UNIVERSITAS SEBELAS MARET
BIOEDUKASI: JURNAL PENDIDIKAN BIOLOGI
https://jurnal.uns.ac.id/bioedukasi
1693-265X (Print) | 2549-0605 (Online)

Mapping Research on the BSCS 5E Instructional Model in Biology and Science Education: A Bibliometric Analysis

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Submission : 27/11/2025

Revision : 29/08/2026

Accepted : 30/08/2026

ABSTRACT

This study maps publications on BSCS and the 5E Learning Model in biology and science education using bibliometric analysis, focusing on research trends, dominant topics, key authors, and influential works. A Scopus search on 25 November 2025 retrieved 146 documents, which were screened to 98 original articles for analysis using RStudio and Biblioshiny to identify publication production, citation patterns, collaboration networks, and thematic mapping. Results show a substantial increase in publications since 2015, with dominant topics including the learning cycle, 5E model, inquiry-based science education, and science education. The United States was the most productive country in terms of publications and received the highest number of citations. It was followed in terms of citations by Lebanon, Turkey, Germany, Indonesia, China, and Australia. The literature spans 1985–2025, with publications showing an annual growth rate of 5.65%. The most productive institutions include Montana State University, Bahir Dar University, and the University of Mataram, while BSCS is identified as a key developer of the 5E Model. These findings indicate that the BSCS and 5E Models are developing as prominent pedagogical frameworks in biology and science education, and open opportunities for research on technology integration, model expansion, and strengthening students' inquiry skills. It is important to note that this analysis is based exclusively on English-language publications indexed in the Scopus database, which may limit the generalizability of the findings to non-English or non-Scopus indexed literature.

Keywords: BSCS, 5E Model, Bibliometrics, Biology education, Science education

Introduction

Education Science and biology education faces major challenges in designing curricula and learning models that can improve student understanding. Since the mid-20th century, learning innovations have evolved beyond information delivery to encourage critical thinking, scientific process skills, and scientific attitudes.

Two prominent contributions are the Biological Sciences Curriculum Study (BSCS) and the 5E Learning Model, which consists of the stages of Engage, Explore, Explain, Elaborate, and Evaluate (Bybee et al., 2006; Pratika & Permatasari, 2024). BSCS was established in 1959 by *the American Institute of Biological Sciences,* with support from *the National Science Foundation,* in response to the suboptimal quality of biology teaching in secondary schools (Suryani *et al.,* 2017). Its contributions include curriculum development and the 5E learning cycle model, now one of the most influential learning strategies in science education (Pratika & Permatasari, 2024). The BSCS approach emphasizes developing students' understanding through active engagement with scientific ideas and inquiry-oriented learning (Bybee et al., 2006).

The 5E Model is based on constructivist theory, where students are at the center of the learning process (Kelana *et al*., 2020). Bybee et al. (2006) describe the 5E Model as a learning cycle that provides a coherent sequence of instructional phases to engage students in constructing, developing, and applying scientific understanding. Each phase is designed to help students build knowledge gradually through experience and prior understanding (Sinaga *et al*., 2025). BSCS was established as a curriculum development organization, while the 5E instructional model was developed within the BSCS framework as a learning cycle approach to science instruction (Bybee et al., 2006). Although the 5E model is rooted in the broader learning cycle tradition, this study focuses specifically on research that addresses the BSCS 5E model, including "Learning Cycle" in the search strategy to ensure comprehensive coverage.

Recent studies confirm the model's effectiveness. A synthesis of 20 articles by Sinaga *et al.* (2025), published between 2017 and 2025, shows that the 5E Model creates active and meaningful learning, with N-Gain values between 0.37 and 0.69 (moderate to high category). Batubara *et al.* (2025) also found a significant increase in science literacy with an N-Gain of 0.61 (moderate category), while research by Larasati *et al.* (2025) reported an increase in scientific inquiry, problem-solving, and scientific reasoning among secondary school students. Many studies report the benefits of BSCS and the 5E Model on important aspects of learning, such as learning outcomes, problem-solving abilities, science process skills, science literacy, and the development of scientific attitudes (Ardyagarani *et al*., 2024; Batubara *et al*., 2025; Larasati *et al*., 2025; Pratika & Permatasari, 2024).

Beyond these benefits, bibliometric analysis has proven valuable for mapping research development in science education (EJMSTE, 2024). Wang *et al.* (2024) , for example, conducted a bibliometric analysis of 1,148 articles from Web of Science and found three clusters of knowledge development in science learning design: *theoretical frameworks and methodology*, *cognitive load theory*, and *multimedia instructional design*.

However, although bibliometric studies have examined science education and science learning design more broadly, research on the implementation of BSCS and the 5E Model in biology and science education has not yet been systematically mapped. The intellectual, conceptual, geographical, and collaborative structures of this specific body of literature remain unclear. Such a focused analysis is needed to clarify the research landscape and identify how these approaches have developed within the field.

As publications on the application of BSCS and the 5E Model in various educational contexts around the world increase, studies are needed to map the overall development of research. Bibliometric analysis is a quantitative method that can assess research developments through scientific publications over a certain period (Wang *et al*., 2024). This approach enables the analysis of academic collaboration networks, citation patterns, dominant topics, and *research gaps* in a field.

This study aims to bibliometrically map publications on BSCS and the 5E Model in biology/science education, covering publication trends, dominant and *emerging topics*, collaboration networks, and influential articles in the field. The results are expected to provide a comprehensive overview of research development and open opportunities for future studies to improve science education quality.

