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Analyzing research connections in the development of systems thinking for science problem solving: A systematic literature network analysis (SLNA) approach

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Abstract

This study investigates the emerging trends and research opportunities focused on promoting systems thinking within the context of scientific problem-solving. To facilitate this exploration, the research employs the Systematic Literature Network Analysis (SLNA) method. This study is based on the analysis of scientific articles related to systems thinking in science education, collected from the Scopus database of science direct from 2020-2024. Initially, a total of 7,512 relevant articles were retrieved, then 1,000 were successfully retrieved, but through the removal of duplicates and non-journal sources, a more accurate data set was created. Following a preliminary screening process based on article titles, the dataset was narrowed down to 250 articles. Further refinement involved keyword searches and specific inclusion criteria, which culminated in the selection of 9 articles for comprehensive analysis. The most frequently discussed topics include "system thinking," with strong connections to other concepts such as problem-solving strategies and inquiry-based learning. While research on system thinking in science education is well-established, there are still underexplored areas, such as the development of innovative teaching models that integrate system thinking facilitation. Future research could focus on developing innovative instructional models that incorporate strategies to facilitate system thinking, offering new ways to enhance students' ability to approach complex science problems.

Keywords

System thinking, Science, Problem solving, Systematic literature network analysis

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Introduction

The evolution of systems thinking (ST) has garnered significant attention in scientific research, largely because of its powerful ability to improve problem-solving skills across a wide range of disciplines. At its core, systems thinking promotes a comprehensive and holistic approach to tackling complex issues, emphasizing the importance of recognizing interconnections, feedback loops, and the intricate dynamics that govern various systems [1]. This perspective has proven to be especially valuable in both the natural and social sciences, where the challenges faced are often intricate, multifaceted, and deeply intertwined [2]. By adopting this paradigm, researchers and practitioners can better navigate the complexities of real-world problems, leading to more effective and innovative solutions.

The integration of systems thinking into the realm of science problem-solving has demonstrated significant potential for fostering innovation and enhancing decision-making processes across various fields. Systems thinking, which emphasizes understanding the complex interconnections and interactions within a system, has become particularly valuable in tackling sustainability challenges. By employing systems thinking, researchers and practitioners can gain a comprehensive perspective on the long-term impacts that their decisions have on a wide array of factors, including ecosystems, social structures, and economic frameworks [3]. This holistic view is essential for developing sustainable solutions that take into consideration the intricate balance between environmental health, societal needs, and economic viability.

In addition to sustainability, systems thinking has emerged as a vital method for addressing complex issues such as climate change, intricate healthcare systems, and the multifaceted nature of supply chain management. It provides tools and frameworks for modeling and analyzing the underlying dynamics of these systems, allowing for a better understanding of how various components interact and influence one another over time [4]. For instance, in the context of climate change, systems thinking aids in identifying feedback loops and potential leverage points that can amplify or mitigate environmental impacts, thereby informing more effective interventions.

Despite the growing recognition of systems thinking's importance in these areas, there remains a considerable amount of ambiguity regarding the most effective strategies for implementing this approach in different scientific contexts. Researchers and practitioners often face challenges in translating the theoretical principles of systems thinking into practical applications tailored to their specific disciplines. As such, further exploration and clarification of methodologies for integrating systems thinking into diverse scientific practices are essential for unlocking its full potential and maximizing its benefits for tackling contemporary global challenges.

There is a significant gap in our understanding of how research contributions are interconnected and how the theoretical and methodological developments in systems thinking have evolved over time. Recent studies indicate that there is no unified framework that clearly outlines the principles, methods, or applications of systems thinking across different disciplines [5]. This lack of integration has resulted in fragmented research trajectories and challenges in comparing findings from various fields. Consequently, it hinders the broader adoption of systems thinking as a standard approach to scientific problem-solving [6].

In order to address the existing gaps in the literature, this article adopts a Systematic Literature Network Analysis (SLNA) methodology. This innovative approach is employed to meticulously map the progression of systems thinking research, particularly within the context of science problem-solving. By utilizing SLNA, the study facilitates the identification of key themes that have emerged over time, as well as pinpointing influential research studies that have made significant impacts in the field. Furthermore, it uncovers the interconnected relationships among scholars, thereby providing a more comprehensive understanding of the intellectual landscape associated with systems thinking. Through a careful tracing of these academic connections, this study seeks to unveil the pivotal developments in the realm of systems thinking. It emphasizes the scholarly contributions that have been instrumental in shaping the application of systems thinking to address real-world challenges, thus illustrating the evolving nature of this crucial area of research and its relevance to contemporary problem-solving endeavors.

In the context of scientific problem-solving, systems thinking is becoming increasingly important as it allows for a nuanced understanding of complex phenomena, which are often non-linear and interdependent. Modern scientific challenges, such as global health crises and environmental degradation, require solutions that not only consider immediate impacts but also long-term consequences across multiple domains. Systems thinking enables researchers to identify key leverage points within a system, facilitating more effective and sustainable solutions. According to Meadows [7], “Effective problem-solving in science requires a deep understanding of the interconnections within the system, where even small changes can have disproportionate effects on the whole system.” By applying this approach, scientists are better equipped to anticipate unintended consequences, adapt strategies, and design interventions that are more resilient in the face of uncertainty.

Moreover, systems thinking provides a robust framework for navigating the increasing complexity of interdisciplinary research, where problems span multiple areas of knowledge. This holistic perspective is essential for addressing issues that transcend the boundaries of individual disciplines, such as climate change and public health, where interactions between biological, social, economic, and political factors must be considered. As highlighted by Voulvoulis et al. [8], "Systems thinking offers a means to integrate insights from diverse fields, fostering collaborative solutions that are both practical and transformative." In scientific inquiry, this interconnectedness is vital, as real-world problems are rarely isolated to a single discipline. A cross-cutting approach to problem-solving is necessary to acknowledge and address the interconnected nature of these challenges.

The purpose of this study is to thoroughly examine the current state of systems thinking research and its vital role in addressing complex scientific problems. Through this analysis, we aim to provide practical guidance on how to integrate systems thinking into scientific inquiry, identify effective frameworks for its application across various disciplines, and highlight the benefits of this approach in promoting innovation, collaboration, and long-term sustainability. Additionally, this study intends to propose actionable future directions for advancing systems thinking as an essential tool for improving decision-making and problem-solving processes in both science education and real-world applications. By mapping the evolution and interconnections of systems thinking research, we seek to demonstrate its potential for driving transformative solutions to the interconnected challenges faced by contemporary science.

Method

The adopted Systematic Literature Network Analysis (SLNA) method integrates the Systematic Literature Review (SLR) approach with bibliographic network analysis. It consists of two distinct phases (see Figure 1).

