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Study of the Specificities of Thinking in Chemistry Education within the Science Education Cluster

Nisyya Syarifatul Husna[1], Hernani[1], Ahmad Mudzakir[1*]

[1] Science Education Doctoral Study Program (FPMIPA), Universitas Pendidikan Infdinesia, Bandung, Indonesia.

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Corresponding Author:
Ahmad Mudzakir
mudzakir.kimia@upi.edu

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Abstract: The aim of this research is to explore the concept of systems thinking in relation to the specificities of systems thinking in science education by conducting a content analysis of studies published between 2010 and 2020. Most of the articles were published between 2017 and 2019. This study employs a descriptive content analysis method on 40 articles about systems thinking in science, utilizing a literature review of international articles. The instruments used include a content analysis format created by the researcher and two expert researchers. Doubtful data were discussed holistically in relation to the content analysis. The results of the research reveal the specificities of systems thinking within the science field. In the realm of chemistry, a systems-based approach through the integration of green chemistry and systemic synthesis questions has proven effective in enhancing systems thinking skills and awareness of sustainability. The application of molecular sustainability principles in chemistry education can lead students to complex thinking, with an understanding of chemistry linked to various systems such as social, economic, and environmental contexts, fostering a holistic understanding. Integrating systems thinking approaches in science education can enhance students' comprehension of the complexities of the real world and equip them with the necessary skills to address increasingly dynamic and interconnected global challenges. The practical implications of these findings highlight the importance of developing a systems-oriented curriculum to support more comprehensive and integrative learning.

Keywords: Chemistry Systems Thinking; Literature Review; Pedagogy; Systems Thinking; Science Education.

Introduction

A system is an entity that maintains its existence and function through the interaction of its parts, forming a complex and cohesive unity to achieve specific goals. Understanding systems encompasses various fields, from social and technological to natural domains, all interconnected through feedback and relationships among variables (Assaraf & Orion, 2005). Therefore, systems studies have become a significant focus across various disciplines (Kim & Senge, 1994; Mandinach, 1989).

Systems thinking involves a holistic perspective on a problem or situation. It considers how different elements interact within a system and how these interactions affect the overall behavior of the system (Arnold & Wade, 2015). By understanding patterns and dynamics within systems, individuals can be more effective in addressing complex global issues, such as climate change and environmental sustainability (Wiek et al., 2011). This enhanced understanding is crucial for tackling increasingly complex and global future challenges (Ho, 2019; Penner, 2000).

Science education plays a vital role in developing systems thinking skills. Through curricula focused on understanding complex systems, such as ecosystems and technological systems, students are encouraged to see cross-disciplinary relationships and integrate broad knowledge (Hung, 2008). This is essential for equipping students to confront the dynamic and complex real-world problems (Matlin et al., 2016).

This research is significant because it aims to explore systems thinking approaches in science education. By analyzing literature from 2010 to 2021, this study seeks to identify trends and specificities in developing systems thinking skills among students.

Furthermore, it emphasizes the importance of integrating systems thinking skills into learning, such as the need to design learning stages that allow students to connect content with various aspects like environmental, social, economic, and political dimensions. With this approach, students can better understand the relationships and impacts of a system in a broader context and how applying systems thinking skills can prepare future generations to tackle increasingly complex and interconnected global challenges.

Method

In this study, a descriptive content analysis method was used to determine the specificities of systems thinking in chemistry education within the science field, employing qualitative research. Data were categorized based on the scientific domains of chemistry, physics, biology, and general science.

Population and Sample

The sample for this research consists of international articles published between 2010 and 2020 related to systems thinking skills in science. The sample was selected based on the relevance of the material within the science discipline.

The keywords used in the search for research samples included "systems thinking" and "complex systems" in the context of science as a whole. In contrast, the field of physics primarily utilized the keyword "complex systems," with only a few articles using "systems thinking." Thus, the analysis regarding physics indicates that complex systems are closely associated with systems thinking.

