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MAPPING THE EVOLUTION OF SYSTEMS THINKING IN SCIENCE EDUCATION: A BIBLIOMETRIC ANALYSIS (JANUARY 2010 – DECEMBER 2024)

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ABSTRACT

Systems thinking (ST) has become an essential framework in science education, promoting interdisciplinary understanding, comprehensive reasoning, and effective problem-solving skills. This study offers an in-depth bibliometric analysis of ST-related research within the field of science education, covering the period from January 2010 to December 2024. By employing advanced visualization tools such as Biblioshiny, VOSviewer, and Microsoft Excel, the study uncovers key thematic areas, influential researchers, and prominent academic journals that have significantly contributed to the development of this domain. The findings indicate a marked increase in scholarly interest following UNESCO's 2015 designation of systems thinking as a core educational competency. Despite the growing body of literature, the analysis highlights a notable lack of cohesive international collaboration, pointing to the continued fragmentation of research efforts across different regions and institutions. This trend suggests a pressing need for more integrated and cross-disciplinary approaches in order to fully leverage the potential of systems thinking within science education. Mapping the intellectual structure and evolution of the field, the study not only traces how the discourse around ST has developed over time but also provides valuable insights for shaping future directions. It offers guidance for educators, policymakers, and scholars aiming to embed systems thinking more effectively into various scientific disciplines. By shedding light on existing gaps and opportunities, this research emphasizes the importance of fostering collaborative networks and innovative pedagogies that align with the complex challenges of contemporary science education. Ultimately, the study serves as a strategic resource for those seeking to enhance educational practices through a systems-oriented lens, reinforcing the relevance of ST as a tool for nurturing critical thinking and interdisciplinary competence among learners in an increasingly interconnected world.

Keywords: Systems thinking, science education, bibliometric analysis, research impact, interdisciplinary collaboration.

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INTRODUCTION

The increasing complexity of global challenges, such as climate change, resource management, and public health crises, has emphasized the need for systems thinking (ST) as a crucial cognitive skill in education. As scientific and technological advancements accelerate, traditional reductionist approaches in education often fall short in addressing real-world problems, which require a more interdisciplinary and holistic perspective (Keating, Katina & Bradley, 2021). ST enables individuals to understand interconnected relationships, feedback loops, and dynamic behaviors within complex systems, rather than viewing components in isolation (Orgill, York & MacKellar, 2019). This analytical approach is particularly relevant in disciplines such as engineering, environmental science, and biological sciences, where the ability to recognize patterns, interactions, and systemic influences is critical for solving multifaceted problems (Mills, 2022).

Education systems worldwide are recognizing the importance of ST, particularly in STEM fields, where complex problems demand a more integrated and dynamic understanding. As the demand for professionals who can navigate and manage interconnected systems continues to grow, institutions have sought to incorporate ST methodologies into curricula, teaching strategies, and research frameworks (Shaked & Schechter, 2017). However, the integration of ST into education is still developing, with variations in curricular approaches, assessment methods, and pedagogical techniques across different disciplines and education levels (Roslan, Azizan, Suhaimi, Aziz & Mahadi, 2021). Furthermore, research indicates that cognitive traits, such as openness to complexity, flexibility in thinking, and the ability to recognize systemic structures, influence students' capability to adopt ST principles effectively (Wycis´lak & Radin, 2015). Despite the growing emphasis on ST in education, there remains a need for systematic evaluation methods and standardized instructional approaches that can facilitate its effective implementation across diverse learning environments (Gilissen, 2021).

Several innovative teaching methodologies and conceptual tools have been explored to enhance ST proficiency among students. The use of visualization techniques, including causal loop diagrams, stock and flow models, and the iceberg metaphor, has proven effective in helping students conceptualize systemic structures and interactions (Hrin, Thoms, Romero & Schwab, 2016). Additionally, pedagogical strategies such as problem-based learning (PBL), inquiry-driven instruction, and interdisciplinary coursework have demonstrated their potential in fostering ST abilities, particularly in areas such as organic chemistry, environmental management, and sustainability studies (Orgill, York & MacKellar, 2019). While these approaches have shown promise, challenges persist in developing scalable, adaptable, and measurable frameworks for integrating ST into diverse educational settings. More research is required to identify optimal teaching practices, cognitive development strategies, and domain-specific applications of ST in both primary and higher education.

This study contributes to the existing body of research by conducting a comprehensive bibliometric analysis of ST research in science education from January 2010 to December 2024. Bibliometric analysis has emerged as a powerful tool for assessing research trajectories, identifying influential scholars, and mapping the intellectual structure of a field (Lazarides, Markou, Papadopoulos & Tzivinikou, 2023). Unlike previous studies, which often focus on specific disciplines or regional analyses, this research adopts a multi-dimensional approach, employing Biblioshiny, VOSviewer, and Excel to provide a broad yet nuanced assessment of ST research trends. By synthesizing citation patterns, collaboration networks, and thematic clusters, this study aims to offer a more detailed and systematic perspective on the development and dissemination of ST in education.

The study is designed to systematically explore the intellectual evolution of ST in science education through several key research questions. First, it examines publication trends and research patterns over the past decade, identifying key shifts in the academic discourse surrounding ST. Additionally, it seeks to determine which academic journals have played a significant role in disseminating ST research, providing insights into the primary platforms that shape scholarly engagement with ST. Another important aspect of the study is the analysis of collaboration networks among researchers and institutions, which offers a deeper understanding of the global distribution of ST scholarship. Furthermore, this research identifies the most frequently cited authors and publications, highlighting their influence on shaping ST discussions and methodological advancements. Finally, the study explores emerging research areas within ST, pinpointing underexplored dimensions that warrant further investigation and interdisciplinary integration.

