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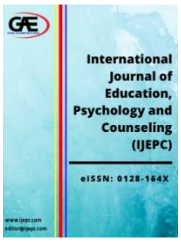

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CRITICAL THINKING IN SCIENCE EDUCATION: A BIBLIOMETRIC ANALYSIS

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Abstract:

This study examines critical thinking in science education through a bibliometric analysis, aiming to provide insights into research trends and inform strategies for enhancing critical thinking skills in science curricula. The objectives of this study are to identify leading authors, significant journals, emerging themes, and gaps in the research on critical thinking within science education. Bibliometric analysis was conducted using data extracted from multiple academic databases, including publication trends, citation patterns, and thematic clustering. Bibliometric tools such as co-citation analysis, keyword mapping, and network visualization were applied to evaluate the evolution of research over recent decades. The findings reveal historical developments, current approaches, and underexplored areas in integrating critical thinking into science education. These insights are intended to guide educators, researchers, and policymakers in promoting critical thinking skills and shaping future research directions in this critical field.

Keywords:

Bibliometric, Education, Curricula, Clustering, Thinking

Introduction

The rapid advancement of science and technology in the 21st century has significantly impacted societies, necessitating the cultivation of critical thinking skills among citizens (Budimansyah & Fitriasari, 2020; Sarıgöz, 2024). Critical thinking is increasingly recognized

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as an essential competency, particularly in science education, where students must navigate complex information, evaluate evidence-based claims, and make informed decisions (Heard et al., 2020; Kumar & Choudhary, 2024). In science education, critical thinking is not only crucial for academic success but also for fostering an informed citizenry capable of addressing global challenges such as climate change, public health crises, and ethical concerns in technology (Alfaro-Ponce et al., 2024; Shutaleva, 2023).

Traditionally, science education has emphasized content knowledge and the acquisition of specific facts and procedural skills (Jamil et al., 2024; Kennedy & Sundberg, 2020). However, recent educational reforms and pedagogical shifts have highlighted the importance of fostering higher-order cognitive skills, such as analysis, evaluation, and synthesis. These competencies enable students to critically engage with scientific knowledge and apply it to real-world contexts (Dare et al., 2021; Prusty et al., 2024). Consequently, the systematic integration of critical thinking into science curricula has become a global priority, influencing policy and classroom practices (Cáceres et al., 2020; Nahar, 2023).

Critical thinking is widely acknowledged as a multifaceted and complex skill, encompassing diverse theoretical frameworks, pedagogical approaches, and assessment strategies (Ma et al., 2023). Understanding historical and contemporary trends in critical thinking research within science education offers valuable insights into the field's evolution, key milestones, and gaps in knowledge. Bibliometric analysis provides a systematic method for identifying patterns in the scientific literature, enabling the mapping of research trends, intellectual structures, and key contributions in each area (Passas, 2024). This study utilizes bibliometric analysis to trace the development of critical thinking research in science education, focusing on identifying leading researchers, influential publications, and emerging research areas.

Literature Review

Critical thinking has emerged as a cornerstone of science education, recognized for its role in fostering students' analytical abilities and promoting informed decision-making (Moustaghfir & Brigui, 2024; Nobutoshi, 2023). Scholars and educators emphasize critical thinking as a vital component in preparing students for complex real-world challenges by enhancing their capacity to evaluate evidence, understand scientific processes, and construct logical arguments (Jamil et al., 2024; Sarwari & Kakar, 2023). However, research on critical thinking in science education spans a wide spectrum of definitions, instructional approaches, and assessment techniques, reflecting the diversity and complexity of the field.

The concept of critical thinking is deeply rooted in philosophy and psychology, with early contributions from Dewey (1933), who described it as reflective thinking, and Ennis (1985), who defined it as reasonable, reflective thinking focused on deciding what to believe or do (Hitchcock, 2020). In the context of science education, critical thinking encompasses skills such as analysis, evaluation, interpretation, and inference, which are necessary for understanding scientific concepts and principles (Forawi, 2016; Santos, 2017). Kuhn (1999) further suggests that critical thinking in science extends beyond basic comprehension to include the ability to question assumptions and understand scientific methodologies (Cartiff et al., 2021; Magarelli, 2024). This conceptual grounding has shaped how educators and researchers approach the integration of critical thinking into science curricula.

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Various instructional strategies have been employed to promote critical thinking in science education, including inquiry-based learning, problem-based learning (PBL), and argumentation (Dewi et al., 2021; Sutiani et al., 2021). Inquiry-based learning encourages students to engage in scientific investigations, fostering a mindset that is curious, skeptical, and open to evidence-based conclusions (Eswaran, 2024). Studies by Osborne (2001) and others have shown that inquiry-based methods effectively enhance students' ability to think critically by immersing them in the scientific process (Alqahtani, 2023).

Similarly, PBL has gained attention for its emphasis on real-world problem-solving, encouraging students to apply their scientific knowledge critically to address complex scenarios (Williamson, 2023). Research suggests that PBL helps students develop higher-order thinking skills, as it requires them to analyze problems, generate solutions, and reflect on their approaches (Singha & Singha, 2024; Williamson, 2023). Argumentation, on the other hand, promotes critical thinking by allowing students to formulate, present, and defend scientific arguments based on evidence (Lombardi et al., 2024; Torregoza & Aliazas, 2024). This approach has been found to improve students’ ability to evaluate evidence and construct reasoned arguments (Wilson et al., 2024).

Assessment of critical thinking in science education remains a challenging and debated issue. Traditional assessments, which often emphasize factual recall, do not adequately measure critical thinking skills, leading educators to seek alternative assessment methods. Rubrics, reflective journals, and portfolio assessments have been explored as means of capturing students' critical thinking abilities, with each method offering unique advantages and limitations (Braun et al., 2020). For instance, rubric-based assessments can provide structured feedback on specific critical thinking skills, while portfolios allow students to showcase their reasoning over time (Hohmann & Grillo, 2014). Despite these efforts, consensus on effective assessment tools is still lacking, underscoring the need for continued research in this area.

Over the past few decades, research on critical thinking in science education has grown substantially, influenced by shifts in educational policy and curriculum reform worldwide (Ma et al., 2023). Bibliometric analyses have revealed significant trends in this body of research, highlighting the increasing emphasis on critical thinking as a key learning outcome in science education (Wang & Jia, 2023). Key studies have emerged as foundational, with researchers focusing on diverse areas such as instructional design, teacher education, and the impact of critical thinking on scientific literacy (Sharon & Baram-Tsabari, 2020). Recent studies also explore the role of digital technologies, such as online simulations and interactive modules, in enhancing critical thinking skills, suggesting that technology integration offers new pathways for developing these competencies (Rahmawati et al., 2023).

Despite the robust body of research on critical thinking in science education, several gaps remain. First, while various instructional strategies have been shown to promote critical thinking, their implementation often varies widely, leading to inconsistent outcomes (Dinsmore & Fryer, 2023). More research is needed to establish best practices and provide educators with practical guidelines for integrating critical thinking into science curricula. Second, although the assessment of critical thinking has been a focal point, there is still a lack of reliable, standardized tools that can capture the depth and complexity of students' critical thinking abilities (Alsaleh, 2020; Cargas et al., 2017; Jabali et al., 2024).

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Another emerging area of interest is the influence of cultural and contextual factors on critical thinking (Guamanga et al., 2024). Research suggests that critical thinking is influenced by students' cultural backgrounds and prior experiences, yet studies often lack consideration of these factors, which may impact the generalizability of findings (Carbajal et al., 2024). Future research could benefit from a cross-cultural approach to explore how critical thinking develops in diverse educational settings.