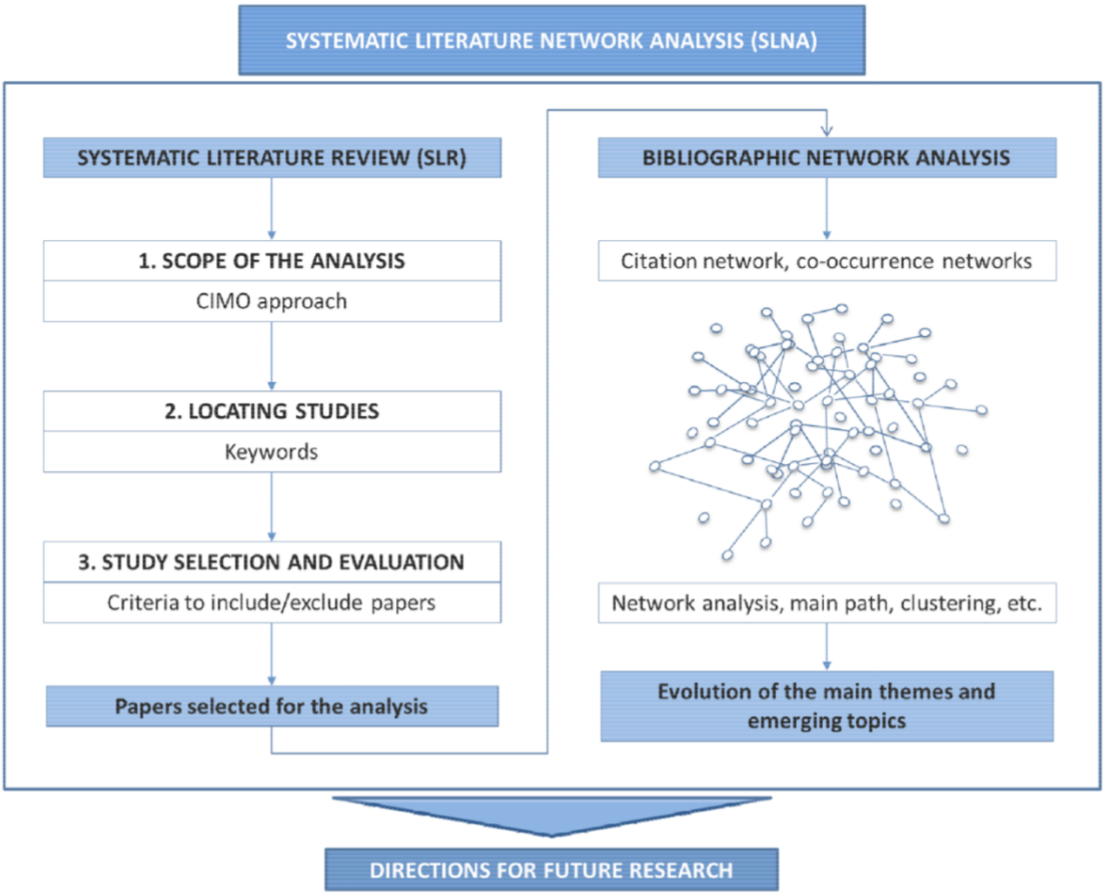

Figure 1. Systematic Literature Network Analysis (SLNA) diagram

The diagram outlines a systematic approach to conducting a literature review known as Systematic Literature Network Analysis (SLNA). This method merges a systematic literature review (SLR) with bibliographic network analysis to provide a comprehensive understanding of a research topic. The process starts by defining the scope of the analysis, often employing the CIMO framework (Context, Intervention, Mechanism, Outcome).

Once the scope is established, relevant studies are identified using specific keywords. The next step involves selecting and evaluating studies based on predetermined criteria. Selected papers are then analyzed using network analysis techniques to uncover key themes, relationships between concepts, and emerging trends. By visualizing these relationships in a network diagram, researchers can gain deeper insights into the research landscape and identify potential gaps or inconsistencies in the existing literature.

Recent studies have highlighted the usefulness of SLNA across various fields. For instance, Faust et al. [9] revealed that there is a growing interest in the application of machine learning techniques to healthcare. The study identified several emerging trends, such as the use of deep learning for medical image analysis and the development of explainable AI models for clinical decision support. This article demonstrated how SLNA can be employed to map the evolution of a particular research area over time. Additionally, Wakid et al. [10] illustrated that SLNA can help identify influential papers and researchers within a specific field. By providing a visual representation of the knowledge base, SLNA can facilitate the development of new research questions and encourage interdisciplinary collaboration.

This study is based on a thorough data collection process focused on scientific articles related to systems thinking in science education. The initial search conducted in the Scopus database of ScienceDirect identified a significant number of 7,512 potentially relevant articles published between 2020 and 2024. After retrieving the data and removing duplicates, we refined the set to 1,000 articles. We then excluded non-journal sources to create a more targeted dataset. A preliminary screening of the article titles further narrowed the selection to 250 articles. To ensure we included the most relevant research, we refined the dataset further through keyword searches and the application of specific inclusion criteria. This multi-stage selection process ultimately led to the identification and inclusion of 9 articles for in-depth analysis, which forms the foundation of this study.

Result and Discussion

Growth of Systems Thinking Research in Science Education (2020-2024)

The graph (Figure 2) illustrates the increase in the number of articles pertaining to systems thinking in science education over a five-year period, from 2020 to 2024. The number of articles began at 93 in 2020 and has exhibited a consistent and notable annual increase. In 2021, the figure rose to 207, followed by further growth to 264 in 2022. By 2023, the number reached 449, and projections indicate it will rise to 775 by 2024. This data underscores a significant upward trend in scholarly interest and research focused on systems thinking in the domain of science education, suggesting a growing acknowledgment of its importance and application within this field. The sustained growth over the years reflects an increasing interest in and the integration of systems thinking approaches into educational practices and research methodologies.