Data Collection Tools

The literature review process involved several stages, including searching for articles based on overarching topics, grouping articles by scientific discipline, educational level, and year of research, followed by organizing the explanatory structure and comparing related data. The presentation of the research is based on both subjective and objective perspectives of the researchers (Borg and Gall, 1983). The research design is presented in the following diagram:

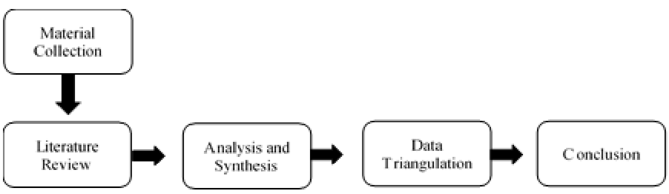

Figure 1. Qualitative Content Analysis Stage

The categories included in the reviewed articles and the choices to be provided have been presented according to the opinions of two experts in the field of content analysis. The arrangement has been made in accordance with expert opinions. Doubtful data were discussed holistically in relation to the content analysis.

Data Analysis

The literature review was sourced from reputable international articles, followed by the collection of data totaling 40 articles that met the criteria established for this research context. These articles were grouped based on their respective scientific fields and presented in graphical form. The data from the graphs were then analyzed descriptively in accordance with the research objectives and presented in tabular format. After all articles were analyzed, a synthesis process was conducted by comparing systems thinking in chemistry articles with those in physics, biology, and general science qualitatively. Data triangulation was performed by two expert researchers, leading to the conclusions.

Results and Discussion

Data Collection

In the literature search, the keywords "systems thinking" or "complex systems" were used for each scientific field. Figure 1 shows the distribution of the articles reviewed in the field of learning with systems thinking skills in science education according to their respective scientific domains.

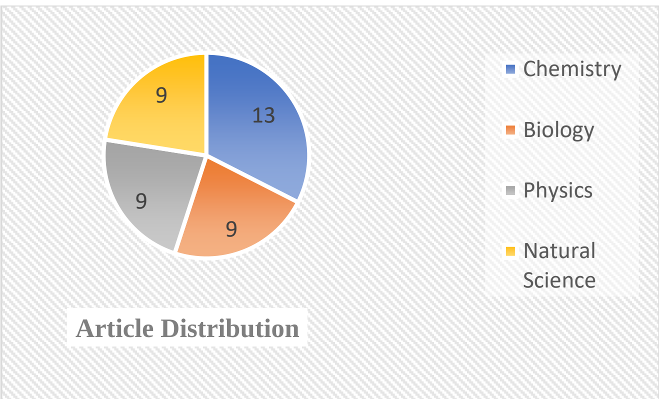

Figure 2. Distribution of articles in science clusters

Descriptive Analysis

All literature in Figure 1 is grouped based on their respective sciences into a table. Then it is analyzed descriptively, the analysis is carried out by reducing the content of the article briefly while maintaining its essence, several contents that contain the same meaning can be combined, following the content analysis is presented in Table 1,2,3 and 4.

Table 1. Analysis of Chemical Science Content

Articles	Analysis Results
(Hrin et al., 2016) (Connell et al., 2012)	A systems-based approach in education, whether through the use of systemic synthesis questions or teaching methods focused on understanding systems, is effective in developing systems thinking skills essential for addressing complexities in their respective fields.
(Aubrecht et al., 2019) (Anastas & Zimmerman, 2016)	The integration of green chemistry into the curriculum, as suggested by Aubrecht et al. (2019), along with the foundational understanding of molecular sustainability outlined by Anastas & Zimmerman (2016), collectively enhances students' skills in systems thinking, safety, and sustainability. This is crucial for building deep knowledge of how sustainable chemical practices can support environmental and social well-being in the future.
(Ho, 2019)	Four challenges can be transformed into opportunities for introducing concepts relevant to systems thinking, thereby enhancing students' conceptual understanding of chemistry. These include how chemistry is delivered to students, the emergence of underutilized chemistry concepts, ensemble thinking and ideals, and feedback loops.
(Mahaffy et al., 2019)	A molecular basis can guide students to think systemically. The concepts acquired are organized into a System-Oriented Concept Map Extension (SOCME) to illustrate how educators can help students move beyond reductionist thinking to see the interconnected concepts and topics within systems.
(Talanquer, 2019)	Systems thinking in the field of chemistry involves integrating mechanistic reasoning approaches, context-based focus, and sustainable action perspectives.
(Orgill et al., 2019)	The STH model incorporates "understanding the hidden dimensions of systems" as one of the high-level systems thinking skills. Since chemistry involves many parts and "hidden" processes, it is important to consider the best ways to help students access and contemplate these hidden dimensions when engaging in systems thinking.
(Fowler et al., 2019) (Hayes et al., 2020)	Students can analyze system components, relationships, and the properties of their technological designs, connecting scientific concepts with technological platforms and societal components, and discussing how these factors influence one another and the success of technology.
(York & Orgill, 2020)	Aligning systems thinking skills with five important characteristics in chemistry education includes: viewing the system as a whole, understanding the relationships among parts, identifying causal variables, observing behavior over time, and interacting with the environment.
(Busta & Russo, 2020)	The module outline (based on scientific methods) can enhance systems thinking skills.