The literature on critical thinking in science education highlights its essential role in equipping students with skills that are crucial for scientific inquiry and lifelong learning. While significant progress has been made in understanding how to foster and assess critical thinking, challenges remain in terms of effective implementation, reliable assessment, and cross-cultural applicability. Through a bibliometric analysis, this study aims to build upon existing literature by providing a comprehensive overview of trends, key contributors, and thematic shifts, thereby informing future research and practice in critical thinking within science education.

Table 1: Summarizing The Findings Of Past Studies On Theoretical Frameworks Related To Critical Thinking In Science Education.

Author(s)	Theoretical Framework	Findings/Key Contributions	Year
Dewey	Reflective Thinking	Introduced the concept of reflective thinking as the foundation of critical thinking. Emphasized systematic reasoning processes.	1933
Ennis	Critical Thinking Skills	Defined critical thinking as "reasonable, reflective thinking focused on deciding what to believe or do." Developed a skills-based model.	1985
Kuhn	Scientific Reasoning and Inquiry	Highlighted the importance of questioning assumptions and understanding methodologies in scientific thinking.	1999
Forawi	Critical Thinking in Science Education	Linked critical thinking skills (analysis, evaluation, and inference) directly to the understanding of scientific concepts.	2016
Santos	Critical Thinking for Scientific Literacy	Advocated critical thinking as a core element of scientific literacy and global citizenship.	2017
Osborne	Inquiry-Based Learning	Found that inquiry-based approaches effectively enhance critical thinking by immersing students in the scientific process.	2001
Williamson	Problem-Based Learning (PBL)	Demonstrated that PBL fosters critical thinking through real-world problem-solving and reflective practices.	2023
Lombardi et al.	Argumentation and Evidence-Based Reasoning	Identified argumentation as a key method to improve students' ability to evaluate evidence and construct logical arguments.	2024
Rahmawati et al.	Digital Technology Integration	Explored how online simulations and interactive modules enhance critical	2023

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		thinking by creating engaging learning environments.	
Dinsmore & Fryer	Implementation of Critical Thinking Strategies	Highlighted challenges in the practical implementation of critical thinking strategies, emphasizing the need for standardized methods.	2023

Research Question

1. What are the research trends in critical thinking in science education according to the year of publication?
2. Who are the prominent authors in this area, and how much research have they published?
3. Who are the authors of the most cited articles, and what are their institutional affiliations?
4. Which countries have been the most prolific in publishing research on critical thinking in science education in 2014 to 2024?
5. What are the co-occurrence patterns, co-citation networks, and international collaborations in critical thinking research in science education?

Methodology

This study employs bibliometric analysis to explore the research trends, patterns, and emerging areas in the field of critical thinking within science education. Bibliometric analysis involves the collection, management, and systematic analysis of bibliographic data from scientific publications, enabling the identification of key research contributions, influential authors, journals, and the evolution of thematic clusters within a specific academic domain (Hassan & Duarte, 2024).

Data Collection and Management

Data for this study were collected from Elsevier's Scopus database, which is well-regarded for its extensive coverage of peer-reviewed journals across various disciplines, including science education. Scopus was chosen for its comprehensive indexing, particularly for recent publications (Tomaszewski, 2023), and its ability to capture high-quality, multidisciplinary research trends. Unlike other databases, such as Web of Science (WoS), Scopus provides more thorough indexing of recent publications, ensuring that the study reflects the most up-to-date trends in critical thinking research (Simard et al., 2024).

The inclusion criteria for this analysis were:

- Peer-reviewed journal articles published between 2014 and 2024.
- Articles focusing on critical thinking in science education.
- Exclusion of non-peer-reviewed literature, such as books, conference proceedings, and grey literature.

The selected dataset was further refined using keywords relevant to the study, such as "critical thinking," "science education," and "curriculum," to ensure a focused analysis. Literature screening involved an iterative process to filter out irrelevant or redundant articles, with an

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emphasis on ensuring that only those publications aligned with the research goals were included in the final dataset (Marzi et al., 2024).

Technique of Analysis

The analysis was conducted using advanced bibliometric techniques to explore the research trends and intellectual structure of critical thinking in science education. Descriptive statistics were first employed to review basic bibliometric indicators, such as publication trends by year, prominent journals, and author classifications. This approach helped to establish a broad understanding of the overall scope of the research field (Passas, 2024). In addition, co-citation analysis was utilized to examine the relationships between cited references, enabling the identification of clusters of research topics and providing insights into the intellectual structure of the field. By analysing which articles or authors are frequently cited together, co-citation analysis helps reveal the relatedness of various research topics (Hassan & Duarte, 2024).

Furthermore, keyword mapping and network analysis were applied to identify and visualize key terms and their interconnections across the literature. This technique offered valuable insights into the emerging themes and evolving research directions within the domain of critical thinking in science education (Tomaszewski, 2023). To further refine the findings, thematic clustering was employed, using clustering algorithms to group publications into distinct thematic areas. This facilitated the identification of major research themes and highlighted emerging topics within the field.

The entire analytical process involved iterative data refinement and result validation, ensuring that the analysis remained aligned with the research objectives and accurately reflected the current state of knowledge in critical thinking research in science education (Marzi et al., 2024).

Data Analysis Flowchart

Below is the flowchart representing the systematic approach employed for the bibliometric analysis process:

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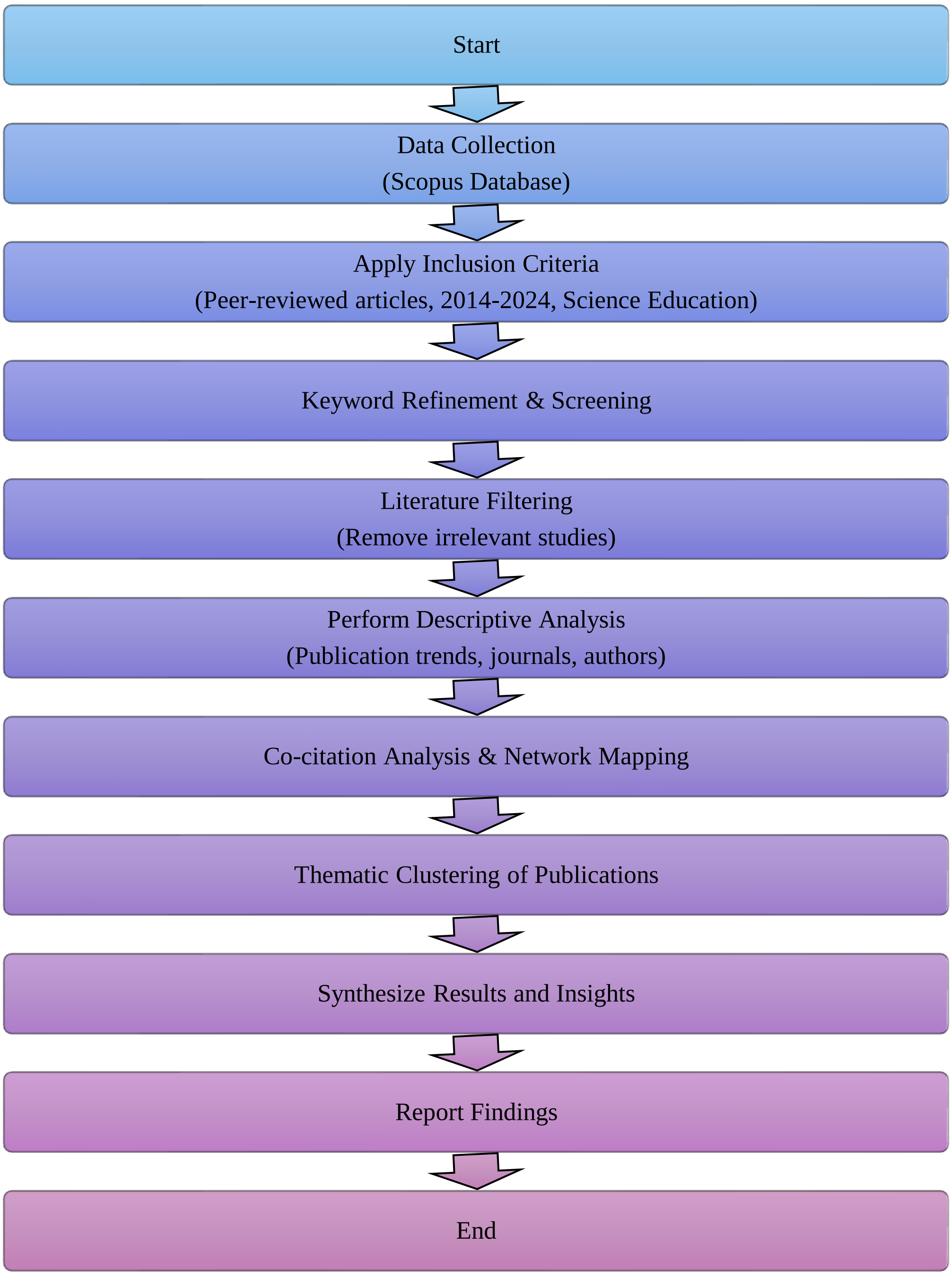