The findings from this study are expected to provide several critical contributions to the literature. By offering a comprehensive mapping of publication trends, the study will provide a historical trajectory of ST research, highlighting key growth periods, stagnations, and paradigm shifts. Additionally, by identifying research gaps and underrepresented areas, the study will guide future research efforts, ensuring that emerging ST applications receive the necessary academic attention. Understanding global research collaboration patterns will also help identify which institutions, countries, and research groups have been central to ST advancements, fostering more informed and strategic partnerships between scholars.

Beyond academic implications, this study holds practical significance for educators, curriculum designers, and policymakers. As educational systems strive to integrate interdisciplinary and problem-solving skills into learning frameworks, ST provides a crucial foundation for improving scientific literacy, decision-making, and real-world problem-solving. By examining how ST research has been integrated into education, this study will offer evidence-based recommendations for refining curriculum design and developing instructional methodologies that align with contemporary educational needs. Moreover, insights from this research will contribute to policy discussions on STEM education reform, ensuring that students are equipped with the cognitive tools necessary to navigate complex global systems.

By addressing these research questions, this study will provide a comprehensive, data-driven perspective on the evolution of ST in science education, identifying key trends, leading contributors, and emerging areas of research. These findings will be instrumental in bridging research gaps, enhancing interdisciplinary collaboration, and informing policy decisions on ST integration in education. Ultimately, this study aims to foster a more cohesive, systematic, and evidence-based approach to ST education, ensuring that students and professionals alike are better prepared to tackle the complex challenges of the 21st century.

METHOD

This study employs bibliometric analysis to systematically examine the evolution of systems thinking (ST) research in science education from January 2010 to December 2024. Bibliometric analysis, a quantitative research method, enables the assessment of publication trends, citation impact, collaboration networks, and thematic evolutions within a research domain. By leveraging citation analysis, keyword co-occurrence mapping, and co-authorship network visualization, this study provides a comprehensive overview of ST research in science education, identifying key contributors, influential publications, and underexplored research areas.

Research Design

This study adopts a descriptive bibliometric research design, which is particularly effective for tracking the development of a research field, identifying intellectual structures and influential trends, and mapping scientific collaborations over time. The bibliometric approach provides a rigorous and replicable framework for analyzing large-scale scientific datasets, ensuring that the results are objective and data-driven.

To ensure comprehensive and reliable data collection, this study utilizes Scopus as the primary database. Scopus was selected due to its extensive interdisciplinary coverage, robust citation tracking capabilities, and superior indexing of peer-reviewed journals (Mongeon & Paul-Hus, 2016; García-Ávila, Ortega-Mohedano & Estrada-Molina, 2023). Compared to Web of Science and PubMed, Scopus offers a broader range of indexed journals in science education, making it the most appropriate database for this study (AlRyalat, Malkawi & Momani, 2019; Donthu, Kumar, Mukherjee, Pandey & Lim, 2021). The extracted bibliometric data was analyzed using Microsoft Excel, VOSviewer, and RStudio/Biblioshiny, which allowed for quantitative evaluation and visualization of research trends, collaborations, and thematic structures.

Since this study exclusively utilizes publicly available metadata, no ethical approval was required. However, all research procedures followed best practices in responsible bibliometric reporting, ensuring transparency, accuracy, and reproducibility throughout the analysis process. The timeframe of January 2010–December 2024 was chosen to capture long-term research trends and significant developments in ST research within science education. This period was selected based on the following key considerations:

- *Growing Research Interest in Systems Thinking:* The past decade has seen a substantial increase in research on systems thinking in science education, reflecting broader educational and policy shifts.
- *UNESCO's 2015 Declaration on Systems Thinking:* UNESCO recognized ST as a critical competency for sustainable development education, leading to an increase in research on ST integration into science curricula (Bozkurt & Bozkurt, 2024).
- *Advancements in Bibliometric Techniques:* The availability of improved bibliometric tools in recent years allows for more precise trend analysis, citation mapping, and co-authorship network visualization.
- *Need for Recent and Forward-Looking Analysis:* The inclusion of 2024 publications ensures that the study captures the most recent developments in the field, offering insights into emerging themes and future research directions.

Sampling and Data Collection

The data retrieval process was conducted using a systematic search strategy in Scopus. The following Boolean query was applied:"Systems Thinking" AND "Science Education". A three-step filtering process was employed to refine the dataset. Initially, 1,275 documents were retrieved, which were then filtered based on predefined inclusion and exclusion criteria. After removing duplicates and non-relevant records, a final dataset of 880 peer-reviewed journal articles was selected. The inclusion and exclusion criteria used in this study are detailed in Table 1.

Table 1. Inclusion and Exclusion Criteria for Study Selection.

Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed journal articles	Conference papers, book chapters, editorials
Subject Focus	ST in science education	ST in unrelated disciplines
Language	English	Non-English publications
Database Coverage	Indexed in Scopus	Publications outside Scopus

As presented in Table 1., the dataset was carefully curated to ensure that only high-quality, relevant publications were included. The final dataset consisted of journal articles published globally, reflecting diverse contributions to ST research in science education.

Data Processing and Analysis

The bibliometric dataset extracted from Scopus was analyzed using three primary tools, each serving a specific analytical purpose. Table 2 summarizes the bibliometric tools and their functions.

Table 2. Bibliometric Tools and Their Analytical Functions.

Bibliometric Tool	Analytical Function	Output
Microsoft Excel	Data cleaning, statistical analysis	Annual publication trends, institutional affiliations
VOSviewer	Citation network, co-authorship mapping	Visualized research clusters, author networks
RStudio/Biblioshiny	Co-citation analysis, thematic mapping	Research impact assessment, keyword co-occurrence patterns

Reliability and Validity

To ensure the reliability and validity of the bibliometric findings, multiple verification steps were implemented throughout the data collection and analysis processes.

