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Integration of STEM-Based Learning in Improving Critical Thinking in Mathematics Learning: a Bibliometric Analysis

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ABSTRACT

Objective: *This study aims to analyze global research trends on the integration of STEM-based learning to improve students' critical thinking skills in mathematics education during 2021–2025. It seeks to map publication growth, identify dominant keywords, and explore thematic relationships among research topics.* ***Method:*** *A bibliometric analysis was conducted using data from the Scopus database (2021–2025). The study followed five systematic stages: research design, data compilation, analysis, visualization, and interpretation. Keyword mapping was performed using VOSviewer software with terms such as "STEM," "education," "critical thinking," and "mathematics."* ***Results:*** *A total of 144 relevant articles were identified. The number of publications increased significantly from 2021 to 2025, with "STEM education" emerging as the most dominant keyword. Visualization revealed strong relationships among STEM education, critical thinking, problem solving, and collaborative learning, reflecting a growing global emphasis on developing 21st-century skills through contextual and project-based learning.* ***Novelty:*** *This study presents the first comprehensive bibliometric mapping focused on the intersection between STEM integration and critical thinking in mathematics education. It also highlights emerging research directions integrating digital technology and artificial intelligence (AI) into STEM learning to support innovative, future-oriented educational practices.*

INTRODUCTION

Critical thinking skills are among the higher-order cognitive abilities emphasized in 21st-century education frameworks. In mathematics learning, these skills involve not only conceptual understanding and procedural fluency but also the ability to analyze, evaluate, and connect mathematical ideas to solve problems logically and reflectively (Saxton et al., 2022). Despite their importance, various studies have shown that students' critical thinking skills remain below expectations. For instance, data from the Programme for International Student Assessment (PISA, 2022) revealed that Indonesian students ranked 71st out of 81 countries in mathematical literacy, indicating limited analytical and evaluative reasoning abilities (OECD, 2023). Similarly, Ilyas et al. (2022) found that many students tend to rely on memorization and teacher guidance, showing difficulty in making independent judgments during problem solving. Several studies have confirmed that STEM integration improves students' analytical and reflective abilities (Feziyasti et al., 2025; Lou et al., 2023).

Low performance in PISA, especially in mathematical literacy, underscores the need for pedagogical innovations, such as STEM integration, to develop analytical and problem-solving competencies. To address these challenges, the integration of STEM

(Science, Technology, Engineering, and Mathematics) learning has been widely recognized as an innovative approach for enhancing critical thinking in mathematics. STEM learning encourages students to engage in inquiry, experimentation, and design-based problem solving through authentic, real-world contexts (Bybee, 2020). When integrated into mathematics, STEM activities allow students to connect abstract mathematical concepts with technological and engineering applications, thereby fostering reasoning, creativity, and reflective thinking (Lou et al., 2023). Recent meta-analyses support this view; STEM-based project learning significantly improves students' critical thinking (effect size = 0.61) and creativity across various subjects, including mathematics (Feziyasti et al., 2025).

However, although research on STEM integration in education has increased exponentially, studies that specifically map the relationship between STEM learning and critical thinking in mathematics remain limited (Abdi et al., 2024; Tashtoush et al., 2024). For example, bibliometric analyses by Ha et al. (2020) and Julius et al. (2021) showed a rising trend in STEM education research globally. However, only a small proportion directly addressed mathematical thinking or higher-order reasoning. Moreover, most previous studies focused on classroom implementation rather than comprehensive mapping of scientific collaboration, keyword relationships, or thematic developments in this field. This gap highlights the need for a systematic bibliometric study to analyze publication patterns, keyword networks, and thematic evolution concerning STEM integration and critical thinking in mathematics education.

Therefore, this study aims to conduct a bibliometric analysis of international publications on integrating STEM-based learning to enhance students' critical thinking in mathematics education from 2021 to 2025. The analysis seeks to (1) map global research trends, (2) identify the most influential keywords and themes, and (3) explore the interconnections between STEM education and critical thinking development. This study is expected to provide a comprehensive mapping that helps educators and policymakers identify emerging themes and design more effective STEM-based mathematics learning strategies.