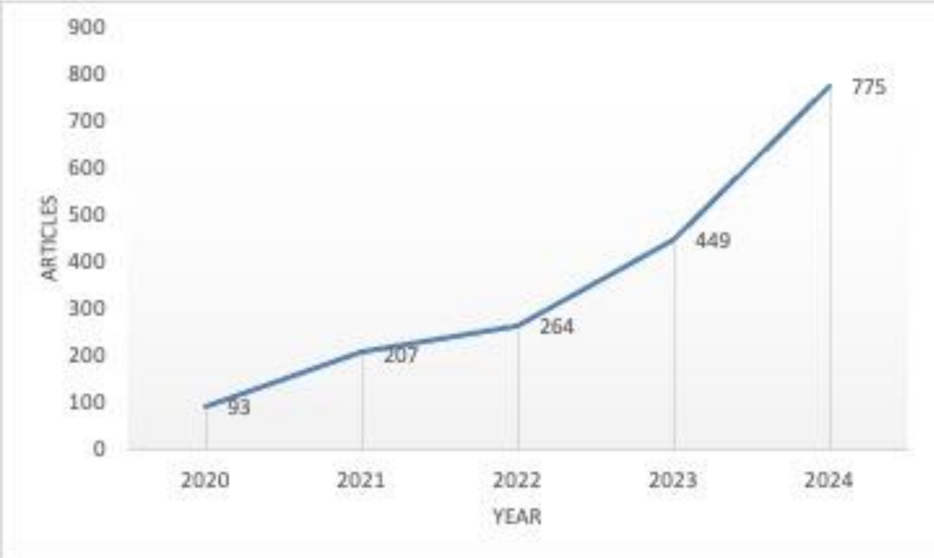

Figure 2. The Increasing Trend of Systems Thinking Research in Science Education

The graph clearly shows a significant increase in the volume of research articles related to systems thinking in science education, reflecting a growing acknowledgment of its importance in addressing contemporary scientific challenges. The steady rise in the number of publications from 2020 to 2024 highlights a critical shift in how educators and researchers are beginning to recognize the value of systems thinking for tackling the complex, interdisciplinary issues prevalent in modern science. This upward trend in scholarly output not only indicates greater academic attention but also suggests a broader integration of systems thinking into both curricula and research methodologies used in science education. Recent studies indicate that applying systems thinking in education can enhance problem-solving skills by encouraging students to consider multiple variables and their interconnections, thus better preparing them for the multifaceted nature of real-world scientific problems [11].

In line with this growth, numerous studies have emphasized the transformative impact that systems thinking can have on scientific inquiry. The increased interest in this approach reflects a wider trend in scientific research, where complex issues such as climate change, public health, and sustainability demand interdisciplinary solutions that go beyond traditional disciplinary boundaries. As Jackson [4] noted, "systems thinking is key to navigating the complexity and interconnectedness of modern global challenges, enabling researchers to adopt holistic perspectives and more effective problem-solving strategies." This expanding body of research contributes not only to more effective educational practices but also lays the groundwork for innovations in scientific problem-solving that require a systemic rather than isolated approach to complex issues. The projected increase to 775 articles in 2024 further illustrates the momentum toward adopting systems thinking as a cornerstone of scientific education and practice, reinforcing its growing importance as a tool for addressing the urgent, interconnected challenges facing contemporary science.

This section contains answers to the questions "what have you found". Therefore, only representative results from the research are presented. What is meant by "representative results" are results that represent the research findings, which lead to the discussion. Generally, research results are presented in figures or tables, but can also be in the form of descriptions for certain cases.

Network Visualization of Systems Thinking in Research: Trends and Interdisciplinary Connections

Figures 3 and 4 illustrate a network visualization of articles related to systems thinking, analyzed using VOSviewer, a bibliometric analysis tool. These visualizations show the interconnections between key themes and concepts within systems thinking research. The size and color of each node reflect the frequency and significance of specific terms found in the scholarly literature.

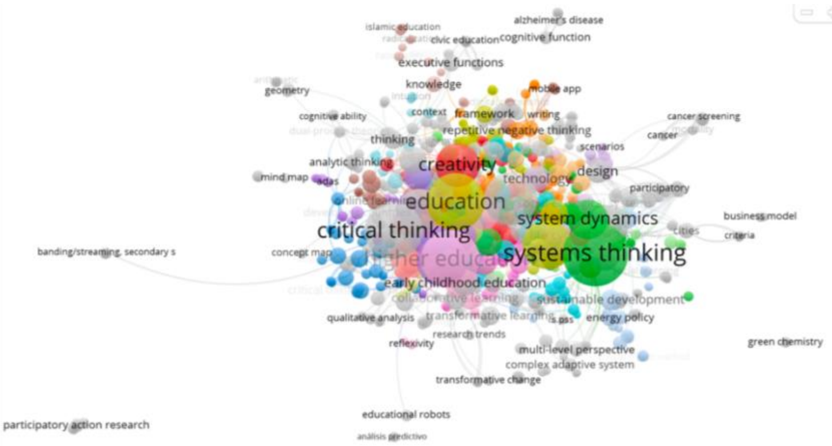

Figure 3. Expanding Applications of Systems Thinking in Education and Sustainability

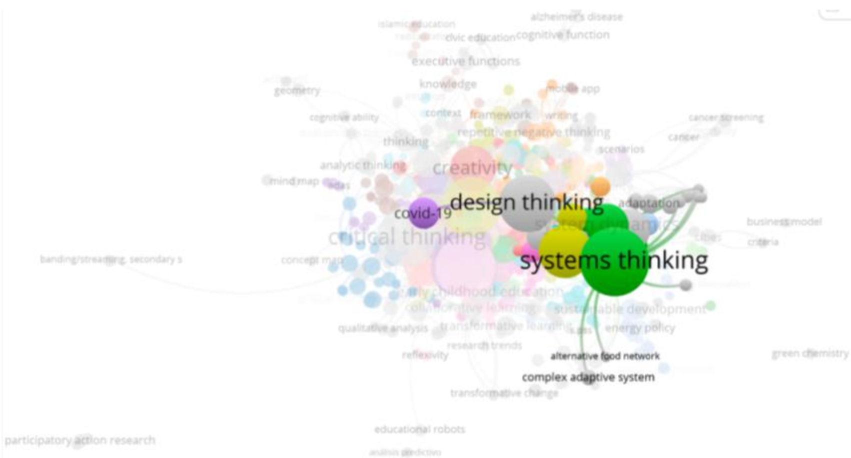

Figure 4. Interdisciplinary Connections in Systems Thinking Research

In Figure 3, systems thinking is positioned as a central theme, surrounded by terms like "design thinking," "creativity," and "critical thinking." This arrangement highlights its increasing relevance across various scientific fields. The network demonstrates a clear overlap with other research areas, emphasizing the interdisciplinary nature of systems thinking and its growing importance in addressing complex problems [2; 3].

Figure 4 provides a more detailed network, featuring terms such as "education," "higher education", "system dynamics", and "sustainable development." This visualization underscores the application of systems thinking in educational contexts and its broader implications for societal challenges, including sustainability and policy development [12; 13]. The larger clusters within this network indicate the increasing prominence of these concepts in academic discourse, illustrating the expanding role of systems thinking in tackling real-world issues.

These visualizations emphasize the growing body of research related to systems thinking, highlighting its increasing importance in addressing complex scientific problems. The rise in scholarly articles on this topic indicates its expanding application in fields such as sustainability, climate science, healthcare, and other interdisciplinary areas, where understanding interconnected systems is essential for effective problem-solving. As scientific challenges become more complex and multifaceted, the role of systems thinking in shaping the future of scientific inquiry is becoming increasingly significant. This trend suggests that systems thinking is not only enhancing scientific understanding but also fostering innovative problem-solving approaches, enabling researchers to tackle global challenges in a more holistic and integrated way.