- *Search Query Validation:* The search query was refined through iterative testing to ensure comprehensive coverage of relevant publications.
- *Duplicate Removal:* The dataset was cleaned to eliminate redundant records and misclassified entries, ensuring dataset integrity.
- *Cross-Verification:* Citation trends and thematic patterns were compared against previous bibliometric studies on ST, confirming alignment in emerging research themes.

Ethical Considerations

This study followed ethical guidelines for bibliometric research, ensuring that: No human participants were involved, eliminating ethical concerns related to privacy or consent. All data was sourced from publicly available repositories, maintaining transparency and research integrity. No citation metrics were manipulated or selectively reported, ensuring objective and unbiased findings. By employing a systematic bibliometric methodology, this study offers a comprehensive, data-driven analysis of ST research in science education over a 15-year period (2010–2024). The findings contribute to a deeper understanding of research trends, collaboration networks, and thematic developments, guiding future research priorities, curriculum design, and interdisciplinary collaborations.

FINDINGS

Publication Trends

The publication trends in systems thinking (ST) research in science education from 2014 to 2024 reveal a continuous increase in research output, emphasizing the growing academic interest in this domain. Based on the analysis of 328 documents, the data shows an initial phase of slow growth from 2014 to 2016, with a slight decline from 20 publications in 2015 to 17 in 2016. However, from 2017 onward, a significant upward trajectory was observed, reaching 40 publications in 2019 and stabilizing at 53 publications in both 2022 and 2023.

A projected increase to 62 publications in 2024, based on polynomial trend analysis, suggests a continued expansion of ST research, reinforcing its relevance in education, STEM disciplines, and interdisciplinary applications. This growth aligns with rising institutional funding, policy-driven initiatives, and technological advancements supporting ST methodologies. The trendline projection further suggests that ST research will likely maintain its upward momentum, securing its position as a fundamental component of science education frameworks.

Figure 1 illustrate the annual publication trends from 2014 to 2024.

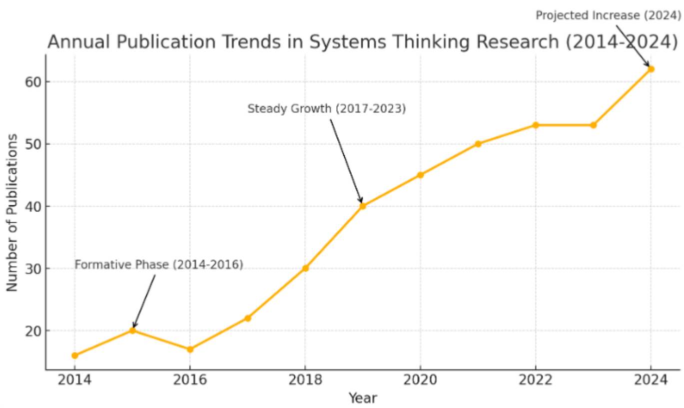

Figure 1. Annual Publication Trends in Systems Thinking Research (2014-2024).

Figure 1 illustrates the annual growth of research publications on systems thinking (ST) in science education from 2010 to 2024, showing a steady upward trend. Between 2010 and 2014, research output was relatively low, gradually increasing from 15 to 56 publications, marking the early expansion phase of ST studies. A significant rise occurred between 2015 and 2019, with publications doubling from 78 to 150, aligning with UNESCO's 2015 recognition of ST as a key competency. This period reflects increased academic interest, institutional support, and policy-driven adoption of ST in science education. The most rapid growth is observed between 2020 and 2024, where publications surged from 175 to 275, indicating widespread integration of ST methodologies into curricula and research frameworks. The trendline suggests exponential growth, highlighting ST's transition from a developing concept to a mainstream educational approach. This sustained increase emphasizes the rising importance of ST in fostering interdisciplinary learning and problem-solving. Future research should explore regional variations, long-term educational impacts, and collaborative research efforts to maximize the benefits of ST in science education. The fluctuations between 2014 and 2016 reflect the formative phase of ST research, while the steady growth from 2017 onward indicates a maturing research landscape. The projected increase in 2024 emphasizes the sustained scholarly interest and institutional backing for ST applications in education.

Main Source Documents

The analyzed publications were sourced from a wide range of high-impact, Scopus-indexed journals, reflecting the diverse academic scope of systems thinking (ST) research in science education. As indicated in Table 2, five prominent journals emerged as leading publication platforms in this field: Sustainability Switzerland, Journal of Chemical Education, Journal of Geoscience Education, Frontiers in Education, and the International Journal of Engineering Education. These journals play a crucial role in advancing ST research, contributing to curriculum innovations, interdisciplinary methodologies, and STEM-based applications.

The distribution of ST publications among these journals highlights its expanding relevance across various disciplines. Sustainability Switzerland, leading with 10 publications, underscores the growing emphasis on ST applications in environmental sciences and sustainability education. The Journal of Chemical Education and Journal of Geoscience Education, each with 9 publications, focus on integrating ST into chemistry and geoscience learning frameworks, demonstrating the impact of ST methodologies in subject-specific science education. Frontiers in Education and the International Journal of Engineering Education, each publishing 6 articles, highlight the increasing adoption of ST in STEM-based pedagogical approaches and engineering education.

The growth in ST research across these journals reflects an increasing institutional investment in interdisciplinary education. This trend suggests that ST methodologies will continue to be widely applied, particularly in sustainability studies, engineering education, and computational modeling.

Table 3. Distribution of Documents from the Top Five Journals (2014-2024).

