

3.5.1. WoS database

In WoS, from the 69 works, 59 documents met the threshold limit, and only 49 papers showed link strength. The largest set of connected items consisted of 49 items. The higher the weight of the citation, the bigger the nodes.

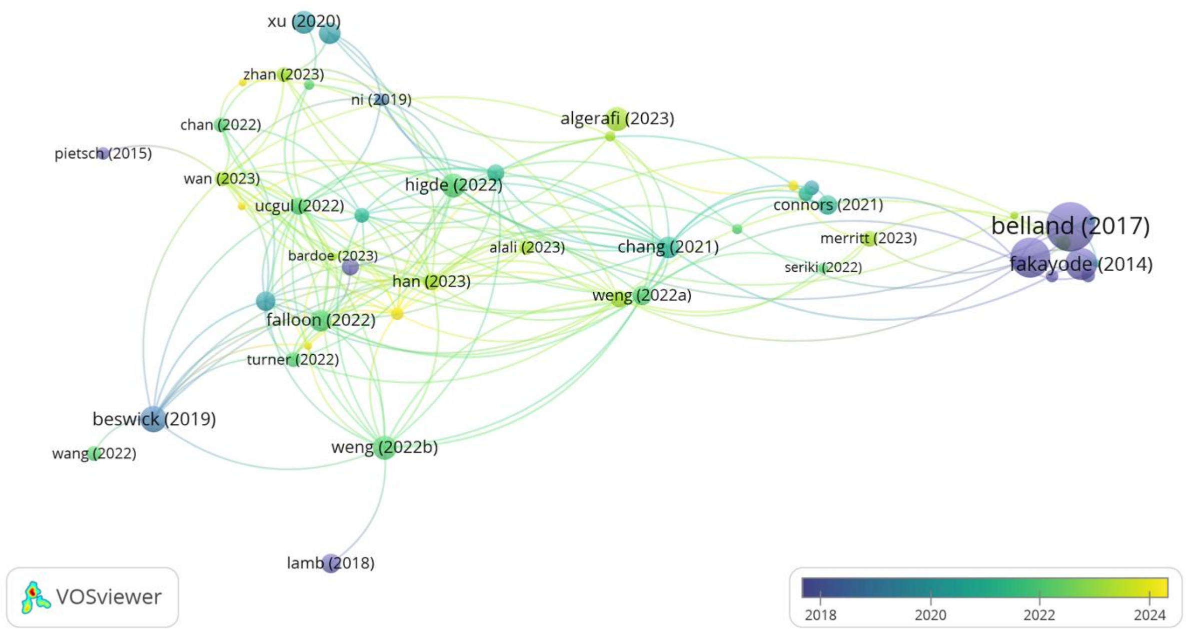

Figure 12. Bibliographic coupling of documents from the WoS database. Details are available in the online version of the map.

Figure 12 depicts that Belland [24] and Wilson (2016) [25,26] are strongly coupled, with the highest link strength, followed by Weng (2022) [27,28], with the highest link strengths of 30, 31, and 29, which are bibliographically coupled and conceptually connected. These authors are the most productive bibliographically coupled authors.

3.5.2. Scopus database

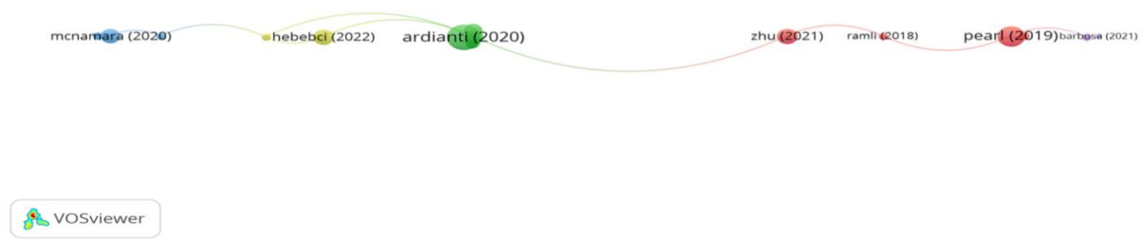

Figure 13. Bibliographic coupling of documents from the Scopus database. Details are available in the online version of the map.

In the Scopus database, all 36 documents with a minimum of 1 citation and the highest bibliometric strength were identified using the VoSviewer. Figure 13 shows that the highlighted calculated bibliographic coupling strength is high (6, 3, 3) among Ucgul (2022) [29], Pearl (2019), and Asrizal (2022).

3.6. Top-ranked journals on STEM education and critical thinking

3.6.1. WoS database

Table 5. Top sources, ranked by number of citations and total link strength.