Application of Systems Thinking in Multidisciplinary Research

Table 1. Exploring the Criteria for Journal Metrics of Eligible Articles

No	Journal	Indeks by H-Indeks/SJR 2023	H-Index
1	Futures	Q1 / SJR:0.85	98
2	Computers & Education	Q1 / SJR: 3.65	232
3	Food Policy	Q1 / SJR:2.12	135
4	Journal of Cleaner Production	Q1 / SJR:2.06	309
5	Journal of Cleaner Production	Q1 / SJR:2.06	309
6	Health and Place	Q1 / SJR:1.28	137
7	Health and Place	Q1 / SJR:1.28	137
8	Energy Research & Social Science	Q1 / SJR: 2.32	113
9	Cleaner and Responsible Consumption	Q1 / SJR:0.75	14

Table 1 illustrates those systems thinking is utilized across various research contexts, including environmental policy, marine ecosystems, and public health. All studies employ a range of approaches, such as qualitative research, experiments, and system dynamics, to tackle complex issues that involve multiple interdependent factors.

Recent research has shown that systems thinking is being applied across various fields to tackle complex problems using a holistic approach. Table 2 presents details of articles that utilize a system thinking approach in their research. This table includes the titles of the articles, the authors, their countries of origin, the research methods employed, the materials analyzed, and the focus of the scientific studies reviewed. The articles cover a wide range of topics, from environmental policy to public health, highlighting the diverse applications of systems thinking in problem-solving across different disciplines.

Table 2. Details of Research Articles Using Systems Thinking Approach in Various Fields of Science

No	Article Title	Author	Author Country	Research Methods	Analysis Materials	Science Study
1	Policy design by "imaginary future generations" with systems thinking : a practice by Kyoto city towards decarbonization in 2050 [14]	Keishiro Hara, Yutaka Nomaguchi, Shinya Fukutomi, Masashi Kuroda, Kikuo Fujita, Yoko Kawai, Masayuki Fujita, Takuro Kobashi (2023)	Japan	Qualitative research	Interviews, Focus Group Discussion, Policy Document Analysis, Systems Modeling/Simulation, Future Scenario Planning, Surveys, Workshops and Public Participation, Network Analysis, Delphi Method, and Environmental Impact Analysis	Environmental science, climate change, and urban policy and planning systems with a sustainability perspective
2	Role design considerations of conversational agents to facilitate discussion and systems thinking [15]	Ha Nguyen (2023)	USA	Experiment	Pre-test and Post-test of systems thinking, Chat Log Data, Coding Scheme, and Post-Test Questionnaire	The concept of marine ecosystems, particularly in relation to biodiversity and management of marine protected areas (MPAs).
3	Food policies for Aboriginal and Torres Strait Islander health (FoodPATH): A systems thinking approach [16]	Jennifer Browne, Troy Walker (Yorta Yorta), Karen Hill (Torres Strait Islander), Fiona Mitchell (Mununjali), Holly Beswick, Stephanie Thow (Pennemuker, Ngˉ ati Porou), Joleen Ryan (Gunditjmara), Simone Sherriff (Wotjobaluk), Amy Rossignoli, Abe Ropitini (Ngati Kahungunu, Ngati Maniapoto), Michael Johnstone, Yin Paradies (Wakaya), Kathryn Backholer,	Australia	System Dynamics (SD)	Organizational consent form, Group Model Building (GMB) Workshop, Questionnaire and voting, Recording and documentation, Data analysis using Microsoft Excel, and Feedback and validation of findings with participants.	Food systems, public health and socio-cultural impacts on food choices in Aboriginal communities in Australia

No	Article Title	Author	Author Country	Research Methods	Analysis Materials	Science Study
		Steven Allender, Andrew D. Brown (2024)				
4	Enhancing systems thinking in corporate sustainability through a transdisciplinary research process [17]	Hanna Ahlstrom, Amanda Williams, Sigurd Sagen Vildåsen (2020)	Norway and Switzerland	Case study	Questionnaire or survey	Ecosystem, social-ecological systems (SES)
5	Contextualising urban sanitation solutions through complex systems thinking: A case study of the South African sanitation system [18]	Andrew Thatcher, Precious Biyela, Tracy-Lynn Field, Diane Hildebrandt, Michael Kidd, Sandrama Nadan, Leslie Petrik, Craig Sheridan, James Topkin (2024)	South Africa and USA	Case study	Questionnaire or survey	Sanitation system
6	Using systems thinking to understand how the South West - School Health Research Network can improve adolescent health and well-being: A qualitative process evaluation [19]	Emily Widnall, Patricia N. Albers, Lorna Hatch, Georgina Hopkins, Judi Kidger, Frank de Vocht, Eileen Kaner, Esther MF van Sluijs, Hannah Fairbrother, Russell Jagoa, Rona Campbell (2023)	UK	Qualitative research	Questionnaire or survey	School Health
7	Building a systems-thinking community workforce to scale action on determinants of health in New Zealand [20]	Anna Matheson, Nan Wehipeihana, Rebecca Graya, Mat Walton, Tali Uia, Kirstin Lindberg, Mathu Shanthakumar, Maite Irurzun Lopez, Johanna Reidya, Riz Firestone, Lis Ellison-Loschmann (2024)	New Zealand	Qualitative Comparative Analysis (QCA)	Questionnaire or survey	Determinants of health

No	Article Title	Author	Author Country	Research Methods	Analysis Materials	Science Study
8	A stakeholder-centred narrative exploration on carbon capture, utilisation and storage: A systems thinking and participatory approach [21]	Jazmín Mota-Nieto & Paola Massyel García-Meneses (2024)	United Kingdom & Mexico	Qualitative research	In-depth Interviews, Focus Group Discussions – FGDs, Questionnaire, and Document Analysis	Carbon capture, utilization and storage (CCUS)
9	Closing the loop: Enabling circular biodegradable bioplastic packaging flow through a systems-thinking framework [22]	Sarah Kakadellis, Zaneta Muranko, Zoe M. Harris, Marco Aurisicchio (2024)	United Kingdom	Comparative Case Study Design	Observations, interviews, and document analysis	Bioeconomy, biodegradable bioplastics (BBPs)

Steps for Training Systems Thinking in Science Education

The Table 3 offers a comprehensive overview of various articles that explore the application of systems thinking in research. It specifically focuses on how systems thinking is trained and applied in different contexts. Each article showcases unique methodologies for promoting systems thinking, including conceptual modeling, scenario simulations, stakeholder engagement, and system mapping. These approaches are designed to tackle complex issues across a range of disciplines, such as urban policy, health systems, and sustainability. By examining these training strategies, we can better understand how systems thinking is implemented and its potential to enhance problem-solving across diverse fields.