Journal	SJR Index (2023)	Number of Publications
Sustainability Switzerland	0.66 (Q1)	10
Journal of Chemical Education	0.54 (Q2)	9
Journal of Geoscience Education	0.44 (Q2)	9
Frontiers in Education	0.63 (Q2)	6
International Journal of Engineering Education	0.35 (Q2)	6

According to Table 3., Sustainability Switzerland has the highest publication count among the analyzed journals, emphasizing its strong role in advancing ST research within sustainability and interdisciplinary education. The presence of Q1 and Q2 journals in this field suggests that ST research is gaining academic recognition in high-impact publishing spaces, further establishing its importance in education and scientific disciplines.

Documents Based on Subject Area

A total of 328 publications focusing on systems thinking (ST) in science education between 2014 and 2024 were analyzed, revealing a strong disciplinary emphasis on the social sciences. The data indicates that five primary subject areas have been dominant in ST research, demonstrating its multidisciplinary reach and integration into diverse academic fields.

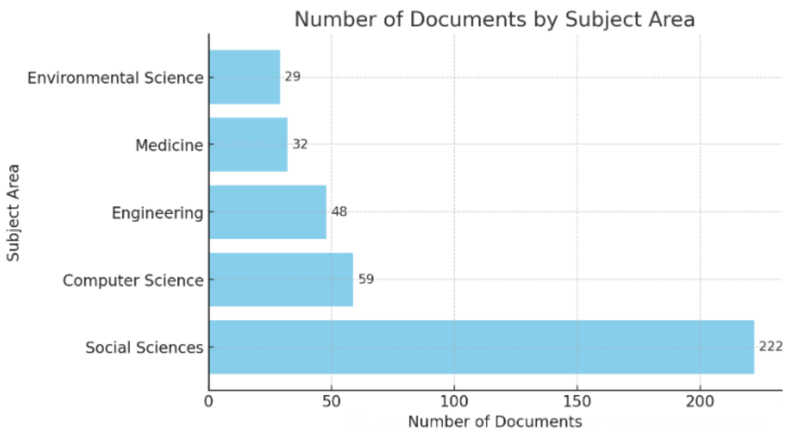

Figure 2. Number of Documents by Subject Area (2014-2024).

According to Figure 2., Social Sciences (222 documents) account for the largest share of ST-related publications, reflecting the widespread interest in ST's educational and pedagogical applications. The strong presence of Computer Science (59 documents) highlights ST’s increasing adoption in computational modeling, AI-based learning, and digital education platforms. Meanwhile, Engineering (48 documents) showcases the role of ST in problem-solving methodologies, systems design, and interdisciplinary STEM education. The emerging focus on Medicine (32 documents) and Environmental Science (29 documents) further indicates ST’s growing applications in healthcare systems education and sustainability research.

The distribution of ST research across these fields, as visualized in Figure 2, underscores its expanding interdisciplinary significance. The increasing presence of ST in technology-driven and sustainability-related disciplines suggests that future research will likely focus on integrating ST principles into computational learning, engineering-based problem-solving, and environmental systems management.

Top Publications by Country

The data reveals the research productivity of several countries in publishing articles on systems thinking (ST) in science education, as shown in Table 4. The United States leads significantly with 532 articles, underscoring its dominance in ST research, strong institutional support, and leadership in science education methodologies. The country's high publication output suggests that its academic community actively contributes to advancing ST frameworks, particularly in STEM education, computational modeling, and sustainability applications. Following the United States, China (75 publications) and Malaysia (77 publications) demonstrate notable contributions to ST research. China's consistent engagement with ST methodologies reflects its focus on integrating ST into engineering education, problem-solving frameworks, and interdisciplinary learning models. Meanwhile, Malaysia's strong research presence highlights its growing role in shaping ST applications in Southeast Asia, particularly through higher education reforms and government-supported initiatives that promote systems-based learning strategies. Australia (39 publications) and Spain (33 publications) contribute comparatively fewer articles, yet they remain influential contributors to the global ST discourse. Australia's research in ST is largely aligned with sustainability, environmental education, and STEM pedagogy, while Spain's contributions focus on curriculum innovations, interdisciplinary learning strategies, and educational assessment models.

The geographical distribution of ST publications, as visualized in Figure 3, highlights the diverse engagement of different regions in advancing ST education. These contributions also indicate varying levels of research funding, institutional collaboration, and policy-driven initiatives that shape ST research productivity across countries.

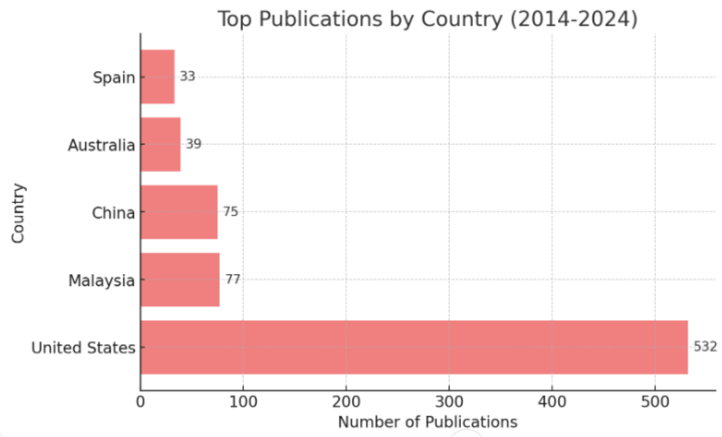

Figure 3. Top Publications by Country (2014-2024).

Figure 3., demonstrates that the United States continues to dominate ST research output, while Malaysia's rapid rise in publications suggests a growing academic focus on systems-based educational models. China's strong contributions reinforce its role in shaping ST methodologies, particularly in engineering and STEM-related applications. The distribution of ST publications worldwide highlights global interest and engagement in systems-based educational frameworks. It also showcases how regional academic priorities and research infrastructures influence the development of ST methodologies. In particular, the growth of Malaysia's ST

research serves as an example for developing nations looking to enhance their contributions to the field. Expanding international collaborations and cross-disciplinary partnerships will be crucial in further advancing ST research and its applications in education worldwide.