Table 2. Analysis of Biological Scientific Content

Articles	Analysis Results
(Tripto et al., 2018)	The measurement instrument using concept maps is considered effective for assessing students' systems thinking abilities. Students are asked to identify at least 15 concepts, create logical sentences that connect two concepts with conjunctions in one sentence, and in the final stage, students construct a concept map that includes all concepts without considering hierarchy at the end of the session.
(Snapir et al., 2017)	Components Mechanisms Phenomena (CMP) are used for conceptual representation. Data analysis is based on the assumption that understanding systems requires perception of all system categories, including the structure within the system (its components), specific processes and interactions at both macro and micro levels (Mechanisms), and phenomena that present macro-scale processes and patterns within a system.
(Jacobson et al., 2017)	Four design guidelines for systems thinking include: starting with a complex problem/question, allowing students to visualize complex biological problems using system models, assisting students in reasoning step-by-step within and among levels of biological organization, and making students explicitly aware of the use of system characteristics in various contexts.
(Mor & Zion, 2021)	The System Thinking Learning Approach (STLA) has the potential to help teachers meet their challenges in facilitating students' understanding of the fundamental principles of homeostasis.
(Gilissen et al., 2020)	Design guidelines for introducing systems thinking involve familiarizing students with seven characteristics: boundaries, hierarchy, components, interactions, input-output, inputs, and dynamics.
(Tripto et al., 2018)	Three main characteristics of complex systems are: (a) hierarchy, (b) homeostasis, and (c) dynamism. Four distinctive learning patterns, each reflecting different forms of development

Articles	Analysis Results
	for systems thinking, are: "from structure to process levels," "from macro to micro levels," "from cellular to organismal levels," and "development in the complexity of homeostatic mechanisms."
(Tripto et al., 2016)	Reflective interviews as a knowledge integration activity were found to be an effective tool for assessing conceptual models of system complexity.
(Tripto et al., 2016)	Three systems theories used are: General Systems Theory (GST), Cybernetics, and Dynamical Systems Theory (DST).

Table 3. Analysis of Physics Scientific Content

Articles	Analysis Results
(Tejeda & Ferreira, 2014)	Systems thinking allows us to understand the various factors and the relationships between different factors in wind energy at a systemic level related to sustainability. Systems thinking enables us to gain a holistic understanding of the system and provides better insights into its behavior.
(Rakbamrung et al., 2015)	A systems thinking approach can be useful as a formative assessment for learning Newtonian concepts.
(Roychoudhury et al., 2017)	Students equate climate change with global warming. They also perceive the effects of climate change in simple, linear relationships.
(Holovatch et al., 2017)	This approach illustrates the complexities of physical systems that transcend traditional boundaries of physics, exploring interdisciplinary connections and applying complexity theory to understand broader phenomena in the real world.
(Breil, 2018)	A systems thinking approach aims to holistically understand why a ball falls, bounces, and stops, integrating physics concepts and system modeling within the context of science education.
(Gilbert et al., 2019)	The systems thinking module begins with terminology and conceptual models and progresses to quantitative modeling, emphasizing metacognition as a key aspect of developing systems thinking.
(Korbel et al., 2018)	Classifying complex systems based on their scaling exponents helps identify underlying scale patterns in these systems within new physics.
(Omotayo et al., 2020)	Sustainable overhead cost reduction in construction projects can be achieved through continuous improvement measures focused on waste reduction during the project execution phase, identifying key activities such as payments to suppliers and subcontractors, as well as purchase orders, as critical factors in this effort.
(Perc, 2018)	Stability of subsystem solutions in agent-based models explores the dynamics of complex systems within the context of applied physics and systems theory.