Table 3. Systems Thinking Training Approach in Research

No.	Article Title	How to train system thinking
1	Policy design by "imaginary future generations" with systems thinking : a practice by Kyoto city towards decarbonization in 2050	1. Holistic Approach: Analyzing decarbonization policies by looking at the relationships and interactions between social, economic and environmental elements. This allows for a broader understanding of the impacts of policies across sectors. 2. Future Projection: Using "imaginary future generations" to consider the long-term impacts of policies, ensuring that current decisions support future sustainability. 3. Simulation and System Modeling: Using dynamic models or simulations to illustrate how decarbonization policies will interact with socio-ecological systems over the long term. 4. Stakeholder Participation: Involving multiple stakeholders in the planning process to gain multiple perspectives, enrich the system analysis and identify more comprehensive solutions.
2	Role design considerations of conversational agents to facilitate	1. Creating a Concept Map: Concept maps help students understand how different elements in a system interact with each other. This is an effective way to train students to think holistically about cause-and-effect relationships in an ecosystem.

No.	Article Title	How to train system thinking
	discussion and systems thinking	2. Interaction with Conversational Agents (CAs): During learning activities, students interact with conversational agents (CAs) designed to facilitate their systems thinking through discussion prompts and questions that encourage systemic analysis. 3. Group Discussion and Collaboration: This discussion emphasizes the dynamic interactions between components in an ecosystem and facilitates their understanding of how changes in one element can affect the entire system. 4. Using System Based Prompts: The system-based prompts used by conversational agents help students see the relationships between elements in an ecosystem. With the help of a conversational agent, students are invited to see changes in one component and predict how it will impact other components. 5. Application to Field Data: This data analysis process allows students to integrate the information they obtain from different elements of an ecosystem (e.g., water quality, fish populations) and apply systems thinking to understand their impact on biodiversity as a whole. 6. Evaluating Change in Systems Thinking: Students are asked to explain cause-and-effect relationships and identify mechanisms present in the ecosystems they study, which reflects their ability to think systemically.
3	Food policies for Aboriginal and Torres Strait Islander health (FoodPATH): A systems thinking approach	1. System Mapping: Participants are trained to view the system as a whole, identify relationships between factors, and understand how changes in one factor can affect other factors in the long term. 2. Stories of Change and Cause-Effect Connections: This process trains participants to think holistically, that is, by considering broader relationships and how changes in one element can affect the entire system. 3. Use of Causal Loop Diagrams: Workshop participants are trained to identify and describe these relationships in causal diagrams. 4. Action Priorities and System Impact: Participants work in small groups to prioritize policies and actions that can improve food systems. 5. Collaboration and Discussion in Groups: During the workshop, participants work in small groups to discuss their ideas and build consensus on the most important factors and the most effective actions. 6. System Map Creation and Revision: After each workshop, the system maps that have been created are reviewed and revised to ensure that all important factors and cause-effect relationships are well covered.
4	Enhancing systems thinking in corporate sustainability through a transdisciplinary research process	1. Understand the Relationships Between Variables: identify key variables and Analyze interdependencies, consider how one variable can influence others. 2. Model Feedback Loops: System thinking emphasizes the importance of feedback (both positive and negative) within a system. Through this analysis, you can identify whether there are cycles that reinforce or weaken relationships between the variables in the study. 3. Adopt a Holistic Approach to Data Collection: Instead of gathering data on just one variable (e.g., trust), aim to collect data on all the variables and how they interrelate. When gathering data, consider measuring multiple variables simultaneously. 4. Use a Dynamic Approach: Over time, the relationships between variables may evolve. For instance, reputation of Bukalapak may improve over time as the company introduces better policies, which can increase trust and purchase frequency. 5. Analyze Complex Causality: Rather than just examining direct relationships between one variable and intention to use, look for indirect or mediating relationships.

No.	Article Title	How to train system thinking
		6. Goal-Oriented Systems: In this case, the ultimate goal of the system is intention to use. Think of the system as a whole that is organized to achieve this goal. 7. Contextual Understanding: Each component in this system is influenced by a broader context, such as changes in e-commerce trends, technology, or even government regulations.
5	Contextualising urban sanitation solutions through complex systems thinking: A case study of the South African sanitation system	1. Identify the Key Variables and Relationships: Begin by identifying the main variables in the research: perceived usefulness, perceived ease of use, reputation, trust, purchase frequency, and intention to use. Understand that these variables are interconnected and influence each other in a feedback loop. 2. Map Out Feedback Loops: System thinking focuses on the idea that changes in one part of the system affect other parts. The loops both positive and negative are critical in understanding how the system evolves. 3. Consider Dynamic Relationships Over Time: System thinking emphasizes the importance of understanding how relationships between variables change over time. 4. Simulate Scenarios: Develop different scenarios to explore how certain changes in one variable (e.g., improving reputation or enhancing ease of use) can influence intention to use. This allows you to think through potential outcomes of various actions or interventions. 5. Understand the System's Goals: System thinking involves recognizing that all components of the system such as perceived usefulness, reputation, and purchase frequency work together to achieve this goal. 6. Identify Leverage Points: These are key variables or factors that, when adjusted, can have a large impact on the overall system. In this study, leverage points might include improving trust or enhancing the user experience (e.g., through better ease of use), which could have significant downstream effects on other variables like purchase frequency and intention to use. 7. Use System Tools to Formalize Thinking: Tools like Vensim, Stella, or Insight Maker can be used to formally model system dynamics. These tools allow you to create simulations of the system and experiment with different assumptions about how the variables interact over time. By running simulations, you can better understand the system's behavior and test potential interventions before implementing them in the real world. 8. Analyze Complex Causality: System thinking requires an understanding of not only direct cause-and-effect relationships but also indirect and mediated effects. 9. Look Beyond the Immediate Effects: System thinking involves considering not just the immediate effects of changes but also their long-term consequences. Focus on how short-term changes can lead to long-term impacts and plan interventions accordingly. 10. Use Multi-Disciplinary Approaches: System thinking encourages the integration of insights from various disciplines, such as psychology (for understanding user behavior), economics (for understanding market dynamics), and information technology (for understanding user interaction with the app). By combining these insights, you can gain a more comprehensive understanding of how the system functions as a whole.
6	Using systems thinking to understand how	1. Understand the Relationships Between Variables: he first step in system thinking is to understand how key variables like Perceived Usefulness (PU), Perceived Ease of Use (PEOU), Reputation, Trust,