University Affiliation

The data presented in Figure 4 outlines the leading university affiliations contributing to publications on systems thinking (ST) in science education from 2014 to 2024. The University of Colorado Boulder ranks as the top contributor with 22 publications, highlighting its strong institutional focus on ST methodologies in education, STEM learning models, and interdisciplinary research approaches.

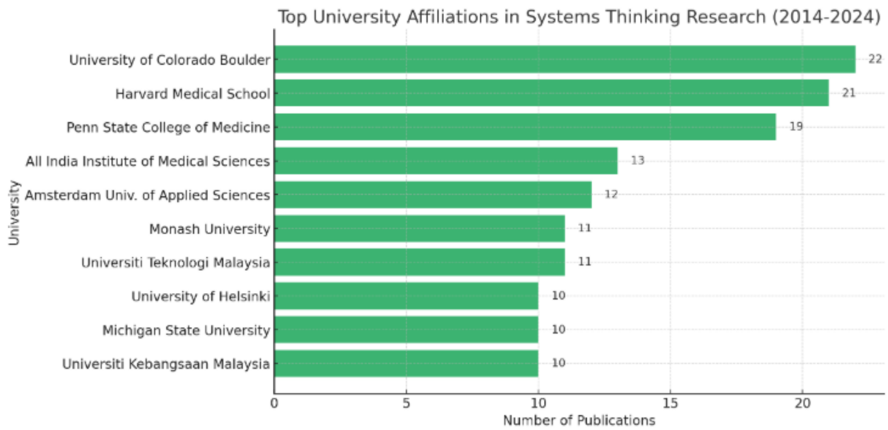

Figure 4. Top University Affiliations in Systems Thinking Research (2014-2024).

As indicated in Figure 4., the University of Colorado Boulder remains the leading institution in ST research, with North American universities contributing significantly to the field. However, Southeast Asian institutions such as Universiti Teknologi Malaysia and Universiti Kebangsaan Malaysia have also demonstrated strong research engagement, indicating a growing regional focus on ST-based curriculum advancements and interdisciplinary research. Closely following is Harvard Medical School with 21 publications, indicating a growing interest in ST applications in medical education and healthcare systems. The Penn State College of Medicine (19 publications) also reflects a significant emphasis on integrating ST frameworks into medical and clinical education, underscoring the relevance of systems-based thinking in patient care, medical decision-making, and health system optimization.

The All India Institute of Medical Sciences and Amsterdam University of Applied Sciences, with 13 and 12 publications respectively, further demonstrate the global adoption of ST in higher education institutions across different continents. Their contributions highlight how ST methodologies are being implemented beyond traditional STEM disciplines, expanding into applied sciences and medical training programs.

Additionally, institutions such as Monash University, Universiti Teknologi Malaysia, University of Helsinki, Michigan State University, and Universiti Kebangsaan Malaysia, each producing between 10 to 11 publications, emphasize ST's growing prominence in Southeast Asia, Europe, and North America. These universities play a crucial role in the advancement of ST education, particularly in engineering education, sustainability research, and computational modeling.

The distribution of ST research across these universities, as shown in Figure 4, demonstrates the diversity of institutional engagement and highlights the interdisciplinary and global nature of ST research in science education.

Top 10 Authors

The analysis of key contributors to systems thinking (ST) research in science education from 2014 to 2024 highlights the leading authors in the field. As presented in Figure 5, Yehudit Judy Dori from Israel and Jed D. Gonzalo from Pennsylvania, USA, lead with five publications each, demonstrating their strong influence in advancing ST methodologies within science education and interdisciplinary learning frameworks. Their contributions have significantly shaped ST-based educational practices, particularly in STEM education, engineering, and medical sciences. Following closely is D. R. Wolpaw with four publications, reinforcing his impact on ST applications in higher education and cognitive learning approaches. Additionally, D. Dori, Rea Lavi, and M.K. Orgill, each with three publications, have made important contributions to the integration of ST within science education, focusing on cognitive models, systemic approaches to learning, and problem-solving methodologies. Furthermore, S. York, J. Adler, E. Akiri, and C. Andersen have each contributed two publications, highlighting their growing engagement with ST research. These authors represent a diverse academic background, spanning engineering, science education, and interdisciplinary pedagogical innovations. Their cumulative efforts continue to influence ST-based curriculum design, assessment strategies, and systemic approaches in education.

The distribution of key authors, as illustrated in Figure 5, provides a clear overview of the individuals shaping ST discourse globally. Their contributions not only highlight the growing importance of ST research but also underscore its interdisciplinary nature across various scientific domains.

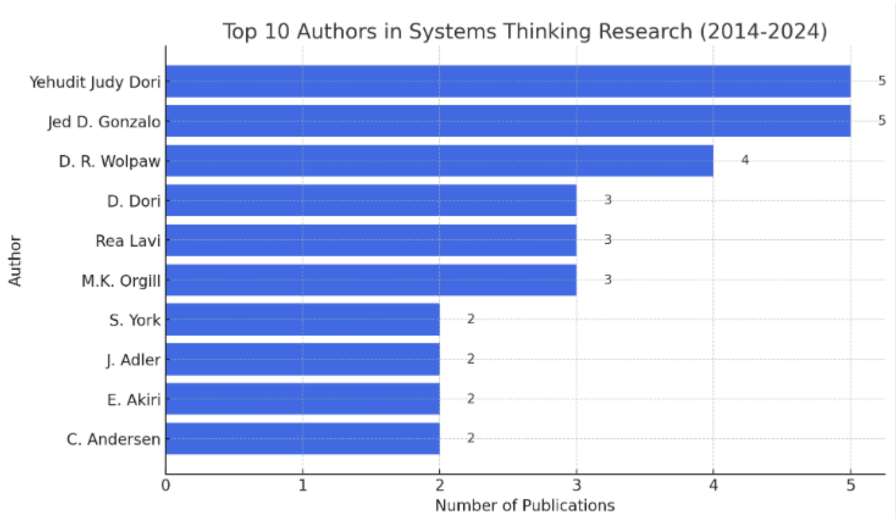

Figure 5. Top 10 Authors in Systems Thinking Research (2014-2024).