Research Questions

1. What are the trends in research publications on BSCS and the 5E Model in biology and science education?
2. What are the dominant and *emerging* research topics in the implementation of these two models?
3. Who are the key actors (researchers and institutions) contributing to this field, and what are the patterns of their international collaboration based on single-country and multiple-country publications?
4. Which articles have the most significant contribution and influence (most cited) in this field of research?

Through structured and data-driven bibliometric analysis, this research is expected to make a tangible contribution to the sustainable development of science education theory and practice.

Methods

A bibliometric analysis was conducted to systematically examine the existing literature and identify publication trends related to research topics. The procedure followed the four-step framework proposed by Donthu *et al.* (2021): 1) defining the purpose and scope of the study, 2) selecting appropriate analytical techniques, 3) collecting bibliographic data, and 4) analyzing and reporting the findings. In this study, the analysis focused on the publication year range and the keywords used to identify relevant literature.

The data were obtained through a search of the Scopus database on 25 November 2025. First, article data were searched for in the international Scopus database. Scopus was chosen because of its extensive collection of research articles in various disciplines and its high credibility in research indexing.

The keyword search was conducted in the titles, abstracts, and author keywords fields using the Scopus TITLE-ABS-KEY function. To ensure that the search logic was explicit and reproducible, the search terms were organized into two concept groups: (1) terms related to BSCS, the 5E Models, and the Learning Cycle; and terms related to biology and science education. The Boolean search string was TITLE-ABS-KEY ((“BSCS” OR “Biological Science Curriculum Study” OR “5E Model” OR “5E Instructional Model” OR “Learning Cycle”) AND (“biology education” OR “science education” OR “biology teaching” OR “science teaching”)).

The criteria for including data were: 1) the research articles reviewed must contain one of the keywords in the title, abstract, or keywords; 2) the search period was not limited; and 3) the articles must be written in English. The criteria for exclusion are: 1) files other than original articles, such as *review* articles, *conference papers*, or *notes*; 2) articles published in languages other than English; and 3) records classified as “Article in Press” or records whose source type did not meet the journal criterion.

Using these search keywords, we obtained 146 publications in the Scopus database, consisting of 109 original articles, 16 *conference papers*, 13 *book* chapters, 4 *review* articles, 2 *errata*, 1 *note*, and 1 *conference review*. In this study, the data used were from 109 original articles, from which 3 were excluded because they were still in the publication stage, 2 were non-journal sources, and 6 were in languages other than English. The final set of articles processed for bibliometric analysis was 98. The literature selection flow chart is shown in Figure 1.

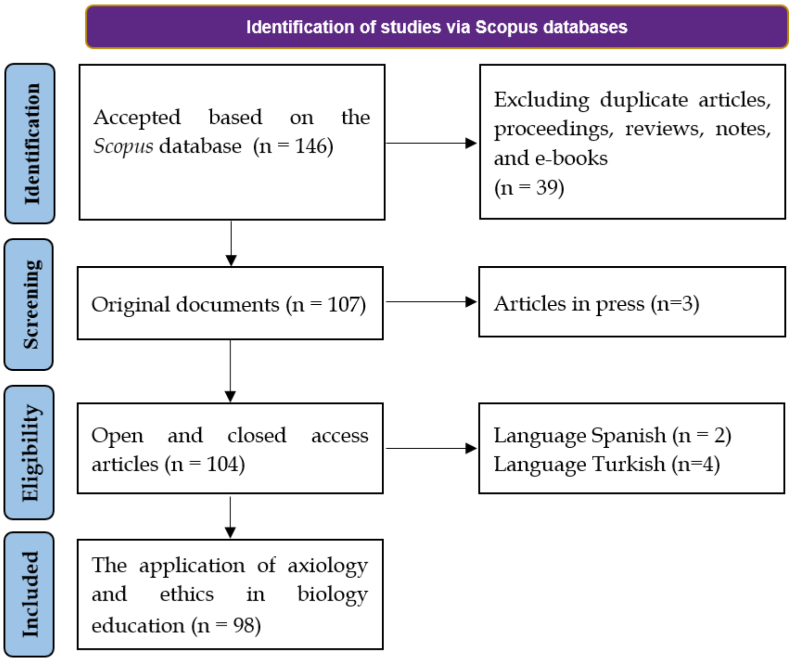

Figure 1. Literature selection flow chart (PRISMA)

One designated author conducted the literature search, screening, and eligibility assessment based on the predefined inclusion and exclusion criteria. Because a single researcher conducted the screening, inter-rater reliability testing was not performed. For example, Ejaz *et al.* (2022) show how citation data and bibliographic information can be downloaded in CSV format from the Scopus database and then analyzed using platforms such as Biblioshiny for visualization and bibliometric mapping. Following this approach, this CSV data was imported into RStudio and analyzed using the Bibliometric package via its web-based interface, Biblioshiny (Aria & Cuccurullo, 2017).

This analysis employed the following parameters: (1) a co-word analysis using the multiple correspondence analysis (MCA) algorithm with a minimum cluster frequency of 5; (2) a thematic map generated using a centrality-density approach with a minimum cluster size of 3 and a minimum number of edges per cluster of 2; (3) a trend topics analysis using the Mann-Kendall test with a minimum word frequency of 3 and a minimum number of years per topic of 2; and (4) a keyword co-occurrence network using the Walktrap clustering algorithm with association strength normalization. These parameters were selected following the standard procedures recommended by Aria and Cuccurullo (2017). Similarly, Moral-Muñoz *et al.* (2020) show how tools such as Biblioshiny can be used together to perform bibliometric analysis of data downloaded in CSV format from Scopus, enabling more in-depth analysis of author networks and research trends.