RESEARCH METHOD

This study employed a quantitative bibliometric research design to map and analyze global research trends by statistical evaluation of publication metadata. The bibliometric method was chosen because it enables researchers to identify the growth, impact, and thematic development of studies on the integration of STEM-based learning and critical thinking in mathematics education (Hallinger & Kovačević, 2019; Kartika et al., 2023). The research flow for the bibliometric analysis is shown in the following diagram.

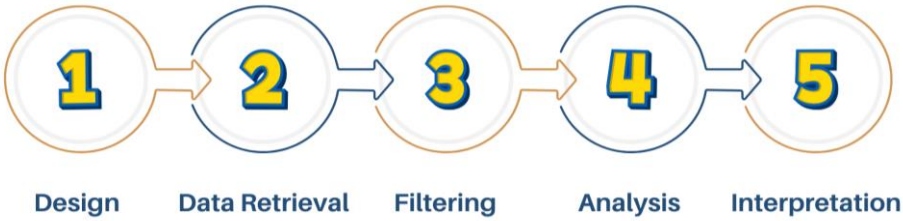


Figure 1. Research design

Type of Research

The study applied a quantitative descriptive approach using bibliometric analysis. This approach provides an overview of publication patterns, keyword distributions, citation networks, and thematic structures within the selected research domain (Lintangesukmanjaya et al., 2025). The analysis was conducted using data obtained from the Scopus database, which is considered the most comprehensive source of peer-reviewed scientific literature in education (Ha et al., 2020).

Population and Data Source

The population of this study consisted of all scientific publications indexed in the Scopus database related to the keywords: "STEM AND education AND critical thinking AND mathematics". The data were collected during January 2021–September 2025. The sample was obtained through purposive selection based on inclusion criteria (document type: article; language: English; subject area: Education, Social Sciences, and Mathematics). A total of 144 documents met the criteria and were included in the analysis. The data were exported in CSV and RIS formats containing bibliographic information such as title, authors, affiliations, keywords, source, and citations.

Data Analysis Technique

The bibliometric analysis followed five systematic stages adapted from Hallinger & Kovačević (2019) and Kartika et al. (2023): (a) Research Design – defining objectives, scope, and keywords. This quantitative bibliometric study analyzes frequency counts, co-occurrence strength, and citation metrics using descriptive statistical analysis. (b) Data Compilation, retrieving and cleaning Scopus data using the chosen search strings. (c) Data Analysis examining publication trends by year, author, country, and source. (d) Visualization generating keyword co-occurrence networks, thematic clusters, and collaboration maps using VOSviewer (version 1.6.20). (e) Interpretation of visual and statistical findings to identify dominant research themes and gaps. Quantitative data (e.g., publication growth) were analyzed using descriptive statistics, and relationships among keywords were examined using network visualization. Each cluster in the visualization represented a group of related topics based on co-occurrence strength.

Research Flow

The research flow in this study followed a structured and systematic sequence to ensure the validity and replicability of the bibliometric analysis. The process began with

data retrieval from the Scopus database using the keywords "STEM AND education AND critical thinking AND mathematics." This stage aimed to collect all publications on the integration of STEM-based learning in mathematics education and its relationship to the development of critical thinking. The second stage was data filtering, where the retrieved documents were refined according to specific inclusion criteria. Only documents classified as articles, written in English, and published between 2021 and 2025 were included. This filtering process ensured that the dataset represented recent and high-quality research outputs relevant to the study's objectives.

Next, the data export phase involved downloading bibliographic information from Scopus in CSV and RIS formats. These formats contained essential metadata, including article titles, author names, affiliations, publication years, keywords, sources, and citation counts, which were required for subsequent analysis. In the fourth stage, data analysis and visualization were performed using VOSviewer (version 1.6.20). The software was used to generate co-occurrence maps, keyword networks, and collaboration visualizations. The analysis produced clusters that represent thematic relationships among keywords, showing how topics such as STEM education, critical thinking, problem-solving, and mathematics learning are interconnected across studies.