S.No	Source (journal name)	Citation	Total link strength
1	International Journal of STEM Education	80	1039
2	International Journal of Science Education	57	969
3	International Journal of Technology Design Education	80	762
4	Journal of Research in Science and Technology	45	761
5	International Journal of Science and Mathematics Education	41	742
6	Journal of Science Education and Technology	47	665
7	Journal of Chemical Education	98	633
8	International Journal of Engineering Education	24	575
9	Sustainability Basal	36	530
10	Journal of Engineering Education	26	515
11	Science Education	38	514
12	Computer Education	43	473
13	Thinking Skills and Creativity	30	463
14	CBE- Life Science Education	64	450
15	Science Education- Netherlands	20	437

Note: Data from WoS was organised to calculate the top sources ranked by number of citations and total link Strength by the VoSviewer.

From WoS (Table 5), among the 15 identified sources, The International Journal of STEM Education (indexed in the Social Sciences Citation Index, SSCI, with an impact factor of 5.6) emerged as the most highly cited journal. Other influential journals include the Journal of Chemical Education (98 citations), International Journal of Technology and Design Education (80 citations), International Journal of STEM Education (80 citations), and Cell Biology Education—A Journal of Life Science Education (64 citations). Furthermore, results indicate that the International Journal of Science Education and the International Journal of STEM Education exhibit the strongest linkages, signifying their key roles in the research network and publication.

3.6.2. Scopus database

Table 6. Highly cited sources and their link strength in the Scopus database.

S.No	Source (journal name)	Citations	Total link strength
1	Journal of Science Education and Technology	10	84
2	ACM International Conference Proceeding Series	19	57
3	International Journal of Science Education	12	34
4	International Journal of STEM Education	18	34
5	Science Education	12	31
6	Journal of Research in Science Teaching	11	20

Note: Data from SCOPUS was organised to calculate the top sources ranked by number of citations and total link strength by the VoSviewer.

Table 6 presents the Scopus database analysis, with a citation threshold of 12, corresponding to the maximum number of citations received by a source. Out of 1337 sources, only 6 met this threshold. The most highly cited sources include the ACM International Conference Proceedings Series, the International Journal of STEM Education (18 citations), the International Journal of Science Education (12 citations), and Science Education (12 citations). In terms of co-citation link strength, the leading sources are the Journal of Science Education and Technology (84) and ACM International Conference Proceedings Series (57). Additionally, the International Journal of Science Education and the International Journal of STEM Education also demonstrate notable link strengths (34 each)

4. Overview

The role of bibliometric analysis is to identify emerging trends and patterns in interdisciplinary research by evaluating relevant literature. It has some limitations and challenges associated with applying bibliometric analysis in research evolution.

4.1. Navigating research trends and patterns

The findings indicate a clear upward trajectory in STEM education research, particularly after 2009, which coincides with global educational reforms emphasising STEM education's contribution to 21st-century skill development. STEM contributes to the development of skills that drive innovation, employability, and economic development. The surge in publications reflects the integration of STEM into national curricula, increased funding opportunities, and growing recognition of its role in fostering 21st-century skills such as problem-solving, creativity, and critical thinking. The limited research activity between 2004 and 2008 suggests that STEM education had not yet gained substantial academic attention, possibly due to its nascent stage in policy frameworks and institutional adoption.

4.2. Synthesis of WoS and Scopus findings

4.2.1. Bibliometric analysis of Scopus and WoS over the last two decades (2004–2024)

This bibliometric analysis provided insight into research frequencies and their growth, scope, and evolving research gaps around research on STEM education and critical thinking. A total of 5091 articles were published: 3839 in Scopus and 1251 in WoS. This represents a large body of research. However, only 61 articles in Scopus and 69 in WoS (130/5091, just 0.025% of all articles) directly addressed the link between STEM education and critical thinking. This shows that, while STEM education has grown, research on it and its link to critical thinking remains limited.

4.2.2. Comparative bibliometric insight (WoS vs. Scopus): temporal visualisation

Temporal visual images of the Scopus and WoS databases clearly indicate an exponential growth of intensity of linkage among the major keywords between the period 2016 and 2024. This result shows an acceleration in researchers' and scholars' attention toward STEM-oriented research. Further keyword analysis in the study also supports this statement. Few keywords, namely "STEM education”, “STEM”, “critical thinking”, 21st-century skills, “creativity”, “inquiry-based learning”, and “science education”, dominate the whole discourse on STEM. One of the most prominent keywords is “STEM”, which has co-occurred 31 times with a link strength of 24, followed by another prominent word, “critical thinking”. The “critical thinking” keyword has a comparable link strength to “STEM”, co-occurring almost 14 times, much lower than “STEM” but higher than many other, more dominant keywords. All other keywords, such as “creativity”, “21st-century skills”, “attitude”, “science process skills”, “active learning”, “assessment”, “nanotechnology”, and “decision-making”, appear less frequently. Since these keywords are comparatively underrepresented, this highlights a possibility for future research. This may help researchers broaden unexplored fields beyond the current focus. WoS data showcases a more structured, pedagogically connected, and grounded research landscape, whereas Scopus reflects a broader covered area but a scattered and innovation-oriented landscape.

4.2.3. Citation analysis

In WoS, the citation analysis reveals that a few countries, especially the USA and China, contributed to the genesis of knowledge in STEM education, with limited citations. Other countries’ participation in research is either moderate or very low. The uneven global research landscape underscores the need for broader cross-national collaboration to diversify perspectives in STEM education and critical thinking research.