Results and Discussion

Trends in research publications

Research on BSCS and the 5E Model has developed progressively over the last decade, particularly since 2022. Renner, Abraham, and Birnie (1985) conducted the first study in this field, pioneering the use of the learning cycle in science education. Their work laid the foundation for what would later become the 5E Model, demonstrating that inquiry-based approaches could improve concept achievement, long-term retention, and attitudes toward science (Nur & Noviardila, 2021).

Since then, the field has evolved significantly. The BSCS and 5E Model have moved beyond simple learning cycle frameworks to become the foundation of science learning design that emphasizes higher-order thinking skills, science literacy, and scientific argumentation, while also being modified or combined with other approaches (Resmol & Leasa, 2022).

This study analyzed 98 articles from the Scopus database on BSCS and the 5E Model in biology and science education, covering the period 1985-2025. The bibliography yielded 98 documents from 64 sources, with an annual growth rate of 5.65% (Table 1). The average document age was 10.8 years, with an average of 16.56 citations per document and 832 total references. Table 1 shows 232 authors, 27 single-authored documents, an average of 2.5 authors per article, and an international collaboration rate of 9.18%. All analyzed documents are scientific articles, in accordance with Scopus publication standards.

Table 1. Main information about Scopus data

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1985:2025
Sources (Journals, Books, etc.)	64
Documents	98
Annual Growth Rate %	5.65
Average Document Age	10.8
Average citations per document	16.5
References	832
DOCUMENT CONTENTS	
Keywords Plus (ID)	109
Author's Keywords (German)	296
AUTHORS	
Authors	232
Authors of single-authored documents	27
AUTHORS COLLABORATION	
Single-authored documents	27
Co-Authors per Document	2.5
International co-authorships %	9.18
DOCUMENT TYPES	
article	98

Figure 2 shows the annual publication trend. Publications remained low until 2010, then increased steadily and surged to more than 9 publications per year in 2019-2021. This pattern aligns with Wang et al. (2024) and reflects growing interest in inquiry-based learning frameworks in the early 2000s. The growth may be attributed to the increasing global emphasis on STEM education and constructivist pedagogies (Bybee, 2019).

The 5E Model has also been widely recognized as an effective framework for developing scientific literacy and inquiry skills (Sinaga et al., 2025). In addition, technology integration in science education has opened new contexts where the 5E Model can be applied (Jibril, 2024). The slight decline in recent years may reflect a natural maturation phase, in which foundational studies are well established, and researchers are shifting toward more specialized applications. This pattern mirrors what Chen et al. (2022) and Fischer & Klemm (2019) observed in other pedagogical frameworks.

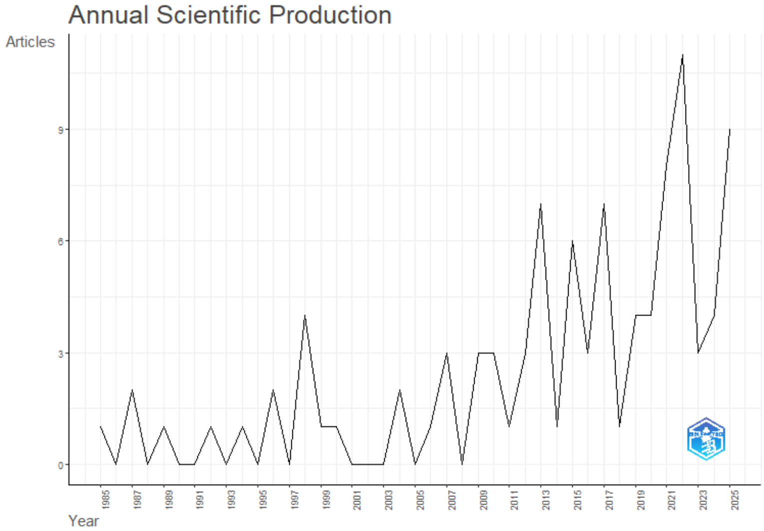

Figure 2. Number of publications per year ("Annual Scientific Production" in Overview).

Figure 3 presents the average citations per year. Early publications received fewer than one citation per year. A significant spike occurred in 2007 with approximately 5 citations per year, followed by a peak in 2010 with over 6 citations per year. Another peak appeared in 2020-2021 with around 4 citations per year. This cluster of highly influential articles between 2007 and 2010 suggests that this period was critical for consolidating research on the 5E Model. The renewed interest from 2019 onwards indicates that the model continues to gain academic recognition, especially in the context of science curriculum reform. This aligns with Wang et al. (2024) observation that pedagogical frameworks in science tend to experience similar acceleration in citation impact over time.