Table 4. Analysis of Science Content

Articles	Analysis Results
(Ben-Zvi-Assaraf & Orion, 2010)	Facilitating the construction of efficient and enduring students' systems thinking models, learning experiences should leverage metacognitive learning patterns, which play a crucial role in building systems.
(Keynan et al., 2014)	The use of repertory grids as a tool to assess the development of students' ecological systems thinking skills demonstrates an innovative approach to educational assessment aimed at enhancing understanding of ecological system complexities. There are three stages in developing the instrument: creating elements, identifying emerging constructs in a bipolar format, and providing ratings.
(Hmelo-Silver et al., 2017)	Examining the understanding of experts and novices regarding complex systems, by comparing their thoughts on concepts such as fish behavior, stone behavior, and respiration processes, highlights the differences in understanding across expertise levels and implications for science education.
(Lee et al., 2019)	Discussing the teaching of systems thinking in the context of the water cycle emphasizes approaches to enhance students' understanding of the complexities of interactions between various components in the water cycle through integrated teaching strategies and practical approaches.
(Billie & Dorit, 2017)	Developing a curriculum unit to enhance complex systems thinking through the use of system dynamics models and agent-based models in the context of population growth demonstrates an innovative educational approach that integrates two modeling methods to deepen students' understanding of system dynamics and complexities.

Articles	Analysis Results
(Engström et al., 2021)	Systems and systems thinking are not explicitly connected to social or environmental issues. Issues of control, explanation, and prediction of system behavior, or modeling processes are not addressed. This contrasts sharply with the Freiburg model of systems thinking, where interpretation, creation, and use of models are described as fundamental components.
(Raved & Yarden, 2014)	Concept maps are used to characterize the components of students' systems thinking and to examine potential changes in students' knowledge structures.
(Brandstädter et al., 2012)	Concept mapping (CM) is recommended as a suitable instrument for analyzing students' systems thinking, with computers positively influencing student performance in CM.
(Hmelo-Silver et al., 2007)	Revealing the differences in understanding between experts and novices regarding complex systems, through studies on their thoughts about concepts such as fish behavior, stone behavior, and respiration processes, highlights the challenges in science learning related to this complexity.

Data Triangulation

From the four tables analyzed, the author compared the uniqueness of systems thinking in the field of chemistry with other scientific disciplines. This resulted in identifying similarities and differences in the study of systems thinking in Chemistry, Biology, Physics, and General Science.

Uniqueness of Systems Thinking in Chemistry Education

Systems thinking is manifested in students' ability to understand the interactions and relationships among various chemical components, as well as their impacts on the environment and safety. Studies such as those by Hrin et al. (2016) and Aubrecht et al. (2019) emphasize the importance of systemic synthesis questions and the integration of green chemistry in the curriculum to build critical systems thinking skills. Students are taught to view chemistry not only as a standalone science but also as part of a larger system that encompasses environmental and social aspects. This enables them to apply sustainability principles in their daily chemical practices. In the field of chemistry, the use of molecular-based sustainability principles in chemistry education can lead students to think complexly, connecting chemical understanding with various systems such as social, economic, and environmental, thus forming a holistic understanding. Therefore, the uniqueness of the chemistry discipline does not only discuss the molecular level but also engineering molecules into something or engineering at the molecular (submicroscopic) level.

Uniqueness of Systems Thinking in Biology Education

Systems thinking includes understanding biological hierarchies, interactions among components, and the dynamics of complex systems such as ecosystems and homeostasis. Articles by Tripto et al. (2013) and Snapir et al. (2017) emphasize the use of tools like concept maps and the Components Mechanisms Phenomena (CMP) approach to help students understand and model biological systems. This research shows that systems thinking in biology involves the ability to analyze processes at various levels of organization, from cells to ecosystems, and to understand how interactions at the micro level can influence macro phenomena.