No.	Article Title	How to train system thinking
	the South West - School Health Research Network can improve adolescent health and well-being: A qualitative process evaluation	Purchase Frequency (PF), and Intention to Use (IU) are interconnected. 2. Use Feedback Loops: System thinking involves understanding feedback loops, both positive feedback loops (which reinforce changes) and negative feedback loops (which balance the system). 3. Simulate Different Scenarios: System thinking teaches us to look at possible outcomes of changes in the system, especially related to how variables interact. You can simulate several scenarios to understand how changes in one variable affect the entire system. 4. Focus on Leverage Points: Leverage points are places within the system where small changes can have a large impact on the overall outcome. Identifying leverage points is a core principle of system thinking, as it helps you focus on the most influential factors to intervene and improve the system. 5. Analyze Complex Causality: In system thinking, it is essential to look at both direct and indirect causal relationships. This includes understanding how variables like Perceived Usefulness or Reputation influence Trust, which then affects Purchase Frequency and Intention to Use, both directly and indirectly. 6. Think in Terms of Long-Term and Dynamic Effects: System thinking emphasizes that relationships between variables are not static; they evolve over time. Therefore, it is important to consider long-term changes in the system, not just immediate results. 7. Use Tools and Software for System Simulation: To help you better understand and practice system thinking, you can use system simulation tools such as Vensim, Stella, or Insight Maker.
7	Building a systems-thinking community workforce to scale action on determinants of health in New Zealand	1. Identify the Relationships Between Variables: Try to see how each variable (perceived usefulness, perceived ease of use, reputation, trust, purchase frequency, and intention to use) interacts with each other. 2. Create a Causal Loop Diagram: visual tool in system thinking that helps to map out cause-and-effect relationships between elements in a system. By creating this diagram, you can clearly see how one variable influence another. 3. Analyze Feedback Loops: System thinking also involves analyzing feedback loops, which can be either positive feedback loops or negative feedback loops. 4. Adopt a Holistic Approach: System thinking involves a holistic approach, meaning you should consider the entire system and how each part functions within the larger context. 5. Simulate and Predict Impact of Changes: Try to create simulations about how changes in one variable might affect other variables in the system. 6. Evaluate and Test Assumptions: System thinking also involves questioning assumptions and exploring whether there are variables or relationships that may have been overlooked. 7. Iterate on the Model: System thinking is iterative, meaning the model you create may need to be adjusted and updated over time based on new data or insights. 8. Use Tools and Software: These tools help model relationships between variables and observe how the system behaves over time.
8	A stakeholder-centred narrative exploration on carbon capture, utilisation	1. Cognitive Mapping: This approach treats the topic as a network of interconnected elements, where changes in one element can affect others. This is a characteristic of system thinking, which views problems in relation to the entire system rather than isolated elements.

No.	Article Title	How to train system thinking
	and storage: A systems thinking and participatory approach	2. Discourse Construction and Narrative Development: The individual cognitive maps (created through cognitive mapping) were then translated into stories that represented individuals' views of the topic. This process generated several collective narratives developed through group discussions. 3. Hierarchical Clustering and Data Grouping: This shows how stakeholders from various backgrounds construct their maps and how the broader system can be analyzed using system thinking to identify relationships and patterns that unify complex elements. 4. Identifying High Centrality Variables: The study also highlights how cognitive data are analyzed by focusing on the centrality of various variables, which represent the most influential elements in the topic. Variables with high centrality were considered as key elements in shaping the overall system view. 5. Data Variance and Meme Creation: From the analyzed cognitive maps, memes were created to represent core ideas (such as changes in variable values or new concepts) emerging from the discussions. System thinking is reflected here by using memes to encapsulate major ideas that summarize broader views of the topic and to visualize ideas that unite various perspectives. 6. Participatory Collaboration in Data Analysis: The participatory process used in this study, where stakeholders actively contributed to co-creating narratives and mapping elements within the system, is a key aspect of system thinking. 7. Emphasis on the Coexistence of Perspectives and Narratives: The study emphasizes that while the narratives discovered may appear contradictory, they do not conflict but coexist within the larger system. This aligns with the principles of system thinking, recognizing the complexity of larger systems where multiple perspectives and objectives can coexist and influence one another.
9	Closing the loop: Enabling circular biodegradable bioplastic packaging flow through a systems-thinking framework	1. Identify the System Elements and their Relationships: The first step in applying system thinking is to map out all the elements within the system, as done in the study for biodegradable packaging behavior chains. 2. Acknowledge the Complexity and Non-linearity of Systems: Systems thinking requires acknowledging these complexities and moving away from linear, cause-and-effect thinking. 3. Focus on Feedback Loops and Delays: In systems thinking, understanding feedback loops (both reinforcing and balancing) is essential. 4. Consider Contextual and Temporal Dynamics: Systems thinking emphasizes the importance of context and time. 5. Develop Interventions Based on System Insights: Using insights from network analysis and behavioral data, system thinking helps you identify leverage points key areas in the system where small changes can produce large impacts. 6. Foster Mental Models and Deep Understanding: In training for system thinking, it’s crucial to develop mental models that allow you to visualize and predict system behavior. Use tools like causal loop diagrams or network analysis to help identify and visualize the relationships between system components. 7. Emphasize Holistic and Iterative Problem Solving: Systems thinking encourages an iterative approach to problem-solving, where interventions are tested, results are observed, and systems are adjusted accordingly.

Based on the approaches outlined in the Table 3, here is a proposed step-by-step process for training systems thinking in science education (particularly in the context of natural sciences and environmental education):

Steps for Training Systems Thinking in Science Education:

1. Introduce the Holistic Approach:

Begin by introducing students to the concept of systems thinking, emphasizing the importance of viewing scientific phenomena as interconnected systems rather than isolated parts. Teach students to recognize how biological, physical, and environmental factors influence one another in natural systems, such as ecosystems or climate systems.

2. Use Concept Mapping:

Encourage students to create concept maps to visualize relationships between different components within a system. This can help them understand the cause-and-effect relationships that exist in scientific systems, such as the relationship between energy flow in an ecosystem or the carbon cycle.

3. Scenario-Based Simulations and Modeling:

Engage students in scenario-based exercises where they can model real-world systems using simulations. For example, simulate ecological systems, population dynamics, or climate change to help students visualize the long-term impacts of changes within these systems. Utilize system modeling software or digital tools for hands-on learning.

4. Foster Group Discussions and Collaborative Problem-Solving:

Organize group discussions and collaborative activities where students can work together to analyze a scientific issue from multiple perspectives. This will help them practice identifying different system components, understand the interactions between them, and collaborate to find solutions. For example, students could work together on understanding how pollution impacts an ecosystem.

5. Use Causal Loop Diagrams:

Introduce students to causal loop diagrams to help them visualize and analyze feedback loops within scientific systems. Encourage them to create these diagrams for systems they study, such as water cycles, food chains, or climate models, highlighting the cause-and-effect relationships.

6. Apply Systems Thinking to Real-World Data:

Provide students with real-world data, such as water quality measurements, biodiversity indexes, or climate data, and ask them to apply systems thinking to understand the relationships between different data points. Encourage students to analyze how changes in one variable may affect other parts of the system.

7. Encourage Future Projection and Long-Term Thinking:

Teach students to consider the long-term consequences of scientific decisions by using future projection methods. For instance, have them simulate the impact of deforestation, resource depletion, or environmental policies over extended periods to understand the potential long-term effects on ecosystems and societies.

8. Continuous Evaluation and Reflection:

Throughout the learning process, regularly evaluate students' understanding of systems thinking through quizzes, discussions, and project presentations. Encourage students to reflect on how their understanding of systems thinking has evolved and how it can be applied to solving real-world problems.