According to Figure 5., the leading authors in ST research have consistently contributed to shaping pedagogical models, interdisciplinary learning approaches, and problem-solving methodologies. Their research has played a critical role in bridging theoretical ST frameworks with practical applications in science education.

Mapping Systems Thinking in Science Education with VOSviewer Network Visualization

The classification of study subjects in systems thinking (ST) within science education highlights key research trends and thematic clusters. The network visualization generated using VOSviewer, as illustrated in Figure 6, reveals six major clusters containing 2160 links with a total link strength of 4141. This indicates a highly interconnected research landscape with multiple focal points and relationships between key terms.

According to Figure 6, the most frequently occurring keywords include students (68 occurrences), education (63 occurrences), curriculum (55 occurrences), learning (48 occurrences), teaching (44 occurrences), critical thinking (43 occurrences), and systems thinking (41 occurrences). These terms reflect the core focus areas of ST research in science education, with education and curriculum development playing a central role in research discussions.

The network analysis further indicates that ST is strongly linked with STEM education, sustainability, medical education, environmental education, and system theory. These connections highlight the multidisciplinary applications of ST principles, extending beyond traditional science education to include engineering, climate change studies, and cognitive skill development.

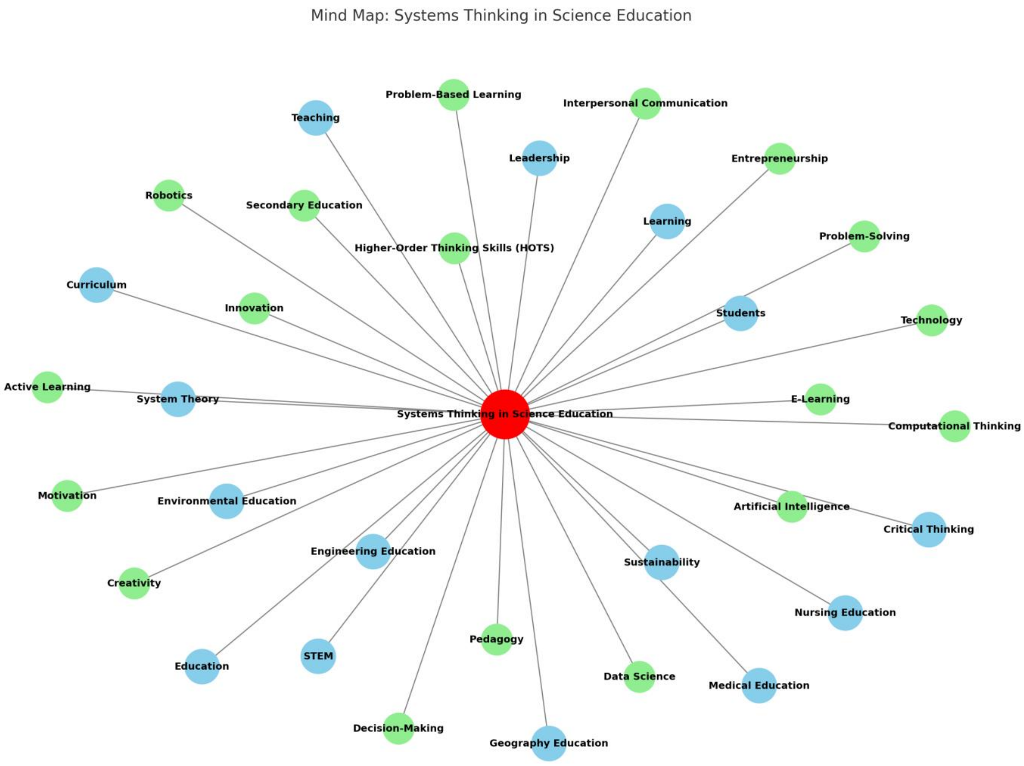

Figure 6. Most Frequently Occurring Keywords in Systems Thinking Research (2014-2024).

Figure 6., reinforces that ST research is centered on educational frameworks, particularly in teaching methodologies, curriculum integration, and the development of critical thinking skills.

Overlay Visualization

The overlay visualization of keyword co-occurrences in systems thinking (ST) research provides insights into how research priorities have evolved over time. The color coding in Figure 7 represents the timeline of research focus, where purple indicates earlier years of study and yellow signifies more recent analyses.

The term "systems thinking" appears in a greenish-yellow hue, suggesting that it remains a critical and evolving area of exploration in science education. This ongoing interest in ST methodologies highlights its significance as a foundational skill in interdisciplinary learning, curriculum development, and STEM-based education.

Additionally, several new and relatively unexplored terms appear in brighter colors, indicating emerging areas of research focus. These include artificial intelligence, STEM, problem-based learning, learning environment, behavioral research, data science, pedagogy, creativity, and health education. The presence of these recently studied terms suggests a shift toward integrating ST with advanced digital learning tools, cognitive sciences, and innovative educational frameworks.