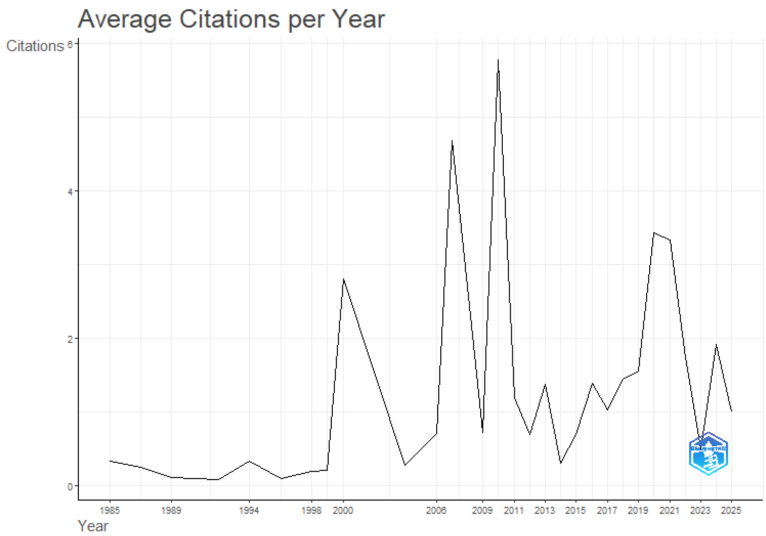

Figure 3. Average citations per year for publications on BSCS and the 5E Model (1985-2025)

Figure 4 shows the most productive journals. The American Biology Teacher ranks first with six documents. Four journals have contributed four documents each: the International Journal of Science Education, the Journal of Baltic Science Education, the Journal of Geoscience Education, and the Journal of Research in Science Teaching. Other journals have contributed one to two publications.

This concentration in biology and science education journals is consistent with the tendency for studies on specific instructional models to appear in field-specific journals rather than general education outlets (Wang et al., 2024). The presence of the Journal of Geoscience Education is noteworthy, suggesting the BSCS and 5E Model have found applications beyond biology into earth science and interdisciplinary STEM contexts. However, compared with other pedagogical frameworks, publications on the BSCS and 5E Model remain relatively modest, indicating considerable room for further research.

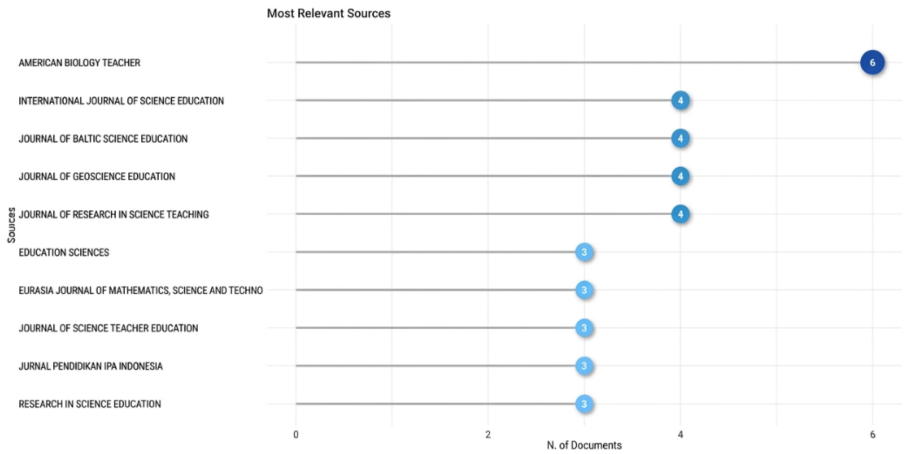

Figure 4. Distribution of publications by the most productive journals

Dominant and emerging research topics

Figure 5 presents the most frequent keywords. The top keyword is "science education" with 26 occurrences. "Learning cycle" appears 16 times, and "5E model" appears 10 times. "5E learning cycle" and "education" each appear 6 times. "Inquiry" and "inquiry-based science education" each appear 5 times. The keywords "biology" and "earth science-teaching and curriculum" also appear.

The dominance of "science education" confirms that BSCS and the 5E Model are firmly situated within the broader science education field. The strong presence of "learning cycle" and "5E model" indicates that the learning cycle approach, particularly the 5E model from the BSCS framework, remains the primary focus of the literature.

However, frequency alone does not establish a keyword's conceptual importance or structural centrality within the research network. To address this, the analysis also considers centrality and density, which provide a more comprehensive picture of the conceptual structure.

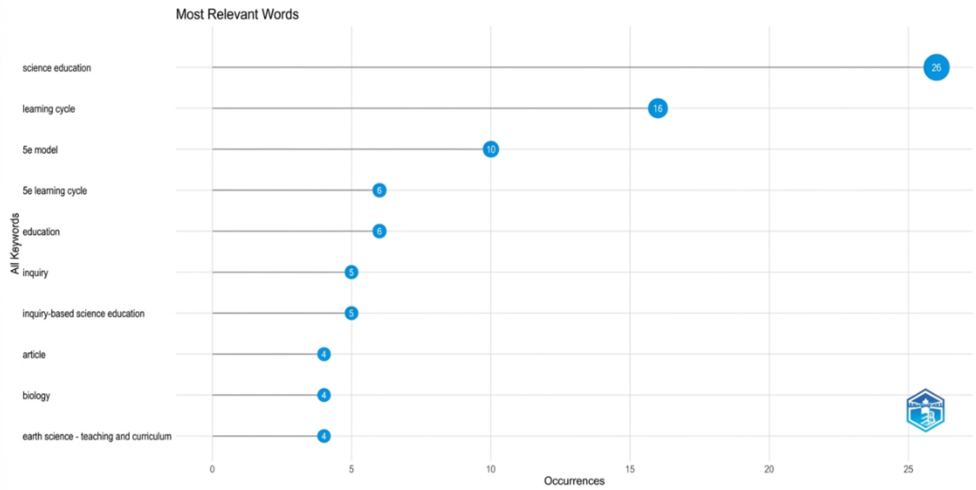

Figure 5. Data on the list of main keywords (Keywords, Author Keywords) with the highest frequency (Conceptual Structure)

The network visualization in Figure 6 shows several interconnected clusters, with the main clusters centered around "learning cycle" and "5E/BSCS", connected to "science education", "inquiry", and related pedagogical terms. These clusters indicate that "science education" and "learning cycle" serve as the field's primary conceptual anchors. The presence of "conceptual change" and "genetics" within the same cluster suggests that 5E Model research is not limited to pedagogical application but extends to discipline-specific content areas and theoretical frameworks of learning.