Ensuring Reliability

To ensure the reliability of the findings, only peer-reviewed articles from reputable academic journals were included, and rigorous screening methods were applied throughout the process. The bibliometric tools used in this analysis allowed for a detailed examination of the intellectual landscape of critical thinking in science education, facilitating the identification of key publications, leading authors, and emerging research topics (Hassan & Duarte, 2024). This methodological rigor guarantees the study's credibility and ensures that the results provide a comprehensive and up-to-date overview of the field.

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Data Search Strategy

This study employed a systematic screening process to refine search terms for retrieving relevant articles. Initially, the Scopus database was queried with the following search string: `TITLE-ABS-KEY ( critical AND thinking AND in AND science AND education ) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND ( LIMIT-TO ( SUBJAREA , "SOCI" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "cp" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )`, resulting in an initial assembly of 1,447 articles. This search strategy focused specifically on publications from 2014 to 2024, ensuring a concentration on contemporary research within the last decade to capture recent trends and developments. To maintain relevance to the field of social science, the search was limited to articles classified under the social sciences subject area, aligning with the study's focus on educational practices and pedagogical research. Furthermore, only document types classified as "article" or "conference paper" were included, as these are generally peer-reviewed and offer substantial empirical or theoretical insights. Conference papers were considered to capture preliminary findings that often precede full journal publications, providing a more comprehensive view of emerging research. Additionally, the language was restricted to English to ensure clarity and accessibility of the results for analysis. Following this initial screening, further refinement was conducted to exclude reviews and other non-research formats, resulting in a final dataset of 1447 articles. This collection was subsequently used for bibliometric analysis, providing a robust foundation for exploring trends, prominent themes, and influential contributors in the domain of critical thinking within science education.

Data Analysis

Acquired from Scopus database covering the period 2014 to 2024, data sets including the study publication year, publication title, author name, journal, citation and keyword in PlainText format were examined in VOSviewer software version 1.6.15. The VOS clustering and mapping techniques were applied in this program to analyse and create maps. VOSViewer is an alternative to Multidimensional Scaling (MDS) approach (Bukar et al., 2023; Van Eck et al., 2010) and it is similar in terms of its aim which is concentrated on placement of items in low-dimensional area in such a manner that the relatedness and similarity of any two items is reflected accurately by the distance between them (Appio et al., 2014; Nadzar et al., 2017). Unlike MDS, which is concentrated on the computation of similarity measures such Jaccard indexes and cosine, VOS implements a more suitable technique for normalising co-occurrence frequencies (Cobo et al., 2011; Van Eck & Waltman, 2010), such as, the association strength (ASij) and is calculated as:

$$\mathrm{AS}_{ij} = \frac{C_{ij}}{W_i W_j}$$

where:

- C_{ij} represents the observed number of co-occurrences between items i and j,
- W_i and W_j represent the total occurrences of items i and j, respectively.

It is "proportional to the ratio between on the one hand the observed number of cooccurrences of i and j and on the other hand the expected number of co-occurrences of i and j under the assumption that co-occurrences of i and j are statistically independent"(Van Eck et al., 2010). VOSviewer thus uses this index to place objects in the form of a map following a reduction of the weighted sum of the squared distances between all item pairs (Van Eck & Waltman, 2014).

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Appio et al.(2016) claim that there was implementation of the LinLog/modularity normalisation. Furthermore, analyses including keyword co-occurrence, citation analysis and co-citation analysis were conducted by using visualisation approaches applied via VOSviewer to the data set, so revealing patterns built on mathematical relations (Klarin, 2024).

VOSviewer thus reduces the weighted sum of the squared distances between all item pairs and then arranges objects in the form of a map with help of this index(Saud et al., 2024). There was implementation of the LinLog/modularity normalisation (Щербаченко & Котенко, 2023). Moreover, analyses including keyword co-occurrence, citation analysis, and co-citation analysis were conducted by using visualising approaches applied via VOSviewer to the data set, so revealing patterns built on mathematical relationships(Shen et al., 2023). Keyword co-occurrence analysis helps one investigate development of research area during a period using popular topics in several domains (Sedighi, 2016). Citation analysis, on the other hand, helps spot important research questions, trends, and approaches as well as in investigating the historical relevance of a discipline's main focus (Karunarathna et al., 2024). One of the often used bibliometric techniques is document co-citation analysis; its outcome is map dependent on the network theory to identify the relevant structure of data (Hassan & Duarte, 2024; Klarin, 2024; Milman & Zhurkovich, 2024; Robledo-Giraldo et al., 2023).

Findings

What Are The Research Trends In Critical Thinking In Science Education According To The Year Of Publication?