By following these steps, educators can effectively train students to think systematically and apply systems thinking to solve complex problems in natural science and environmental education.

Framework for Systems Thinking in Science Education

These frameworks provide structured approaches to analyzing complex systems, identifying key variables, understanding feedback loops, and simulating the long-term impacts of different interventions. The following table (Table 4) summarizes several frameworks of systems thinking applied in various research contexts, showcasing the tools and methodologies used to understand dynamic relationships within systems and to address real-world challenges.

Table 4. Framework for applying systems thinking in science education

No.	Article Title	Framework of system thinking
1	Policy design by "imaginary future generations" with systems thinking: a practice by Kyoto city towards decarbonization in 2050	1. Causal Loop Diagrams (CLDs): CLDs are used to graphically depict the behavior of a system by connecting relevant parameters through cause-and-effect relationships. 2. Integration of Future Generations Perspectives: Future generations' perspectives are incorporated into the system design to ensure that policies not only address current issues but also support future sustainability. 3. System Component Analysis: This framework helps identify key components in the system (such as CO_2 emissions, city infrastructure, energy use) and how their relationships contribute to the goal of a decarbonized society. 4. Iterative Implementation: CLDs are updated iteratively based on participant discussions over multiple workshop sessions, allowing for deeper exploration of potential policies and their impacts on the system.
2	Role design considerations of conversational agents to facilitate discussion and systems thinking	1. Components: Components refer to the elements or parts of a system that need to be understood in the context of systems thinking. 2. Mechanisms: Mechanisms refer to the interactions or relationships that exist between components in a system. 3. Phenomena:

No.	Article Title	Framework of system thinking
		A phenomenon is an observed change or result of interactions between components and mechanisms.
3	Food policies for Aboriginal and Torres Strait Islander health (FoodPATH): A systems thinking approach	1. System Dynamics (SD): Focuses on cause-and-effect relationships and feedback loops between variables in a system. 2. Causal Loop Diagrams (CLDs): To describe the cause-and-effect relationships between the various factors that influence the system. 3. Group Model Building (GMB): A participatory approach in System Dynamics where community members are directly involved in creating system models to understand the problems they face. 4. STICKE (Systems Thinking in Community Knowledge Exchange): Software used to map complex systems and depict cause-and-effect relationships in the form of causal loop diagrams. 5. Principles of Systems Thinking: Holistic, Interdependence, Feedback: Identifying and understanding the feedback loops that exist within the system, and Time Dynamics:
4	Enhancing systems thinking in corporate sustainability through a transdisciplinary research process	1. Causal Loop Diagram (CLD): A tool often used in systems thinking to describe the cause-and-effect relationships between variables in a system. 2. System Dynamics (SD): A more complex framework used to model and simulate long-term system dynamics, taking into account time and variables that change over time. 3. Feedback Loop Model: A classic model in systems thinking that emphasizes two-way interaction between elements in a system. 4. Mental Models and System Archetypes: Refers to the views or perceptions that individuals have about how a system works. These are patterns that are often found in complex systems. 5. Leverage Points: A point in a system that, if given special attention or improvement, can produce a major change in overall system performance. 6. Vensim or Stella (Software Tools for System Dynamics): This tool enables the creation of stock and flow-based simulations, as well as feedback modeling that can help understand how changes in one variable affect other variables over time.
5	Contextualising urban sanitation solutions through complex systems thinking: A case study of the South African sanitation system	1. Mapping Key Variables: Identify the main variables such as Perceived Usefulness, Perceived Ease of Use, Reputation, Trust, Purchase Frequency, and Intention to Use. 2. Causal Loop Diagram: Illustrate how these variables interact through positive and negative feedback loops. 3. Scenario Testing: Simulate how changes in one variable (e.g., improving Trust or Reputation) affect the system over time. 4. Leverage Points: Identify critical leverage points where small changes can lead to large impacts (e.g., Trust and Reputation). 5. Pathways and Mediators: Understand the direct and indirect effects among variables, especially Trust and Reputation as mediators. 6. System Dynamics Modeling:

No.	Article Title	Framework of system thinking
		Use simulation tools to model and simulate the system’s behavior, focusing on feedback loops, time delays, and long-term effects.
6	Using systems thinking to understand how the South West - School Health Research Network can improve adolescent health and well-being: A qualitative process evaluation	1. Identify Key Variables: The first step in the framework is to identify the key variables in the study and understand how they relate to Intention to Use. 2. Causal Loop Diagram (CLD): A Causal Loop Diagram (CLD) is an essential tool in system thinking to visualize the interdependencies between variables and how they affect each other. 3. System Dynamics (SD): System dynamics allows for the modeling of how the system changes over time, considering delays and feedback loops. 4. Scenario Simulation: A key aspect of system thinking is simulating various scenarios to understand the impact of different interventions and how they might affect the overall system. 5. Leverage Points: In system thinking, leverage points are specific areas of the system where small changes can have a large impact on the overall system's performance. Identifying these leverage points is essential for effective interventions. 6. Multi-Variable Analysis: System thinking often involves understanding how multiple variables interact. 7. Dynamic Modeling and Simulation: To formalize the system thinking approach, tools like Vensim, Stella, or Insight Maker can be used to create system dynamics models. 8. Long-Term Impact and Delays: System thinking emphasizes understanding the long-term effects of changes and how delays in feedback loops influence outcomes.
7	Building a systems-thinking community workforce to scale action on determinants of health in New Zealand	1. Causal Loop Diagram (CLD): This framework is used to illustrate cause-and-effect relationships between different elements in a system. 2. System Dynamics (SD): The System Dynamics framework extends the Causal Loop Diagram into a more formal, mathematical model that can simulate the behavior of systems over time. 3. Soft Systems Methodology (SSM): SSM is a more qualitative approach within system thinking used to solve complex, ambiguous problems. 4. The Viable System Model (VSM): VSM is a model designed to understand how organizations or systems can survive in dynamic environments. 5. Dynamic Systems Thinking (DST): DST focuses on applying system thinking more broadly, developing an understanding of how elements in the system can change over time, including system dynamics such as changes in trust levels or app usage. 6. Critical Systems Thinking (CST): CST combines systems thinking with a critique of assumptions underlying problem-solving approaches.
8	A stakeholder-centred narrative exploration on carbon capture, utilisation and	1. Complex System: The topic is viewed as a complex system composed of various interconnected components that influence each other. These components include technical, economic, socio-political, and sustainability elements.