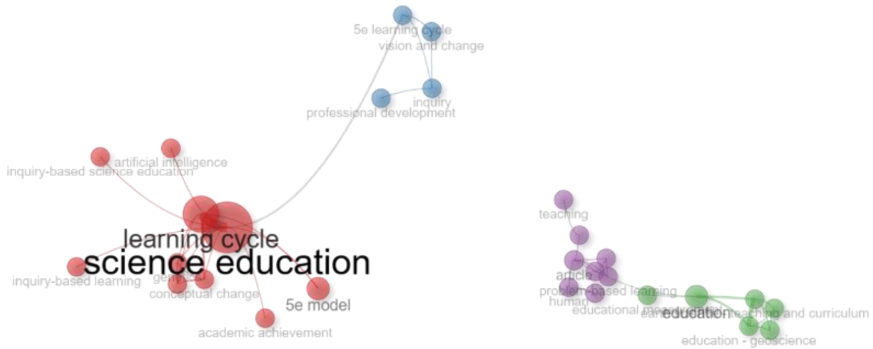

Figure 6. Networks of relationships between keywords in BSCS and 5E Model studies

Other clusters link to "inquiry approaches", "problem-based learning", and curriculum contexts such as "education-teaching and curriculum" and "education-geoscience", indicating that the 5E Model's application has expanded into curriculum implementation and science learning design. The presence of "professional development" in the keyword network suggests that teacher training and competency development are recognized as important aspects of 5E Model implementation.

Together, Figure 5-6 illustrate that the dominance of keywords such as "science education", "learning cycle", and "5E model" is not merely a statistical artifact but reflects an integrated conceptual structure. The structure positions BSCS and the 5E Model as a core framework for developing constructivist, systematic, and inquiry-oriented biology and science learning, consistent with the model's theoretical foundations (Bybee, 2019) and broader bibliometric patterns in science education (Wang et al., 2024).

The strong connection between "inquiry" and the 5E model is not surprising given the theoretical foundations of the model itself. The 5E model was intentionally designed as an inquiry-oriented learning cycle (Bybee et al., 2006). The Engage and Explore phases are built around student-driven investigation, which lies at the heart of inquiry-based science education. This finding matches previous bibliometric studies that consistently identified inquiry-based learning as a central theme in science education research (Chen et al., 2022).

The thematic map in Figure 7 provides a more detailed mapping of research themes based on their level of relevance (centrality) and development (density). The Motor Themes quadrant includes "5E learning cycle", "inquiry", and "biology, confirming that research on the BSCS and 5E Model is centered on inquiry-based biology learning. The Basic Themes quadrant includes "students", "artificial intelligence", and "5E model", suggesting that while the 5E Model is well established, its integration with AI and emerging remains largely unexplored.

The Emerging or Declining Themes quadrant includes "experiential learning" and "7E learning cycle model", indicating model variations gaining attention. The Niche Themes quadrant includes "nature of scientific inquiry" and "pedagogical content knowledge", representing specialized research areas.

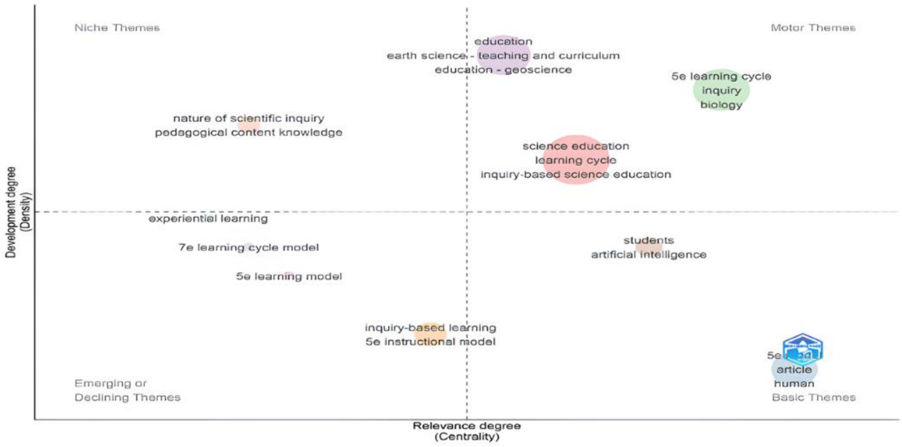

Figure 7. Keyword co-variation network of the thematic map, with the X-axis representing relevance (centrality) and the Y-axis representing development (density)

The placement of "professional development" in the Niche Themes quadrant indicates that research on teacher training and competency development remains relatively specialized and has not yet become a central focus of the broader literature. The prominence of inquiry in the 5E Model, evident across Figures 5-7, also reflects ongoing debates in science education about the effectiveness of inquiry-based versus direct instruction approaches (Kirschner et al., 2016).

Figure 8 shows the dynamics of keyword development. The term "education" appeared earliest, followed by "learning cycle" and "inquiry" around 2010-2015. From 2016 to 2024, the terms "5E model", "5E learning cycle", and "science education" strengthened significantly. This shift reflects the field's maturation, as general pedagogical concepts have gradually given way to more specific, operationalized frameworks. A similar pattern has been observed in research on other instructional models, where initial broad conceptual discussions are eventually replaced by more focused and applied investigations (Chen et al., 2022). The strengthening of the "5E model" and "science education" in recent years also reflects the growing global emphasis on STEM education and constructivist approaches.