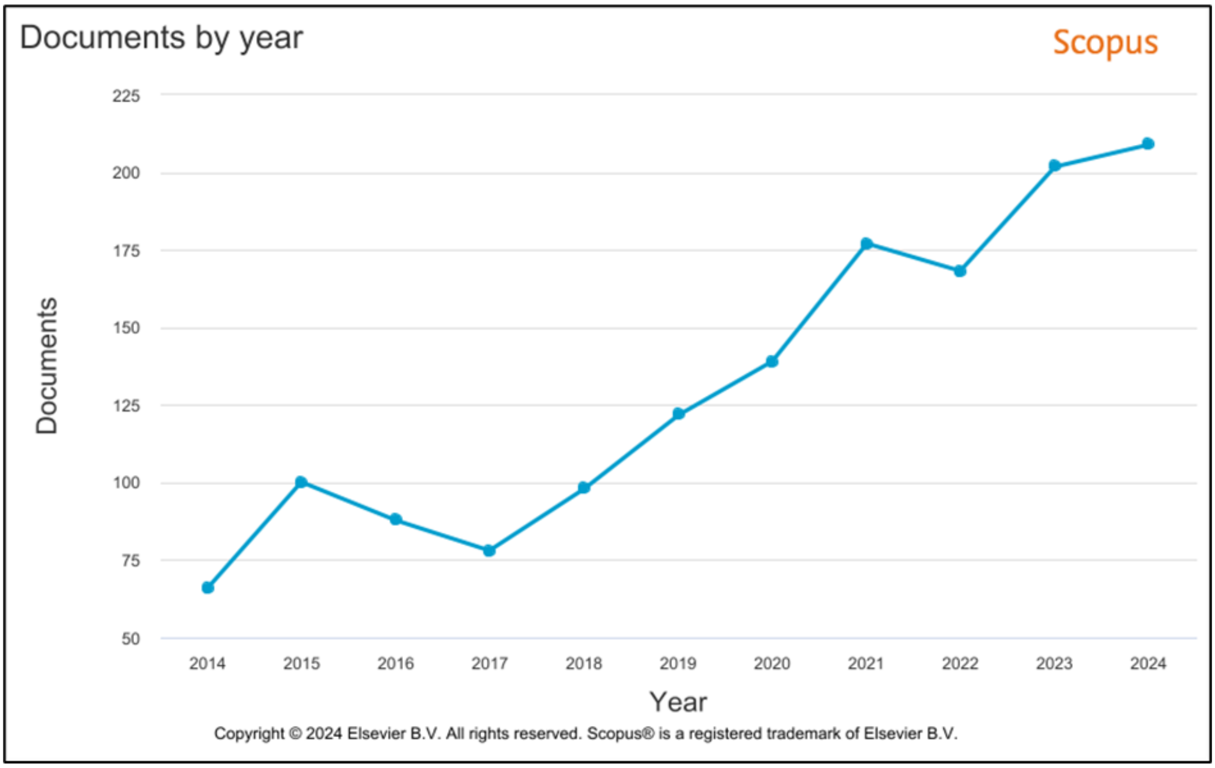

Figure 1: Trend Of Research In Critical Thinking In Science Education By Years

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Table 2: Trend Of Research In Critical Thinking In Science Education By Years

Year	Total publication
2024	209
2023	202
2022	168
2021	177
2020	139
2019	122
2018	98
2017	78
2016	88
2015	100
2014	66

Table 2 shows the number of publications on critical thinking in science education published each year between 2014 and 2024. The figures show that research in this field has demonstrated a steady increase over time, ranging from 66 publications (2014) to 209 publications (2024). There were 66 articles published in 2014, representing 4.56% of total publications; 100 publications in 2015, representing 6.91%; 88 publications in 2016, representing 6.08%; 78 publications in 2017, representing 5.39%; 98 publications in 2018, representing 6.77%; 122 publications in 2019, representing 8.43%; 139 publications in 2020, representing 9.61%; 177 publications in 2021, representing 12.23%; 168 publications in 2022, representing 11.61%; 202 publications in 2023, representing 13.96%; and 209 publications in 2024, representing 14.44% of total publications. We notice that the highest number of publications occurred in the most recent years (2023-2024), indicating a growing interest in critical thinking research in science education. The data suggests a clear upward trend in research output, with particularly substantial growth observed from 2019 onwards, despite a slight fluctuation in 2022.

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Who Are The Prominent Authors In This Area, And How Much Research They Have Published?

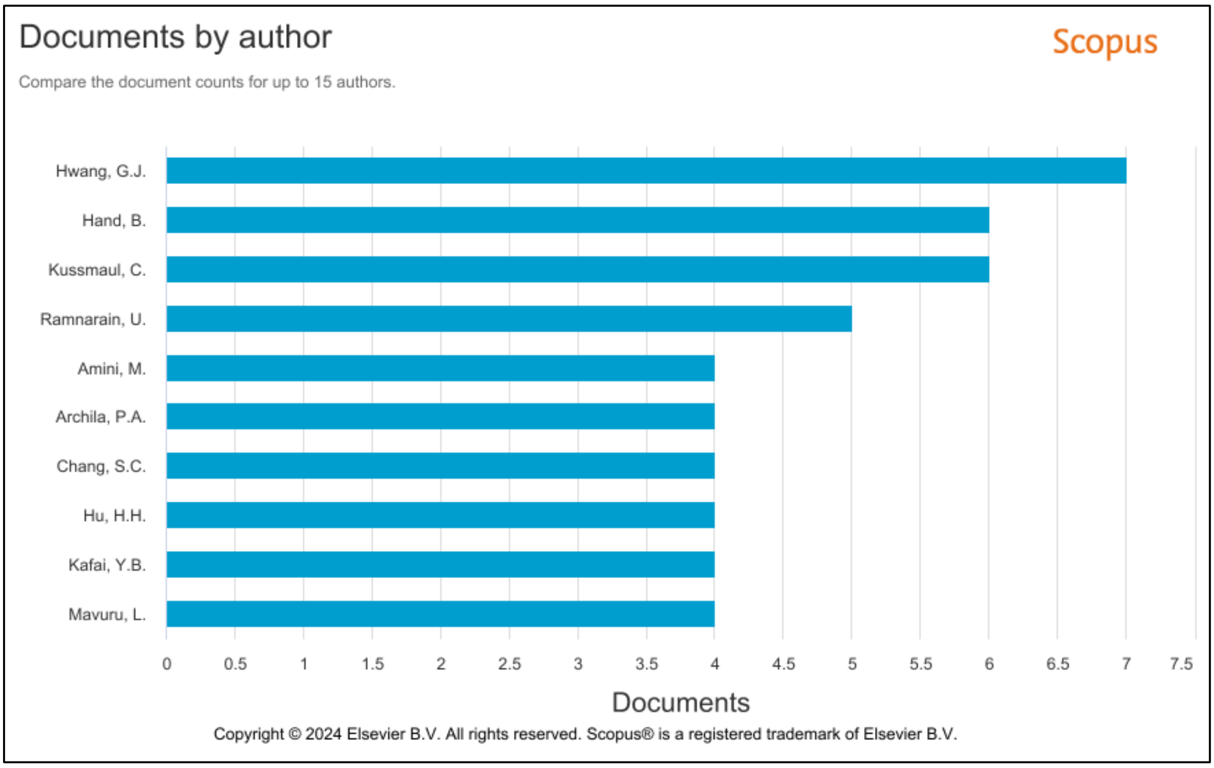

Figure 2 : Prominent Authors In Critical Thinking In Science Education And Number Of Research They Have Published

Table 3: Prominent Authors In Critical Thinking In Science Education And Number Of Research They Have Published

Authors	Number of research they have published
Hwang, G.J.	7
Hand, B.	6
Kussmaul, C.	6
Ramnarain, U.	5
Amini, M.	4
Archila, P.A.	4
Chang, S.C.	4
Hu, H.H.	4
Kafai, Y.B.	4
Mavuru, L.	4

Table 3 presents the most productive authors in critical thinking in science education research. Hwang, G.J. leads with 7 publications (0.484%), followed by Hand, B. and Kussmaul, C., each with 6 publications (0.415%). Ramnarain, U. contributed 5 publications (0.346%), while six researchers which are Amini, M., Archila, P.A., Chang, S.C., Hu, H.H., Kafai, Y.B., and Mavuru, L., each published 4 papers (0.276%) in this field. This distribution of publications among the top authors indicates that although the field has some leading researchers, their

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individual contributions represent a relatively small percentage of the total publications, suggesting a diverse research community where many scholars contribute to the advancement of critical thinking in science education. The analysis reveals that even the most prolific author's contribution (0.484%) represents less than half a percent of the total publications, indicating a well-distributed research effort across the scientific community.