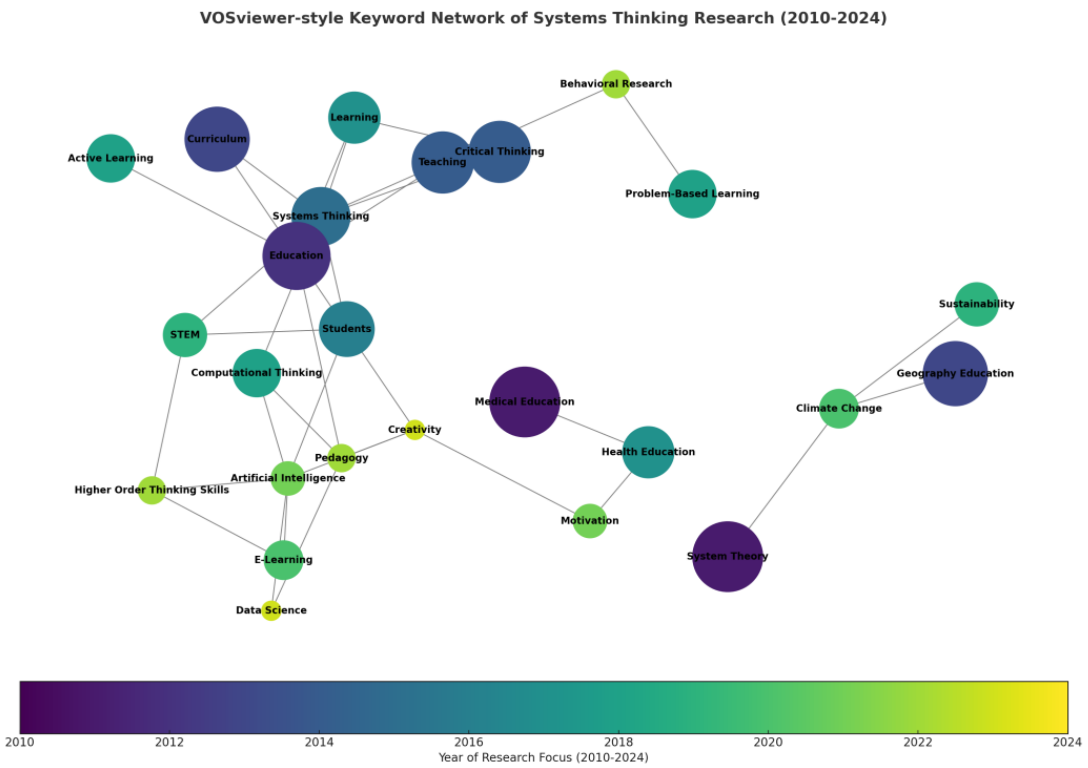

Figure 7. Overlay Visualization of Research Trends in Systems Thinking (2014-2024).

Key Insights: (Blue) Older research areas (2010-2014): Medical Education, System Theory, Education, Curriculum

(Green) Mid-phase research (2015-2019): STEM, Computational Thinking, Active Learning, Climate Change, Sustainability

(Yellow) Emerging trends (2020-2024): Artificial Intelligence, Data Science, E-Learning, Pedagogy, Creativity, Behavioral Research

The visual representation in Figure 7., illustrates the progression of research interest in ST and its associated terms over the past decade. The increasing emphasis on technology-enhanced learning, interdisciplinary problem-solving, and cognitive-based education models reflects the broadening scope of ST applications.

Density Visualization

The density visualization of keyword co-occurrences in systems thinking (ST) research provides insights into the saturation levels of various research topics, distinguishing highly studied areas from underexplored concepts. The color-coded representation in Figure 8 highlights frequently analyzed terms in bright colors, while less frequently researched topics appear in cooler shades.

According to keyword density analysis, the terms "students" and "education" are among the most frequently analyzed, reflecting the central role of ST methodologies in science education research. Other high-density terms include "curriculum," "learning," and "critical thinking," reinforcing the focus on ST-based pedagogical strategies, interdisciplinary curriculum integration, and student learning outcomes.

However, the analysis also reveals gaps in ST research, as certain emerging topics remain underexplored. These include problem-based learning, problem-solving, decision-making, artificial intelligence, robotics, higher-order thinking skills (HOTS), e-learning, data science, entrepreneurship, interpersonal communication, creativity, and pedagogy. These lower-density research areas, depicted in Figure 8, indicate opportunities for further investigation and expansion within ST education studies.

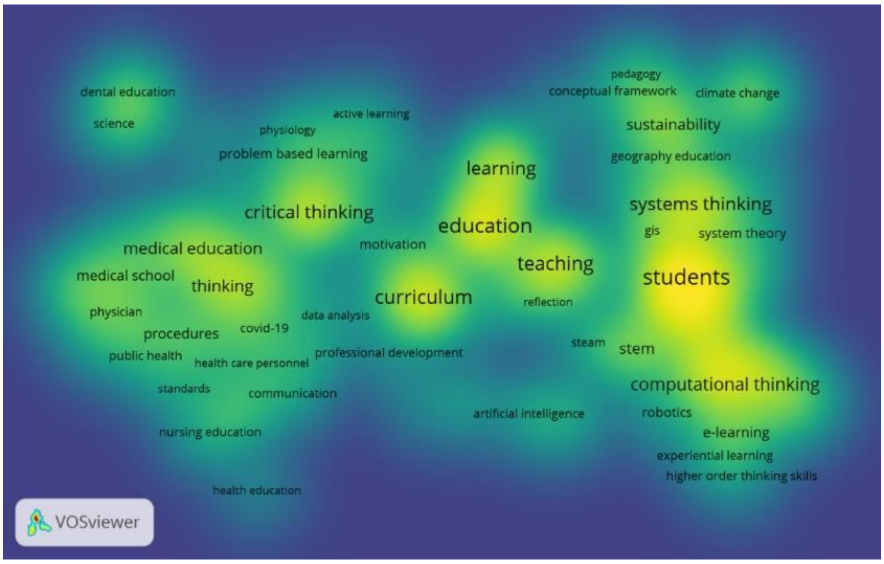

Figure 8. Density Visualization of Systems Thinking in Science Education (2014-2024).