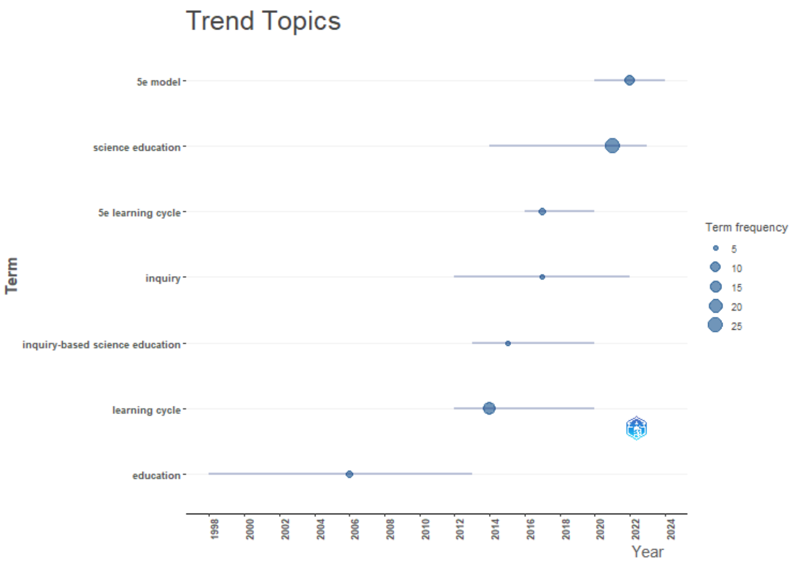

Figure 8. Topic trend figure showing the temporal dynamics of keyword development, with the X-axis representing the time (1998-2024) and the bubble size representing term frequency (5, 10, 15, 20, 25)

Key actors and patterns of international collaboration

Figure 9 shows the analysis of corresponding authors' countries. The United States dominates publication output. Turkey ranks second with more than 10 documents, all of which are Single Country Publications. China recorded 4 SCPs and 1 MCP. Australia had 2 SCPs and 2 MCPs. Indonesia recorded 3 SCPs and 1 MCP. South Africa recorded 4 SCPPs and Ethiopia recorded 2 SCPs. Germany recorded 2 SCPs and 1 MCP and Korea recorded 1 SCP, and 1 MCP.

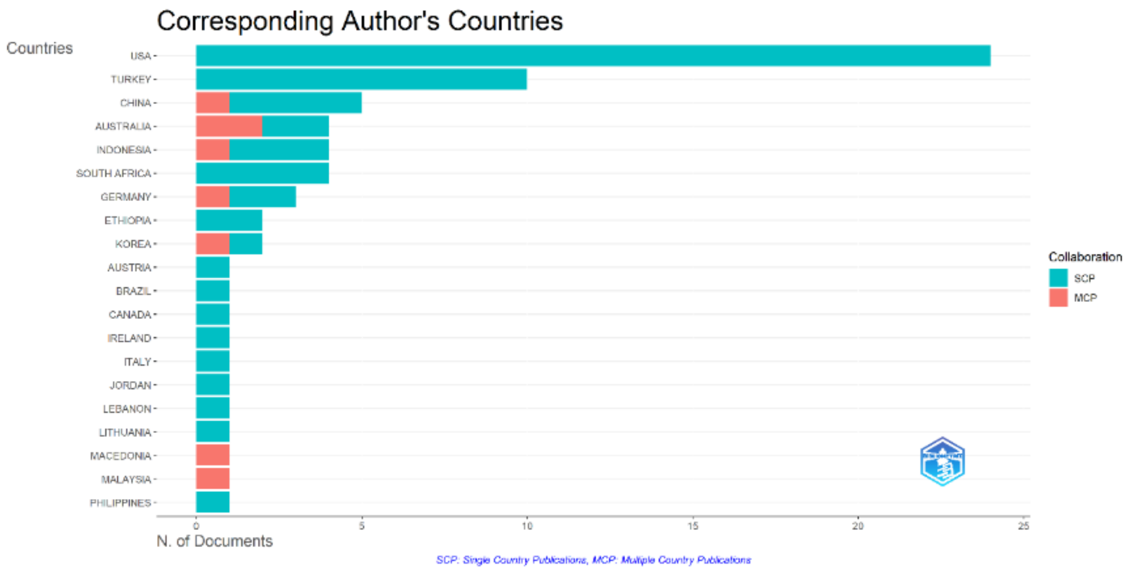

Figure 9. Institutional affiliation and country of origin of authors. The X-axis shows the number of documents. Green bars represent Single Country Publications (SCP), while red for Multiple Country Publications (MCP)

The geographic distribution clearly shows that the United States dominates both publication output and citation impact. This is not surprising for several reasons. BSCS in Colorado originally developed the 5E Model (Bybee et al., 2006). US researchers also benefit from substantial funding from agencies like the National Science Foundation. In addition, US-based journals and the dominance of English as the academic language give American researchers greater global visibility and impact (Lillis & Curry, 2010).

This pattern is consistent with broader bibliometric trends in science education, where the United States consistently leads in both output and citations (Wang et al., 2024; Chen et al., 2022). However, the presence of Turkey, Indonesia, and Ethiopia among the top contributors signals a gradual diversification of research activity beyond Western countries. The inclusion of the University of Mataram in Indonesia and Bahir Dar University in Ethiopia among the most active institutions confirms this trend. It likely reflects growing investment in science education research in these regions.