Finally, in the interpretation stage, the visualization results were analyzed to identify dominant research themes, emerging trends, and gaps in the literature. The findings were synthesized to construct a comprehensive picture of global research on integrating STEM-based learning to enhance critical thinking in mathematics education. This sequential flow, from data collection through filtering, analysis, visualization, and interpretation, ensured that the bibliometric process was transparent, systematic, and aligned with accepted standards in scientific mapping research.

The dominance of STEM education as a keyword aligns with findings by Abdi et al. (2024), who also reported a rapid increase in interdisciplinary STEM research worldwide. This clustering pattern is consistent with Feziyasti et al. (2025), who demonstrated that project-based STEM learning significantly enhances students' critical thinking and creativity. According to Kelley and Knowles (2016), integrated STEM education provides a conceptual framework that connects science, technology, engineering, and mathematics to foster higher-order cognitive skills such as critical thinking.

RESULTS AND DISCUSSION

Results

The database for this study was sourced from Scopus for the period 2021–2025 (the last 5 years), because during this period many articles were published related to STEM integration, education, critical thinking, and mathematics, so it was considered representative for analysis. The figure below shows general information from 144 articles obtained from data searches during 2021–2025. Globally, STEM education research has shown a steady rise since 2021, reflecting increased attention to interdisciplinary learning and cognitive skill development.

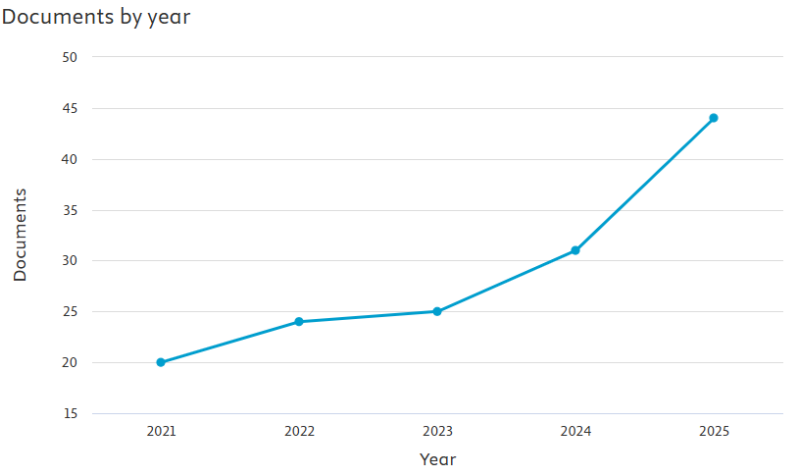


Figure 2. Number of documents by year

Based on the results of searching for articles published between 2021 and 2025 using the keywords "STEM AND education AND critical thinking AND mathematics," 144 relevant articles were found. After filtering using Doctype "article" and Language "English", all documents will be further analyzed as shown in Figure 1. Based on the visualization in Figure 1, there is a trend of increasing publications discussing the integration of STEM in improving critical thinking skills in mathematics learning. In 2021, there were 20 documents; in 2022, 24; and in 2023, 25. A more significant increase occurred in 2024, with 31 documents, and it reached its peak in 2025, with 44 documents. This pattern of increased publications shows that the topic of STEM integration in mathematics learning for the development of critical thinking has attracted researchers' attention over the last five years.