No.	Article Title	Framework of system thinking
	storage: A systems thinking and participatory approach	2. Interdependence: One of the core principles of systems thinking is the interdependence between system components. 3. Participatory Approach: Systems thinking in this study also involves a participatory approach, where various stakeholders are engaged in the cognitive mapping process to co-create a collective understanding of the topic. 4. Cognitive Mapping and Clustering: Cognitive mapping is used to visualize how stakeholders perceive the relationships between different components of the topic. 5. Dynamic Interconnections: In systems thinking, dynamic interconnections mean that systems are always evolving and changing over time. 6. Holistic Approach: The systems thinking framework emphasizes a holistic understanding of the system, meaning that the entire system and its interrelationships are considered, rather than analyzing isolated components.
9	Closing the loop: Enabling circular biodegradable bioplastic packaging flow through a systems-thinking framework	1. Causal Loop Diagram (CLD): Causal Loop Diagram (CLD) is used to map the cause-and-effect relationships between elements in a system. 2. Systems Dynamics (SD): Systems Dynamics involves modeling and analyzing complex systems through dynamic equations to predict how a system behaves over time. 3. Soft Systems Methodology (SSM): Soft Systems Methodology (SSM) is a qualitative approach used to deal with ambiguous or complex problems that involve multiple perspectives. 4. Viable System Model (VSM): Description: The Viable System Model (VSM) is an approach to analyzing organizations or systems that need to adapt and survive in a changing environment. 5. Network Thinking: Network Thinking focuses on relationships and interactions between elements within a system, where these elements are represented as nodes and their relationships as edges.

Based on the frameworks presented in the table 4, here is a proposed framework for applying systems thinking in science education:

Framework for Systems Thinking in Science Education

1. Causal Loop Diagrams (CLDs):
    a. Purpose: To help students visualize and understand the cause-and-effect relationships within natural systems. Students can create CLDs to map interactions between different variables in ecological, environmental, and biological systems (e.g., energy flow in ecosystems or climate change).
    b. Application: Use CLDs to explore how changes in one part of the system (such as pollution or deforestation) impact other elements of the ecosystem.
2. System Component Analysis:

a. Purpose: To identify the key components of a scientific system (e.g., components in a food chain, climate system, or ecosystem) and understand their roles.
b. Application: Students analyze scientific systems by breaking them into components (e.g., water cycle, carbon cycle) and studying the interrelationships between those components.

3. Future Generations Perspective:
   a. Purpose: To encourage students to consider the long-term implications of their actions on the environment and society.
   b. Application: Incorporate scenarios and simulations that help students predict how current scientific and environmental actions will affect future generations (e.g., climate change impact projections).
4. System Dynamics (SD):
   a. Purpose: To examine feedback loops, time delays, and cause-and-effect relationships within complex systems.
   b. Application: Teach students about system dynamics by exploring natural systems like ecosystems or human-environment interactions, focusing on feedback and system behavior over time.
5. Mechanisms and Phenomena:
   a. Purpose: To identify the mechanisms (interactions) that drive phenomena (observed results) in scientific systems.
   b. Application: Students identify mechanisms behind phenomena such as the greenhouse effect, water pollution, or population growth, and how those mechanisms influence broader environmental or ecological systems.
6. Group Model Building (GMB):
   a. Purpose: To use participatory approaches to involve students in creating models of complex systems, facilitating collaborative learning and system analysis.
   b. Application: Organize group workshops where students create systems models (e.g., ecosystem models or climate change models) to understand and discuss complex environmental issues.
7. STICKE (Systems Thinking in Community Knowledge Exchange):
   a. Purpose: To map complex systems and represent them graphically using software tools.
   b. Application: Introduce students to software tools (like STICKE) for modeling and analyzing systems, which can be used for visualizing environmental, ecological, or societal systems in a science classroom.
8. Principles of Systems Thinking:
   a. Holistic: Students learn to view systems in their entirety, understanding that all components are interconnected and interdependent.
   b. Interdependence: Emphasize how components of systems influence one another, such as the interdependence of species within an ecosystem.

c. Feedback Loops: Teach students to identify and understand feedback loops (positive and negative) within systems, using examples like predator-prey dynamics or climate regulation.
d. Time Dynamics: Incorporate the concept of time and delays in systems, such as the long-term impacts of human activities on ecosystems or the delay in feedback within the climate system.

This framework combines theoretical models with practical application strategies, providing students with tools to think critically about the interactions and feedback within natural and environmental systems. Through this approach, students develop a deeper understanding of the complex, interconnected nature of the world around them.

Application of Systems Thinking in Scientific Problem Solving

This study utilized a system thinking approach to effectively analyze and address problems within scientific contexts. Systems thinking is a methodological framework that prioritizes the understanding of interactions and relationships among various components of a larger system, rather than concentrating on individual elements in isolation. By employing this approach, the study facilitates the identification of underlying patterns and minimizes the risk of implementing only partial solutions or short-term fixes, which may overlook potential long-term impacts.

In this research, we employed systems thinking to explore the interconnections among various factors that affect performance outcomes. For example, when developing applications or managing employee performance, elements such as motivation, competency, and leadership style are intertwined, creating complex dynamics. By taking this approach, we could examine the existing issues more comprehensively, uncovering feedback loops between different system components, and ultimately devising more effective and sustainable solutions.

The research revealed that by employing a system thinking approach, what initially seemed like straightforward problems could be broken down into their intricate components. This deeper investigation enabled more precise decision-making and fostered adaptive solutions in response to changing circumstances. As Cabrera & Cabrera [1] eloquently articulated, "Systems thinking helps us see how things are connected and how they influence one another." This perspective provides profound insights into the behavior of systems over time, allowing us to understand the complex interrelationships that shape outcomes [23].

The systems thinking framework proved valuable in understanding the dynamic feedback mechanisms that drive change within organizations. For instance, employee motivation and competencies can influence their performance, which in turn affects leadership styles and organizational outcomes. This creates a feedback loop where changes in one area can have cascading effects throughout the entire system.

Recognizing these feedback loops allows for more targeted interventions and a deeper understanding of the factors that influence results.

Additionally, systems thinking promotes a collaborative and interdisciplinary approach to problem-solving. By involving stakeholders from various fields, it becomes clear that different perspectives are essential to address the complexity of the issues at hand. In this study, insights from management, technology, and psychology were integrated to develop a more comprehensive solution. As Buchanan [24] asserts, “The fundamental nature of systems thinking is to understand the interrelationships between parts of a system, not just the parts themselves”. This holistic perspective is crucial for tackling problems that span multiple domains, offering a more sustainable and effective resolution.

Conclusion

This study explores the integration of systems thinking (ST) into scientific problem-solving, using the Systematic Literature Network Analysis (SLNA) approach. By analyzing scientific articles on ST in science education from 2020 to 2024, the research reveals an increasing scholarly interest in ST, with significant growth in publications over this period. It emphasizes the importance of systems thinking in addressing complex global challenges, such as sustainability, climate change, and health systems. However, despite its growing recognition, challenges remain in effectively implementing ST in educational contexts. The study identifies the need for innovative instructional models that can enhance students' ability to apply systems thinking to real-world problems. It suggests that future research should focus on developing these models and addressing the existing gaps in methodology, thereby advancing systems thinking as a powerful tool for scientific inquiry and education.

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