Figure 10 shows the most active institutions. Montana State University is the most active institution. Bahir Dar University, La Trobe University, the University of Mataram, the University of Missouri, the University of South Carolina, and the University of Salzburg are also major contributors. Other notable contributors include Beijing Normal University, the Biological Sciences Curriculum Study, and the Department of Educational Sciences. The presence of BSCS itself is significant given its historical role in developing the 5E Model.

The international co-authorship rate is only 9.18%, and most countries rely on single-country publications. This suggests that research on the BSCS and 5E Model remains largely nationally oriented. There are several possible reasons. The model's origins in the US may make it seem less relevant to other educational systems. Research funding for science education is often allocated at the national level. Because much 5E research is practical and classroom-based, researchers may prioritize local implementation over international collaboration (Adams, 2013). This pattern is not unique to this field. Similar limitations in international collaboration have been documented in other bibliometric studies of education research, where national funding priorities and local policy contexts tend to shape research agendas more strongly than in the natural sciences (Zupic & Cater, 2015).

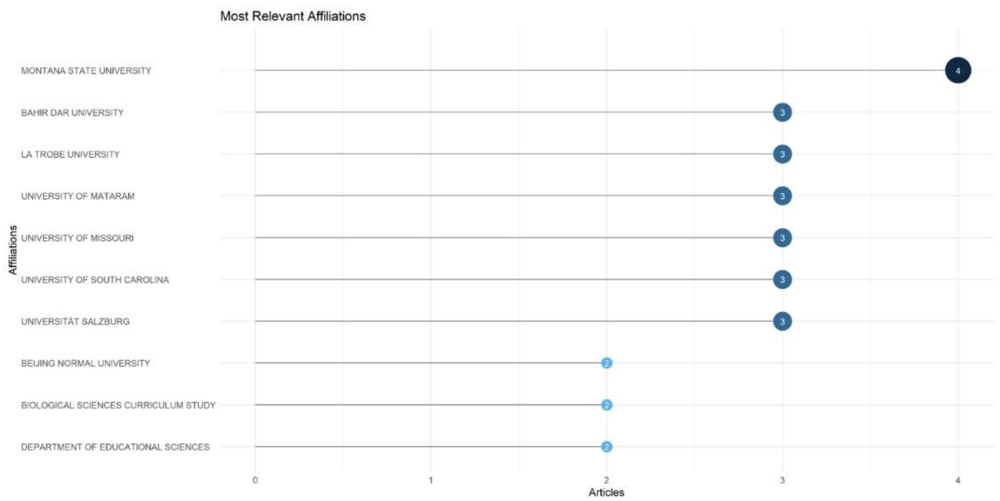

Figure 10. Most active institutions. The Y-axis shows the affiliations, and the X-axis shows the number of articles

Articles with the greatest contribution and influence

Figure 11 shows the most cited countries. The United States has approximately 619 citations. Lebanon has 111, Turkey has 94, Germany and Indonesia have 92 each, China has 64, Australia has 63, South Africa has 30, and Ireland and Portugal have 23 each. Lebanon's strong citation impact, despite its relatively low publication output, is also worth noting. It shows that research impact does not always come from quantity; a small number of highly influential works can make a significant difference. This phenomenon has been observed in other contexts, where researchers from countries with limited publication output can still achieve high citation impact through the quality and relevance of their work.

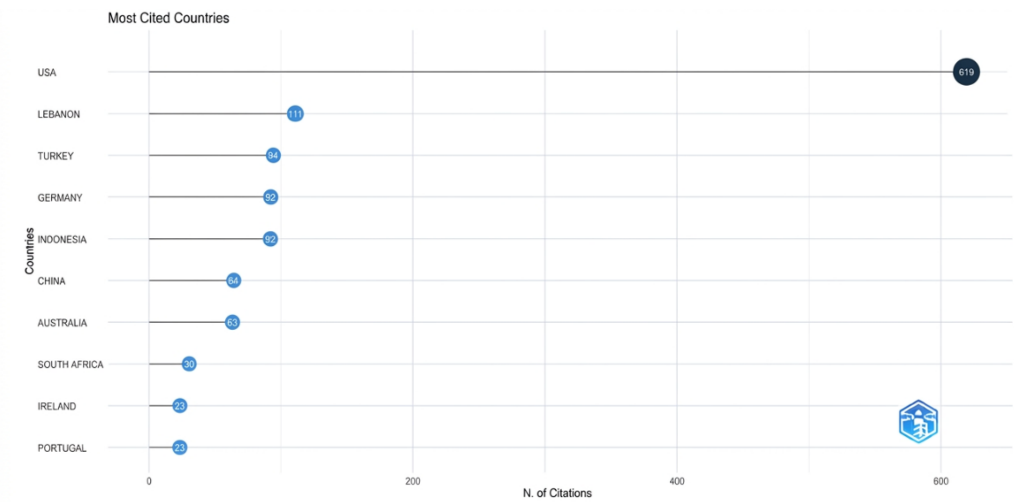

Figure 11. "Most Cited Countries" with total citations and average citations per year. The Y-axis shows the countries, and the X-axis shows the number of citations

Figure 12 shows that Wilson et al. (2010) is the most influential reference with approximately 205 citations. This article has clearly shaped the theoretical foundation for subsequent research. Three other highly cited works from the same period, Chiapetta et al. (2007), Halloun et al. (2007), and Cobern et al. (2010), together with Wilson et al. (2010), confirm that the period between 2007 and 2010 was critical for building the foundational knowledge base of 5E Model research. This concentration of influential works within a short period is a common pattern in the development of pedagogical frameworks, where a few key studies establish the theoretical and empirical foundations that guide subsequent research (Chen et al., 2022).