Based on the results of mapping the keywords "STEM AND education AND critical thinking AND mathematics," the most frequently appearing word is STEM Education. STEM Education appears 42 times in articles published from 2021 to 2025. In addition, the words STEM, engineering education, critical thinking, mathematics, education, teaching, and students each appeared 12 times. Furthermore, based on the relationship between the keywords that appear in the following figure:

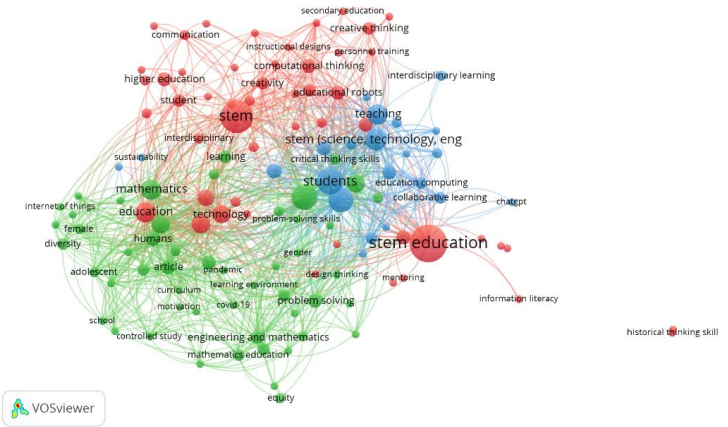
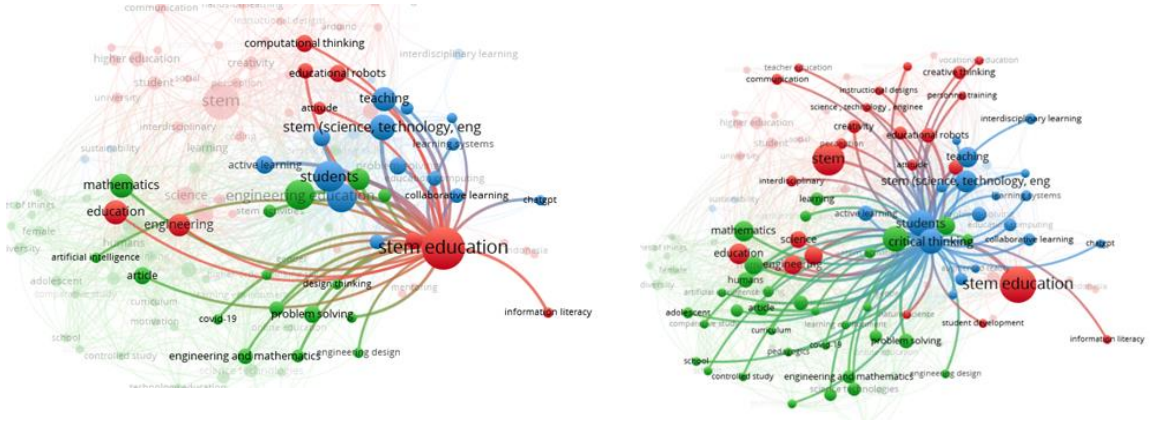


Figure 3. Network visualization

In this topic, there are three clusters. In the red cluster, there are 51 items, with STEM Education as the most significant. Next, in the green cluster, there are 51 items, with the most occurrences being engineering education. In the blue cluster, there are 22 items, with the most occurrences being students. The most significant keywords determine the main topics that attract researchers' attention in the study. Meanwhile, keywords with fewer occurrences indicate that fewer researchers are studying them. Therefore, to find new research on the topic of STEM Education in improving critical thinking in mathematics learning, the research will be conducted using the following image visualization:



(a) (b)

Figure 4. Network visualization: (a) Network with the keyword STEM education; (b) Network with the keyword critical thinking

Based on Figure 4 (a), STEM education is related to several research keywords in other clusters. In the red cluster, there is a close relationship with the keywords science, technology, engineering, and mathematics, reflecting the integration of disciplines in STEM-based learning. In addition, STEM education is linked to teaching and collaborative learning, indicating that much research focuses on the application of collaborative, integrative, project-based learning strategies. In the green cluster, STEM education is linked to engineering, problem-solving, and mathematics, indicating a focus on applying STEM concepts to enhance problem-solving skills and mathematical understanding.