Who Are The Authors Of The Most Cited Articles, Years, And From Which Journal?

Table 4: The Most Cited Articles For Critical Thinking In Science Education

Cited	Authors	Titles	Year	Journals
382	Cooper, G.	Examining Science Education in ChatGPT: An Exploratory Study of Generative Artificial Intelligence	2023	Journal of Science Education and Technology, 32(3), pp. 444–452
319	Kong, S.C.	Developing information literacy and critical thinking skills through domain knowledge learning in digital classrooms: An experience of practicing flipped classroom strategy	2014	Computers and Education, 78, pp. 160–173
171	Morales-Doyle, D	Justice-centered science pedagogy: A catalyst for academic achievement and social transformation	2017	Science Education, 101(6), pp. 1034–1060
142	Stigmar, M.	Peer-to-peer Teaching in Higher Education: A Critical Literature Review	2016	Mentoring and Tutoring: Partnership in Learning , 24(2), pp. 124–136
141	Changwong, K., Sukkamart, A., Sisan, B.	Critical thinking skill development: Analysis of a new learning management model for Thai high schools	2018	Journal of International Studies, 11(2), pp. 37–48
141	Van Vliet, E.A., Winnips, J.C., Brouwer, N.	Flipped-class pedagogy enhances student metacognition and collaborative-learning strategies in higher education but effect does not persist	2015	CBE Life Sciences Education, 14(3), pp. 1–10
125	Chang, S.-C., Hsu, T.-C., Jong, M.S.-Y.	Integration of the peer assessment approach with a virtual reality design system for learning earth science	2020	Computers and Education, 146, 103758
125	Tiruneh, D.T., De Cock, M., Weldeslassie, A.G., Elen, J., Janssen, R.	Measuring Critical Thinking in Physics: Development and Validation of a Critical Thinking Test in Electricity and Magnetism	2017	International Journal of Science and Mathematics Education, 15(4), pp. 663–682

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124	Duncan, R.G., Chinn, C.A., Barzilai, S.	Grasp of evidence: Problematizing and expanding the next generation science standards' conceptualization of evidence	2018	Journal of Research in Science Teaching, 55(7), pp. 907–937
120	RamírezMontoya, M.S., Castillo-Martínez, I.M., Sanabria-Z, J., Miranda, J.	Complex Thinking in the Framework of Education 4.0 and Open Innovation—A Systematic Literature Review	2022	Journal of Open Innovation: Technology, Market, and Complexity, 8(1), 4

Table 4 illustrates the top 10 most cited publications in critical thinking in science education research. The most cited work is by Cooper, G. (2023) titled "Examining Science Education in ChatGPT: An Exploratory Study of Generative Artificial Intelligence," published in the Journal of Science Education and Technology, with 382 citations (24.97% of total citations). The second most influential paper is by Kong, S.C. (2014), "Developing information literacy and critical thinking skills through domain knowledge learning in digital classrooms: An experience of practicing flipped classroom strategy," published in Computers and Education, receiving 319 citations (20.85%). Morales-Doyle, D.'s 2017 publication on "Justice-centered science pedagogy: A catalyst for academic achievement and social transformation" in Science Education ranks third with 171 citations (11.18%). The remaining highly cited papers include Stigmar, M.'s work (142 citations, 9.28%), followed by papers by Changwong, K., et al. and Van Vliet, E.A., et al. (both with 141 citations, 9.22% each), Chang, S.-C., et al. and Tiruneh, D.T., et al. (both with 125 citations, 8.17% each), Duncan, R.G., et al. (124 citations, 8.10%), and Ramirez-Montoya, M.S., et al. (120 citations, 7.84%). These publications span various prestigious journals in the field, indicating the diverse nature of critical thinking research in science education across different educational contexts and approaches.

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Which Countries Have Been The Most Prolific In Publishing Research On Critical Thinking In Science Education In 2014 To 2024?

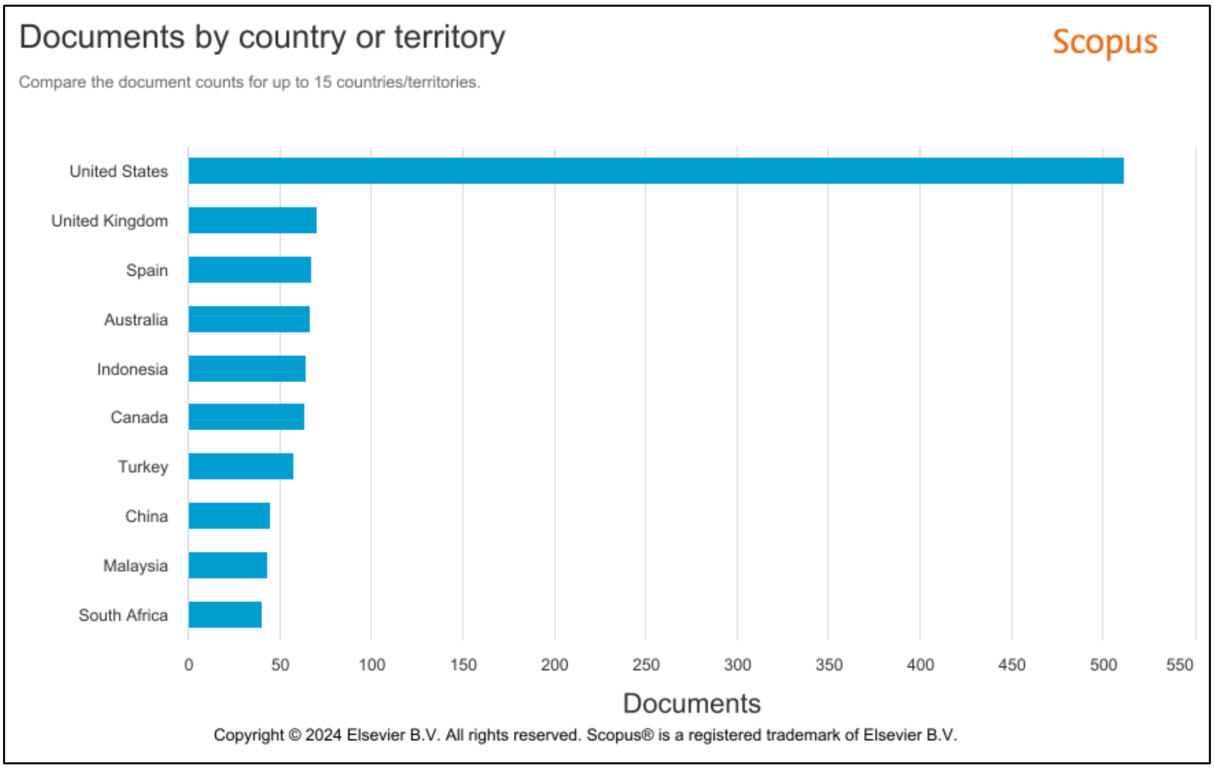

Figure 3: The Most Prolific Countries In Publishing Research On Critical Thinking In Science Education In 2014 To 2024

Table 5: The Most Prolific Countries In Publishing Research On Critical Thinking In Science Education In 2014 To 2024

Country/Territory	**Documents**
United States	511
United Kingdom	70
Spain	67
Australia	66
Indonesia	64
Canada	63
Turkey	57
China	44
Malaysia	43
South Africa	40

Table 5 presents the top 10 most prolific countries in publishing research on critical thinking in science education from 2014 to 2024. The United States emerges as the dominant contributor with 511 publications, representing a substantial 49.61% of the total research output. The United Kingdom follows as the second most productive country with 70 publications (6.80%), while Spain ranks third with 67 publications (6.51%). Australia has contributed 66 publications (6.41%), followed closely by Indonesia with 64 publications (6.22%) and Canada with 63

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publications (6.12%). Turkey has produced 57 publications (5.53%), while China and Malaysia have contributed 44 (4.27%) and 43 (4.17%) publications respectively. South Africa rounds out the top 10 with 40 publications (3.88%). This distribution reveals a significant concentration of research activity in North America, Europe, and the Asia-Pacific region, with the United States producing nearly half of all publications in this field, highlighting its substantial influence in critical thinking research in science education during this period.