The enduring dominance of these foundational works suggests that, more than a decade after their publication, the field has not yet produced new large-scale projects with comparable theoretical impact. This indicates that while the 5E Model is widely applied in practice, the theoretical frameworks underpinning it have remained largely unchanged since the late 2000s, highlighting an opportunity for future research to revisit and refine these foundations in light of contemporary educational challenges such as digital learning environments and student-centered pedagogies.

The citation pattern, with foundational works attracting the highest citations followed by more recent contributions, follows the typical maturation pattern seen in other bibliometric analyses of pedagogical frameworks (Wang et al., 2024). This pattern suggests that the 5E Model has reached a level of theoretical maturity where the core framework is widely accepted, but the field now faces the challenge of producing new foundational studies that can update and expand its theoretical underpinnings for contemporary educational contexts.
More recent articles by Ramdani et al. (2021), Kurup et al. (2021), and Akgunduz et al. (2018) show that research interest in this topic remains strong and continues to produce work that is recognized internationally. These more recent studies reflect the expanding geographic and contextual diversity of 5E Model research, with contributions from Indonesia, Australia, and Turkey.

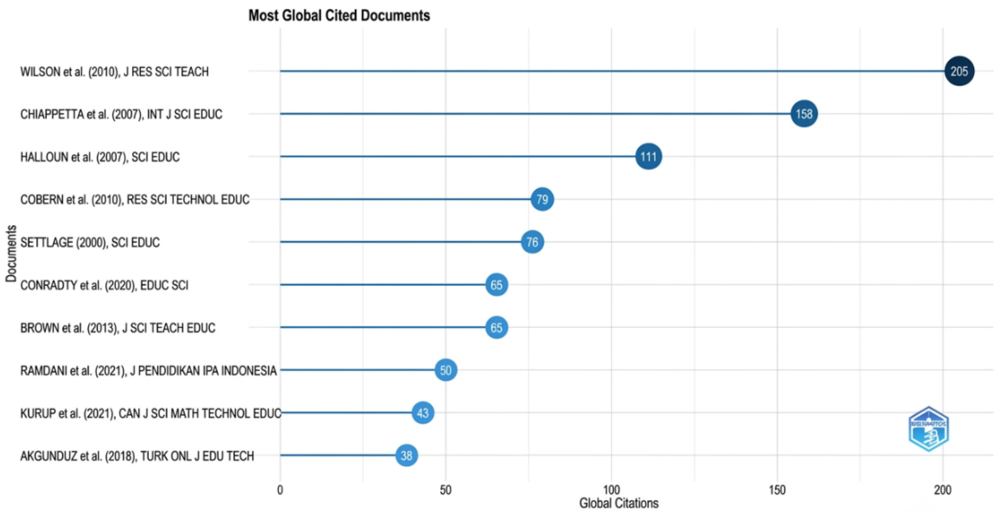

Figure 12. Most Cited Documents with total citations and average citations per year. The Y-axis shows the documents, and the X-axis shows the number of global citations.

Implications and future research directions
This study demonstrates the value of bibliometric analysis for mapping the research landscape in science education. Unlike traditional narrative reviews and meta-analyses, bibliometric analysis provides a macro-level view of the field's intellectual structure through keyword co-occurrence networks, the evolution of research themes over time, the geographic distribution of research activity, and the network of authors and institutions that have shaped the field. These insights, which would be difficult to obtain through traditional review methods, can guide more targeted future research.

These findings suggest several opportunities for future research. Integrating AI and technology with the 5E Model, as suggested by the presence of "artificial intelligence" in the Basic Themes quadrant, is an underexplored area with significant potential. More variations, such as the 7E learning cycle, also warrant further investigation into their effectiveness. The limited international collaboration observed in this study suggests opportunities for building cross-country research networks. Future bibliometric studies could also extend this approach by incorporating multiple databases, extracting citation data per author, and including a broader range of document types such as conference papers and reviews.

Conclusion

This study maps research on the BSCS and the 5E Model in biology and science education based on 98 Scopus-indexed articles published between 1985 and 2025. The findings show a steady increase in publications, particularly since 2015, reflecting growing global attention to cycle-based and inquiry-based learning approaches. However, the 2025 data represent a partial year and should be interpreted with caution. The United States was the most productive and had the highest citation impact, while Turkey, China, Australia, Indonesia, and other countries also contributed substantially to the field. International collaboration patterns are developing, though most countries remain dominated by independent publications. The most influential articles originate from the period 2007–2010, marking an important phase in strengthening the theoretical foundations of this model in science education.

The novelty of this research lies in its comprehensive mapping, integrating publication trends, conceptual keyword structures, collaboration networks, and article influence into a single bibliometric analysis specifically focused on BSCS and the 5E Model in biology and science education. Bibliometric associations describe patterns within the literature but cannot establish causal relationships or determine the effectiveness of instructional models. Further research should explore integrating BSCS and the 5E Model with cutting-edge technologies such as artificial intelligence, investigate model variations such as the 7E learning cycle, and use multi-source bibliometric data for more comprehensive global mapping

Generative AI Disclosure

The use of artificial intelligence in this manuscript is limited to the initial brainstorming of ideas and language translation to improve readability, without affecting the scientific substance, data analysis, or research interpretation.

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