The blue cluster shows relationships among students, technology integration, and learning outcomes, indicating that research also examines the impact of STEM learning on learning outcomes and student engagement. Based on Figure 4 (b), critical thinking is included in the blue cluster. It is related to several other relevant keywords, including STEM education, students, active learning, collaborative learning, and problem-solving. This relationship shows that research on critical thinking focuses on developing students' critical thinking skills through active, collaborative STEM-based learning.

In addition, critical thinking is associated with keywords in the red cluster, such as creativity and higher-order thinking skills, suggesting that critical thinking is often studied alongside these skills. Meanwhile, the correlation with the green cluster, such as

mathematics education, shows the relevance of critical thinking in the context of mathematics learning. Overall, the relationship between these keywords indicates that critical thinking is a key focus of research aimed at improving the quality of STEM learning in mathematics education. Cluster analysis shows the integration of the analytical, evaluative, and inferential aspects of critical thinking within STEM-based problem-solving.

Discussion

The findings of this study reveal a significant increase in research publications on integrating STEM-based learning to improve critical thinking in mathematics education during 2021–2025. This trend indicates a growing recognition among researchers and educators that STEM learning provides a practical pedagogical framework for developing higher-order thinking skills. The pattern of increased publication numbers also reflects the global shift in education toward competency-based learning that emphasizes creativity, collaboration, and critical thinking—skills regarded as essential for 21st-century learners (Honey et al., 2022; Li et al., 2021). According to Facione (2015), critical thinking involves interpretation, analysis, evaluation, inference, explanation, and self-regulation. In mathematics education, these components enable students to reason logically, make evidence-based judgments, and reflect on problem-solving processes. The increasing trend in STEM publications reflects a growing global awareness of the importance of interdisciplinary approaches to enhancing critical thinking in mathematics. However, most studies remain descriptive and lack experimental validation. Few investigations examine long-term effects or causal relationships between STEM integration and critical thinking outcomes (Haydée, 2022; Hacioglu, 2021).

The keyword analysis demonstrates that STEM education remains the most dominant theme, followed by engineering education, students, and critical thinking. The co-occurrence of these keywords indicates that current research focuses on the implementation of interdisciplinary learning models and their effects on students' engagement and cognitive development. The strong link between STEM education, collaborative learning, and teaching further suggests that researchers are increasingly exploring project-based and inquiry-based pedagogies, which are known to promote authentic problem-solving and reflective reasoning (English, 2023; Margot & Kettler, 2019).

The presence of critical thinking within the blue cluster, alongside terms such as problem-solving, active learning, and collaborative learning, suggests that critical thinking is often conceptualized as a product of active, student-centered STEM learning environments. These findings are consistent with those of Tashtoush et al. (2024) and Feziyasti et al. (2025), who demonstrated that STEM-based learning models enhance students' analytical, evaluative, and reflective thinking through experiential and design-oriented tasks. This suggests that the development of critical thinking is most

effective when students are engaged in real-world, interdisciplinary problem-solving contexts that demand collaboration and innovation (Xu, 2023; Shanta, 2022).

Moreover, the close association among critical thinking, creativity, and higher-order thinking skills highlights an emerging trend in which these constructs are viewed as interconnected outcomes of STEM education. Researchers such as Saxton et al. (2022) and Thibaut et al. (2018) argue that these skills collectively represent essential cognitive competencies for addressing complex, ill-structured problems. Therefore, STEM learning not only supports content mastery but also cultivates adaptable, future-ready learners capable of integrating knowledge across domains (Naseer, 2025).

Another noteworthy finding is the strong connection between engineering and mathematics education, which signals a shift from abstract-concept teaching toward applied, design-based learning. Studies by Ilyas et al. (2022) and Hanfy et al. (2022) revealed that contextual and project-driven STEM approaches enhance students' motivation, reasoning, and problem-solving performance. These results emphasize that integrating engineering and mathematics fosters a deeper understanding of mathematical principles through technological and real-world applications. Consequently, mathematics becomes more meaningful and relevant to students, bridging the gap between theoretical understanding and practical implementation (Bybee, 2020; Lou et al., 2023).