What Are The Co-Occurrence Patterns, Co-Citation Networks, And International Collaborations In Critical Thinking Research In Science Education?

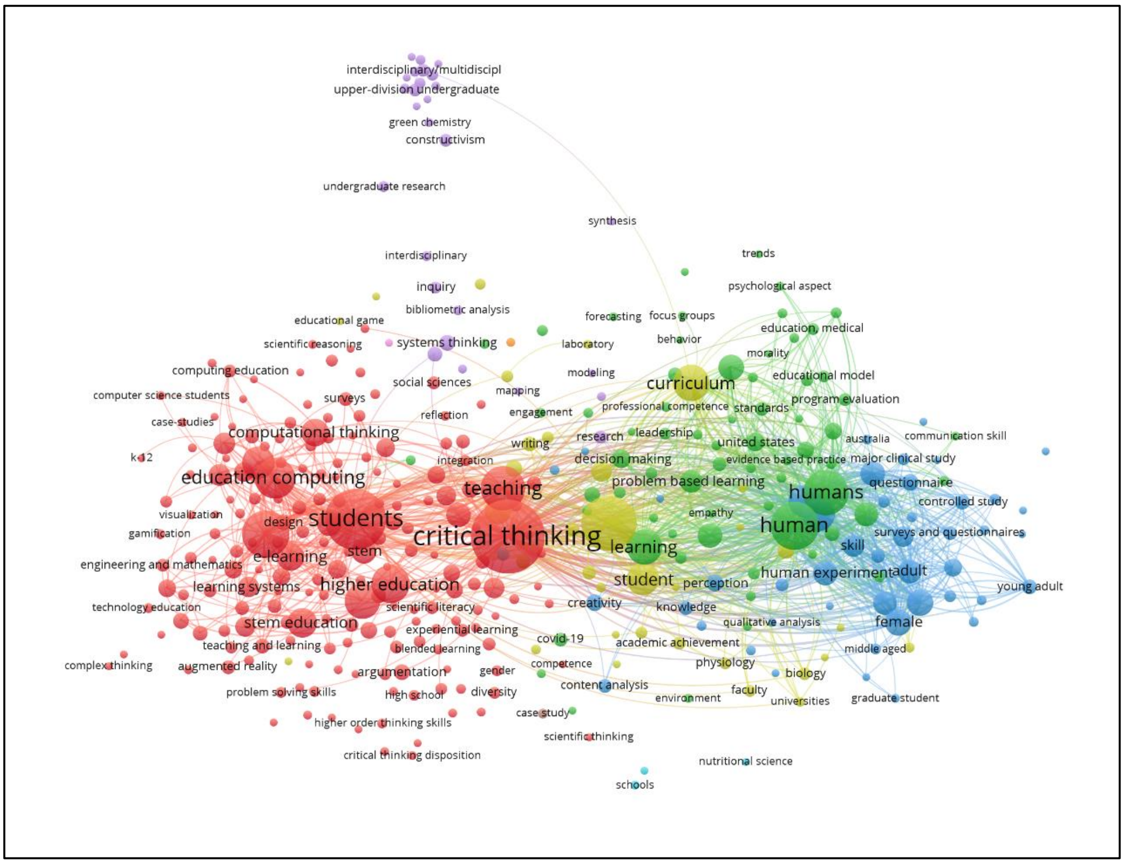

Figure 4: Co-Occurence Patterns For Critical Thinking In Science Education From 2014 To 2024

The visualization presents a comprehensive keyword co-occurrence network map of research on critical thinking in science education. The network reveals distinct clusters, represented by different colors (red, green, blue, and purple), with "critical thinking" positioned as the central node. The red cluster, which is the most prominent, focuses on core science education pedagogy, featuring terms like "students," "stem education," "computational thinking," "e-learning," "science technologies," and "computer-aided instruction," indicating a strong emphasis on technological and modern educational approaches in science teaching. The blue cluster centers around curriculum and learning methodologies, including "problem-based learning," "systematic review," "active learning," and "science reasoning," which reflects the pedagogical frameworks used in science education. The yellow cluster appears to focus on methodological aspects with terms like "surveys," "meta-analysis," and "educational model,"

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while the purple cluster contains terms related to "interdisciplinary approaches," "undergraduate research," and "green chemistry." The size of the nodes and thickness of connecting lines indicate the frequency of keyword occurrence and strength of relationships between terms, with larger nodes representing more frequently occurring terms. This visualization demonstrates the multifaceted nature of critical thinking research in science education, particularly emphasizing the integration of technology, innovative teaching methods, and various pedagogical approaches in STEM education.

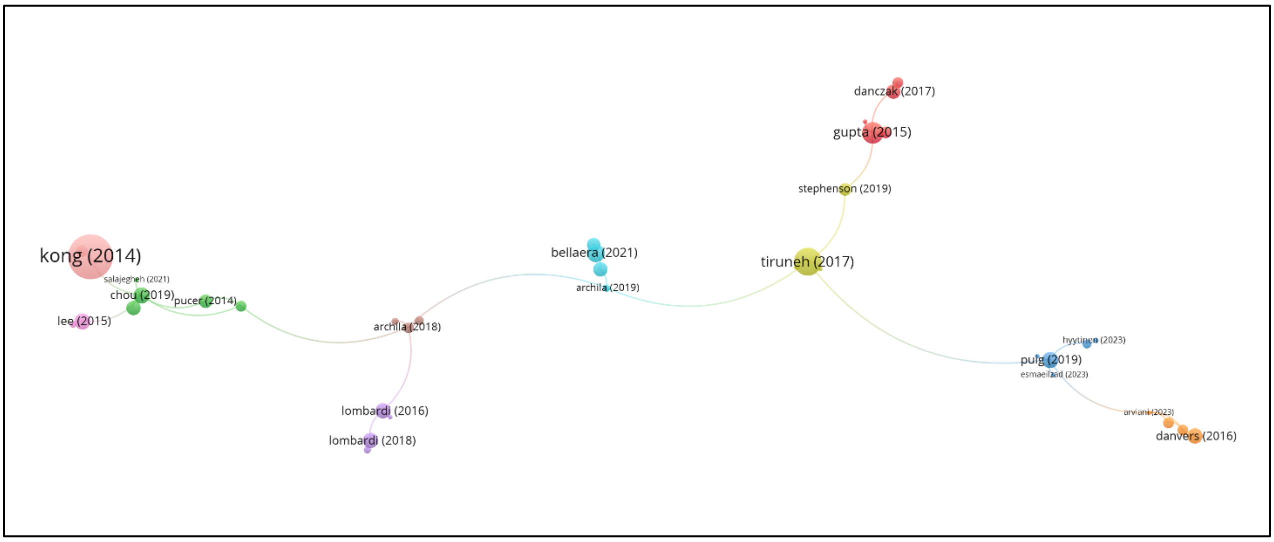

Figure 5: Co-Citation Networks For Critical Thinking In Science Education From 2014 To 2024