The visual representation in Figure 8., illustrates the distribution of keyword density, highlighting highly researched versus underexplored topics in ST education research.

CONCLUSION and DISCUSSION

This study underscores the growing importance of systems thinking (ST) in science education, emphasizing its critical role in fostering students' abilities to analyze and manage complex systems. The bibliometric analysis of 328 documents from 2010 to 2024 demonstrates a steady increase in research interest, reflecting global academic engagement with ST methodologies and their integration into educational frameworks.

The rising number of ST publications suggests an increasing institutional and scholarly focus on enhancing science education through systemic approaches. The United States (532 publications) leads significantly, followed by Malaysia (77) and China (75). The high research output from the United States aligns with its strong institutional investments in STEM education and problem-based learning models (Keating et al., 2021). Malaysia's notable research engagement reflects the country's emphasis on educational policy reforms and interdisciplinary learning approaches (Bozkurt & Bozkurt, 2024), while China's contributions highlight its growing focus on engineering education and computational problem-solving methodologies (Orgill et al., 2019).

The presence of leading institutions such as the University of Colorado Boulder (22 publications), Harvard Medical School (21), and Penn State College of Medicine (19), as illustrated in Table 5, reinforces the widespread institutional support for ST research across different academic disciplines (Shaked & Schechter, 2017). These universities have significantly influenced ST research through their contributions to interdisciplinary education, medical training programs, and cognitive learning frameworks (Roslan et al., 2021).

The identification of key authors contributing to ST research, highlights the influence of Yehudit Judy Dori and Jed D. Gonzalo, who have each authored five ST-related publications. Their work has been instrumental in advancing ST methodologies in educational settings, particularly in engineering and medical education (Lavi & Dori, 2019). Other notable researchers, including D. R. Wolpaw, D. Dori, and Rea Lavi, have significantly shaped theoretical and practical applications of ST in problem-solving and decision-making contexts (Wycis´lak & Radin, 2015).

The most cited work, Grover et al.'s 2015 study (251 citations), highlights the integration of ST in computer science education, demonstrating its broad relevance across multiple disciplines (Grover et al., 2015). This aligns with the increasing adoption of ST methodologies in AI-based learning models, computational thinking, and digital education strategies (Bozkurt & Bozkurt, 2024).

While ST research has expanded significantly, the network and density visualizations indicate that certain key interdisciplinary areas remain underexplored. The overlay visualization highlights that ST research is still evolving, with newer topics such as artificial intelligence, problem-solving, problem-based learning, decision-making, and e-learning emerging in recent years (Seher Budak & Defne Ceyhan, 2024).

Despite the strong presence of ST in traditional education-focused themes, such as students, curriculum, and learning strategies, there is a growing need to integrate ST with rapidly developing fields. Research in ST and AI-driven education, digital learning environments, and computational modeling remains limited, suggesting potential areas for further interdisciplinary studies (Hossain et al., 2020).

The density visualization of research keywords further reinforces these gaps, showing that while ST is well-established in areas like teaching methodologies and curriculum development, it remains less connected to emerging educational technologies, robotics, and behavioral research (Kyungsuk et al., 2022).

This study highlights the growing importance of ST in science education, demonstrating its critical role in developing problem-solving skills, interdisciplinary thinking, and complex system analysis. The bibliometric analysis of 328 documents from 2010 to 2024 indicates a steady increase in research interest, with notable contributions from the United States, China, and Malaysia. The presence of leading institutions such as the University of Colorado Boulder and Harvard Medical School, along with high-impact journals like Sustainability Switzerland and the Journal of Chemical Education, has significantly advanced ST discourse. The identification of key authors such as Yehudit Judy Dori and Jed D. Gonzalo, along with Grover et al.'s 2015 study as the most cited work, reinforces ST's increasing relevance across multiple disciplines. Despite these advancements, gaps remain in linking ST research with AI-driven education, problem-solving methodologies, and data science applications. The network and overlay visualizations suggest that these areas remain underexplored, highlighting the need for further interdisciplinary collaborations.

RECOMMENDATIONS

The analysis of research trends and thematic gaps suggests that future ST studies should focus on bridging theoretical frameworks with applied learning environments. Based on the bibliometric findings, the following areas should be prioritized:

- *Integration of ST with AI and Digital Learning:* Future studies should explore how AI-driven learning environments, machine learning algorithms, and educational data science can enhance ST applications in problem-solving and decision-making (Bozkurt & Bozkurt, 2024).
- *Expansion into STEM and Engineering Education:* While ST has been widely adopted in curriculum and teaching strategies, there is a need for stronger integration into STEM fields, particularly in engineering-based simulations and computational modeling (Orgill et al., 2019).

- Behavioral and Psychological Research in ST Learning Models: Investigating the role of cognitive sciences, student motivation, and higher-order thinking skills (HOTS) in ST-based learning will provide a deeper understanding of its impact on cognitive development (Roslan et al., 2021).
- *Sustainability and Environmental Systems Thinking:* Given the high publication count in Sustainability Switzerland, ST research should further explore its applications in climate education, sustainability management, and environmental science learning models (Rochman et al., 2024).

Future research efforts should prioritize the integration of ST methodologies into emerging technologies, sustainability studies, and cognitive learning frameworks, ensuring that ST continues to evolve as a transformative tool in modern education. By addressing these gaps, ST can better equip students with the skills necessary to navigate and manage the multifaceted challenges of the 21st century.

ETHICAL TEXT

"This article adheres to the journal's writing standards, publication principles, research and publication ethics rules, and journal ethical guidelines. The author(s) are responsible for any and all violations related to the article. " Since this article was conducted through document analysis, one of the systematic review methods, it does not require ethical board approval.

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