Scopus findings highlight a productivity–impact imbalance, in which countries with high research output are not always the most cited, and smaller contributors can have a significant influence. Most countries show low total link strength, indicating weak citation interdependence and limited collaboration within the global research network.

Based on comparative bibliometric insight (WoS vs. Scopus), the United States leads in research productivity and citations. China, Australia, Turkey, and Indonesia are emerging contributors, but their levels of network integration vary. Research on STEM education and critical thinking is concentrated in a few regions, with the Global South having very limited representation. The United States has 48 publications and 553 citations. China has 18 publications and 158 citations. Australia has 6 publications and 175 citations. This clearly indicates the dominance in the field.

4.2.4. Most influential authors and researchers

In WoS, influential researchers include Wilson (2016, 86 citations), Belland (2017, 154 citations), Simpson (2017, 81 citations), Fakayode (2014, 45 citations), and Loyalka (2021, 41 citations), whose works are frequently cited and thus play a pivotal role in advancing scholarship in this domain. In SCOPUS, influential researchers included Widya (2019, 49 citation links), Ardianti (2020, 30 citations), Solod Ikhina (2019, 20 citations), Pearl (2019, 19 citations), and Linh (2019, 18 citations), with “0” link strength. It is evident from Figures 5 and 6 that the Web of Science database has more cited research contributions than the Scopus database.

4.2.5. Top-ranked journals on STEM education and critical thinking

The International Journal of STEM Education and the International Journal of Science Education are leading venues, while the International Journal of Technology and Design Education also makes significant contributions. These journals play a substantial role in knowledge dissemination in the field.

The complete analysis shows that research on STEM education is very extensive. Yet, very few studies have explored its relationship with critical thinking. Publications are also concentrated in a few countries, journals, and keyword clusters. Findings further indicate that critical and equity-oriented perspectives are limited, reflecting their small presence. This shows a significant need to incorporate more critical and inclusive perspectives. Opportunities exist for future research to diversify topics and promote international collaboration. This could enhance understanding of STEM education's role in developing critical thinking. WoS exhibits higher citation counts and stronger intellectual centralisation around a few seminal authors. SCOPUS shows distributed influence with weaker inter-author connectivity.

5. Conclusions

Bibliometric evidence shows that while STEM education has received attention over the past two decades, research explicitly linking it to critical thinking remains minimal, accounting for just 0.025% of total output. Recent global trends include the rise of key terms like "artificial intelligence" in education, "digital and mobile learning", "interdisciplinary teaching", and "sustainability-focused curricula". These developments suggest a stronger alignment of emerging terms with STEM education and higher-order thinking skills, especially critical thinking. However, analysis shows that terms such as creativity, decision-making, active learning, science process skills, and nanotechnology remain underexplored. This indicates that the research community has yet to address the multi-dimensional nature of STEM learning.

Another challenge is the geographical concentration of research. Countries like the USA (48 documents), China (18) and Australia (10) dominate over other research-acclaimed countries that contributed less than 10 documents from 2016 to 2024. These countries also dominate in citations. Due to skewed research contributions, the generalisability of research output gets impacted, thereby limiting diversity. These issues can be addressed by encouraging more research with international collaborations. Open-access dissemination can also help address this imbalance.

Additionally, the dominance of the International Journal of STEM Education and the International Journal of Science Education suggests a strong but narrow knowledge base. Diversifying publication outlets and fostering interdisciplinary dialogue could improve visibility and encourage the exchange of ideas in the field.

Key implications for future research: 1) Artificial intelligence, emerging digital tools, and innovative pedagogical approaches are some other contexts of critical thinking that need to be explored in a 360-degree manner. 2) Massive inclusive global discourse, like gender bias, geographical bias, technocratic bias, and others, needs to be acknowledged through international collaborations of various acclaimed research communities and also by increasing the inclusivity and richness of global discourse. 3) Themes need to accommodate various underexplored but important areas, such as creativity, decision-making, sustainability, and the socio-emotional aspects of STEM learning. Critical debates and deeper theoretical constructs, such as epistemological hierarchy, technocratic biases, and structural inequalities, also need to be accommodated.

Use of Generative-AI tools declaration

The author declares that she has not used Artificial Intelligence (AI) tools in the creation of this article.

AI-assisted tools (ChatGPT and Grammarly) were used to develop professional language and to correct grammatical mistakes. The AI tool was not used for data collection, analysis, interpretation, or generation of research findings. Interpretation and intellectual responsibility rest entirely with the authors.

Conflict of interest

The author declares no competing interests.

Ethics declaration

This study utilised bibliographic records retrieved from the Scopus and Web of Science databases and analyzed them using VOSviewer software. As the research was based solely on publicly available published literature and did not involve human participants, animals, or identifiable personal data, ethical approval and informed consent were not required. All sources were appropriately acknowledged, and the study adhered to accepted standards of academic integrity and responsible research practice.

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