This visualization presents a co-citation network analysis of influential publications in critical thinking in science education research from 2014 to 2024. The network map illustrates how frequently pairs of documents are cited together, revealing the intellectual structure of the field through distinct clusters indicated by different colors. The map shows several key nodes and their interconnections, with Kong (2014) emerging as a significant node in the red cluster, demonstrating its fundamental influence in the field of digital classroom learning and critical thinking development. The network reveals temporal and thematic evolution through various clusters: Gupta (2015) and Danczak (2017) form connections in the upper portion, suggesting work related to science education methodology; Bellaera (2021) and Archila (2019) represent more recent developments in the turquoise cluster; and Tiruneh (2017) connects with Stephenson (2019) in the yellow cluster, indicating research progression in assessment and evaluation methods. The purple cluster, featuring Lombardi (2016, 2018), shows the continuity of research themes over time. The network extends to recent contributions by Hyytinen (2023) and Esmaeilzaid (2023), demonstrating the field's ongoing evolution. The interconnectedness of these citations suggests a cohesive body of literature where researchers consistently build upon and reference each other's work, indicating a mature and well-developed research area in critical thinking within science education.

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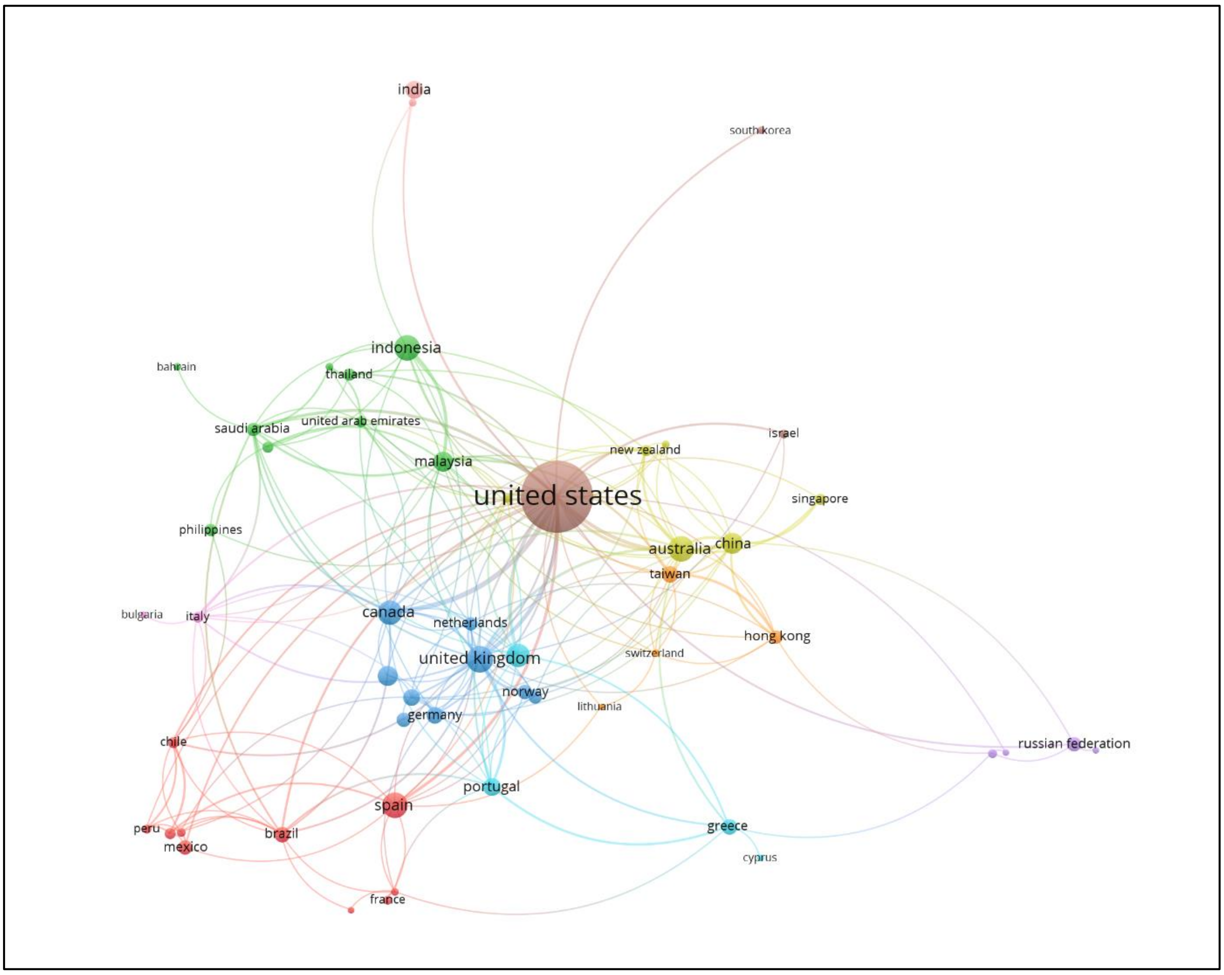

Figure 6: International Collaboration Network In Critical Thinking In Science Education Research

The visualization presents a comprehensive international collaboration network in critical thinking in science education research. The network map reveals distinct clusters of research collaboration between different countries, represented by nodes of varying sizes and connected by lines indicating joint research activities. The United States appears as the largest node in the network, indicating its central role as a major research hub and collaborator with multiple countries. The network shows several clear regional collaboration patterns: a strong European cluster (blue) including the United Kingdom, Netherlands, Germany, and Norway; an Asian cluster (green) featuring Indonesia, Malaysia, Thailand, and the United Arab Emirates; and a Pacific cluster (yellow) connecting Australia, China, and New Zealand. The size of nodes corresponds to the volume of collaborative output, with larger nodes like the United States, United Kingdom, and Australia indicating higher levels of international cooperation. Latin American countries (red cluster) including Brazil, Chile, Mexico, and Peru show interconnected research relationships, while some nations like the Russian Federation appear more peripherally connected. The dense interconnections between nodes suggest a robust international research community in critical thinking in science education, with strong cross-continental collaborations particularly centered around major research-producing nations.

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Summary of Main Findings

Table 6: Summary Of Main Findings

Category	**Key Findings**
Research Trends	Steady increase in publications from 2014 (66) to 2024 (209), with substantial growth from 2019 onward.
Prominent Authors	Leading authors: Hwang, G.J. (7), Hand, B. and Kussmaul, C. (6); diverse contributions across the field.
Highly Cited Articles	Key citations: Cooper, G. (2023) on AI in education, Kong, S.C. (2014) on flipped classrooms.
Prolific Countries	US (511 publications) dominates; other top contributors: UK, Spain, Australia, Indonesia.
Co-occurrence Patterns	Four main clusters: Pedagogy (red), Curriculum (blue), Methodology (yellow), Interdisciplinary (purple).
Co-citation Networks	Notable authors: Kong (2014), Danczak (2017); thematic progression in pedagogical strategies and assessment.
International Collaboration	Strong global collaborations, particularly between the US, UK, Europe, and Asia-Pacific regions.