Furthermore, the emergence of keywords related to technology integration and artificial intelligence (AI) indicates a new direction in STEM education research. Recent studies have begun exploring how AI tools, digital simulations, and virtual laboratories can support reflective learning and enhance critical thinking (Keleman et al., 2021; Feziyasti et al., 2025). This technological dimension reflects the evolution of STEM from a purely interdisciplinary concept toward a digitally enriched ecosystem that promotes adaptive, data-driven, and personalized learning experiences.

Overall, the discussion underscores that STEM-based learning serves as a transformative framework in mathematics education, not only improving students' critical thinking but also nurturing creativity, collaboration, and problem-solving abilities. The integration of multiple disciplines enables students to connect abstract mathematical reasoning with real-world problem contexts, fostering both conceptual depth and practical competence.

However, despite the promising findings, the bibliometric results also reveal a gap in research depth, as many existing studies remain descriptive and focus on classroom implementation rather than longitudinal impacts or large-scale evaluations. Future research should therefore integrate bibliometric analysis with content analysis, systematic literature reviews, or meta-analyses to examine how and why specific STEM learning designs effectively promote critical thinking. Such comprehensive approaches would provide a more detailed understanding of the mechanisms behind effective STEM learning and guide educators in designing evidence-based, contextually relevant instructional strategies.

CONCLUSION

Fundamental Finding : Bibliometric research shows that research on integrating STEM-based learning to improve critical thinking skills in mathematics has increased significantly during the period 2021–2025. This finding confirms that STEM integration is the primary focus of 21st-century educational innovation because STEM-based learning enhances students' critical thinking skills, including analytical, evaluative, and reflective reasoning. The relationship among keywords such as STEM education, critical thinking, problem-solving, and collaborative learning demonstrates the strategic role of STEM in strengthening students' higher-order thinking skills. **Implication :** STEM integration is not only a pedagogical approach, but also an effective strategy for developing mathematics learning that is more meaningful and relevant to the needs of the 21st century. These results serve as a basis for developing innovative learning policies and practices to strengthen students' critical thinking skills. **Limitation :** The data analyzed come only from the Scopus database and cover the period 2021–2025. This means that the research results do not reflect all publications from other databases and do not provide an in-depth content analysis. **Future Research :** Further research is recommended to expand the scope of data by involving more database sources. Further research is needed on the application of digital technology-based STEM learning and artificial intelligence (AI) in mathematics education. Future learning models should integrate project-based digital STEM environments that enhance both technological literacy and critical thinking.

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AUTHOR CONTRIBUTIONS

Muhammad Rafly Eka Rosyadi contributed to the development of the conceptual framework, research design, and validation process. **Wildan Fitroni** was responsible for collecting bibliometric data and conducting the literature review. **Muhammad Rizal Rizqullah, Enggar Eko Prasetio, & Achmad Mujtaba** carried out data analysis and drafted the manuscript according to the journal template. All listed authors have reviewed and approved the final version of this submission.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest, either financial or personal, that could have influenced the content, analysis, or outcome of this research. All authors have conducted the study independently and with full academic integrity.

ETHICAL COMPLIANCE STATEMENT

This manuscript fully complies with recognized standards of research and publication ethics. The authors affirm that this work is original, has not been published elsewhere, and is free from any unethical practices, including plagiarism, data fabrication, or duplicate submission. All procedures followed in conducting and reporting this research adhere to academic and institutional ethical guidelines.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, as supportive aids during the preparation of this article. Specifically, VOSviewer (version 1.6.20) was employed for data visualization and keyword mapping, while ChatGPT (OpenAI, GPT-5) assisted in language refinement, consistency checking, and formatting according to journal guidelines. All AI-generated or tool-assisted outputs were critically reviewed, edited, and validated by the authors to ensure academic accuracy, originality, and ethical compliance. The final responsibility for the content and conclusions of this manuscript rests entirely with the authors.

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