The summary of main findings encapsulates key insights drawn from the research on critical thinking in science education between 2014 and 2024. These findings offer a comprehensive view of the field's development and current state, highlighting trends, influential authors, geographic patterns, and thematic clusters that shape this expanding area of study. In conclusion, the research reveals a dynamic and increasingly important field, characterized by growing research output, diverse scholarly contributions, and significant international collaboration. The heightened focus on critical thinking is reflected in the development of innovative pedagogical approaches, methodologies, and global discussions on effectively integrating critical thinking into science education. These findings underscore the recognition of critical thinking as a vital skill in science education, with far-reaching implications for teaching practices and policy development worldwide.

Discussion

Our bibliometric analysis of critical thinking in science education research from 2014 to 2024 offers a detailed overview of the field's evolution, key contributors, and collaborative dynamics. Firstly, the data indicates a consistent growth in research output over the past decade, with a notable increase in recent years (2023-2024), underscoring a heightened interest in critical thinking as a pivotal component of science education. This trend suggests an expanding recognition of the importance of critical thinking skills for fostering scientific literacy and preparing students for complex problem-solving in modern educational settings.

Prominent authors, as identified in this analysis, have made valuable contributions to advancing the field. However, the distribution of publications shows that individual productivity remains relatively low compared to the overall volume of research, reflecting a broad, distributed effort among numerous scholars. Additionally, while some authors are prolific in publishing, others are distinguished more by the impact of their citations, indicating that influence in the field is not solely based on publication volume but also on the relevance and quality of the work.

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In terms of country-level analysis, the United States stands out as the most prolific contributor, followed by the United Kingdom, Spain, and Australia. While Romania, for example, is productive in publishing, it does not feature among the most cited nations, highlighting the distinction between publication volume and research influence. This phenomenon suggests that certain countries, though contributing fewer publications, exert greater influence, likely through higher-quality research or more impactful studies. Additionally, Australian institutions are noteworthy, as they appear in the top five most cited despite not being among the highest in publication volume.

The co-occurrence analysis reveals a complex network of themes and concepts within critical thinking in science education. Dominant themes include pedagogical approaches integrating technology (e.g., "STEM education," "computational thinking") and active learning methodologies (e.g., "problem-based learning," "science reasoning"). The network map also highlights specific methodologies and interdisciplinary approaches, illustrating the field's multifaceted nature and the varied pedagogical strategies employed to enhance critical thinking skills. Central terms such as "critical thinking," along with closely related nodes like "e-learning" and "science technologies," underscore a significant focus on technology's role in fostering critical thinking within science education.

Our analysis of international collaborations reveals a robust network of partnerships, with the United States as a central hub, fostering collaborations across multiple continents. Regional clusters, such as those in Europe, Asia, and Latin America, demonstrate strong interconnections and collective efforts to advance critical thinking research in science education. This international cooperation enhances the field by enabling diverse perspectives and cross-cultural insights, further enriching the research landscape.

In conclusion, this bibliometric study highlights the sustained growth, key contributors, and collaborative patterns that define critical thinking research in science education. The findings underscore the importance of international collaboration and the centrality of technology and innovative pedagogies in this field. The study also suggests that impact in critical thinking research is not necessarily tied to the quantity of output but to the influence and quality of the contributions, as evidenced by the most cited works and influential countries and institutions. This analysis serves as a foundation for further exploration of emerging themes, particularly in areas like interdisciplinary approaches and the integration of advanced technology, which continue to shape the future of critical thinking in science education.

Conclusion

This bibliometric analysis of critical thinking in science education research from 2014 to 2024 successfully achieved its primary objectives. The study aimed to explore the evolution of research in this field, identify key contributors, and understand the dynamics of international collaboration. Our findings confirm the increasing importance of critical thinking in science education, as reflected by the growing number of publications, the influence of key authors, and the broad geographical distribution of research activity. Furthermore, the study provides insights into the thematic clusters that define this field, particularly those involving technology integration, active learning methodologies, and interdisciplinary approaches.

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The objectives of the study have been met in the following ways:

1. Research Trends: We identified a clear upward trend in the number of publications on critical thinking in science education, indicating growing interest and recognition of its importance in preparing students for the complexities of modern scientific practice.
2. Key Contributors: Prominent authors and institutions have been identified, with significant contributions from countries like the United States, the United Kingdom, and Australia. The distribution of publications and citations revealed the complex relationship between research output and impact.
3. International Collaboration: The study also shed light on the global collaborative networks shaping critical thinking research, highlighting strong interconnections between countries across continents.

Despite these achievements, the study acknowledges several limitations. First, the reliance on Scopus as the primary database means that some relevant studies indexed elsewhere might have been overlooked. Although Scopus is comprehensive, the exclusion of other databases, such as Web of Science or Google Scholar, could potentially limit the breadth of the data. Additionally, the study focused exclusively on articles published in peer-reviewed journals, excluding conference papers, books, and grey literature, which may also contain valuable insights. Another limitation is the focus on quantitative bibliometric measures, which, while useful for mapping research trends, do not fully capture the depth or quality of the studies reviewed.

Limitations

The study's reliance on a single database (Scopus) and the exclusion of non-journal articles may have restricted the scope of the analysis. Although Scopus offers comprehensive coverage, its focus on journals means that important contributions in other formats, such as books or conference papers, were not included. Furthermore, while bibliometric techniques like co-citation analysis and keyword mapping provide valuable insights into research patterns, they do not directly evaluate the impact of individual studies' content. Therefore, future studies could complement bibliometric approaches with qualitative assessments to offer a more complete picture of the field's development and key research contributions.

Future Directions

Future research on critical thinking in science education should focus on several emerging trends to address the evolving needs of this field. One promising area lies in the integration of advanced technologies, such as artificial intelligence, virtual reality, and augmented reality. These technologies have the potential to transform teaching and learning practices by creating immersive and interactive environments that enhance critical thinking skills. Investigating their application in science education could yield valuable insights into their effectiveness and scalability across diverse educational settings.

Another significant direction involves exploring interdisciplinary approaches to teaching and learning. Increasing attention is being directed toward methodologies that bridge science education with other domains, such as the social sciences and the arts. These integrated approaches have the potential to foster critical thinking by encouraging students to apply their cognitive skills in broader, more complex contexts. Future research could assess the effectiveness of such interdisciplinary strategies and their impact on learners' ability to engage with multifaceted scientific and societal challenges.

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Longitudinal studies also represent a crucial area for further exploration. Understanding the long-term effects of critical thinking interventions requires research that tracks the development of students' cognitive abilities over extended periods. Such studies would provide deeper insights into the strategies that lead to sustained improvements in critical thinking, thereby offering evidence-based recommendations for curriculum design and instructional practices.

Finally, the role of global perspectives and cultural contexts in critical thinking research deserves greater attention. As international collaborations continue to grow, comparative studies examining how different cultural and educational contexts influence the integration of critical thinking in science education are essential. These investigations could uncover culturally specific practices and factors that promote or hinder the development of critical thinking skills, contributing to a more inclusive and globally relevant body of knowledge.

In conclusion, this study underscores the increasing recognition of critical thinking as a cornerstone of science education and highlights the need for future research to focus on advanced technologies, interdisciplinary approaches, longitudinal impacts, and global perspectives. These directions will not only enrich our understanding of critical thinking in science education but also inform the development of innovative practices and policies to equip learners with essential cognitive skills for the complexities of the modern world.

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