Uniqueness of Systems Thinking in Physics Education

In the field of physics, systems thinking allows students to understand the relationships between various physical components and concepts such as energy and motion within a broader context. Studies by Tejeda & Ferreira (2014) and Breil (2018) demonstrate that a systems thinking approach helps students see how physics concepts interact in complex and dynamic systems, such as wind energy or the motion of a ball. This aids students in developing a holistic understanding of physical phenomena that cannot be explained solely through linear or reductionist thinking.

Uniqueness of Systems Thinking in Science Education

In science education, systems thinking involves understanding the interactions between physical, chemical, and biological components in both natural and artificial environments. Articles by Hmelo-Silver et al. (2017) and Lee et al. (2019) demonstrate that systems thinking in science encompasses the ability to see how these components are interconnected and how changes in one component can affect the entire system. For example, in the context of the water cycle, students learn to understand how the interactions between the atmosphere, hydrosphere, and lithosphere influence weather and climate patterns.

The uniqueness of systems thinking instruments in the field of chemistry is represented by the System Oriented Concept Map Extension (SOCME), which presents various subsystems in science, technology, and molecular engineering. This illustrates how educators can help students move beyond reductionist thinking to see interconnected system concepts and topics. This uniqueness in the systems thinking concept map not only connects subsystems but also links materials that are often considered unrelated, creating a distinct feature of the chemistry discipline. Furthermore, these materials can be linked to the 17 Sustainable Development Goals (SDGs), particularly considering sustainability in economic, environmental, and social aspects. Other instruments for profiling systems thinking in scientific fields include concept maps, repertory grids, and dynamic thinking and cyclical thinking questionnaires.

In the field of science education, three components of the System Thinking Hierarchy (STH) are already in use, which are detailed into eight indicators. However, the highest stage, which is implementation, does not emerge due to the influence of the students' education level. Science articles at the elementary and junior high school levels find it challenging to reach the highest level in the STH indicators. In contrast, in the field of chemistry, this challenge arises because chemistry involves many components and "hidden" processes, making it crucial to consider the best ways to help students access and reflect on these hidden dimensions as they engage in systems thinking.

In developing systems thinking skills, five terms closely related to this study were identified: System Thinking, System Learning, Complex System, Biological Complexity, Chemical System Thinking, and Chemical Thinking. The term "Complex System" is most commonly found in articles from the physics discipline, although some chemistry and biology articles also use the same term in developing systems thinking skills. "Complex System," "Biological Complexity," and "Chemical Thinking" share a similar pattern in developing systems thinking skills based on content, while "System Thinking," "Chemical System Thinking," and "System Learning" are approached from a contextual perspective. The frequently used search terms in the chemistry field are "System Thinking," "Chemical Thinking," and the combination of both, "Chemical System Thinking." Systems thinking in the chemistry field always involves integrating context-based approaches and perspectives on sustainable action.

The author finds it quite challenging to identify common trends in promoting systems thinking in biology education. First, the available empirical studies are highly diverse in their research perspectives on developing systems thinking, utilizing three system theories: (1) General Systems Theory (GST), which focuses on the System Thinking Hierarchy (STH); (2) Cybernetics, which emphasizes system regulation through feedback; and (3) Dynamical Systems Theory (DST), which focuses on complex systems and nonlinear processes. Second, a closer analysis of the empirical studies shows that learning outcomes can sometimes be disappointing, while other studies present promising results regarding students' systems thinking abilities.

Conclusion

From 40 analyzed articles across various scientific fields, from elementary school to higher education, this article relates to pedagogical studies aimed at developing systems thinking. The approach to systems thinking in chemistry, biology, physics, and science education has its own uniqueness, reflecting the needs and challenges within each field. In chemistry, the focus is on sustainability through the integration of a systems-based curriculum. In biology, emphasis is placed on understanding the hierarchy and complex interactions within living systems. In physics, systems thinking helps students comprehend complex physical dynamics and the interactions between components. Meanwhile, in science education, systems thinking promotes understanding of how various natural and artificial components influence one another within a broader context. Despite differences in application and focus, a commonality among these approaches is the emphasis on holistic and integrative understanding, enabling students to tackle complex and interconnected challenges in the real world.

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Author Contributions
The contributions of the authors to this article are as follows: “Conceptualization: Hernani, Ahmad Mudzakir, and Nisyya Syarifatul Husna; methodology: Nisyya Syarifatul Husna and Hernani; validation: Hernani and Ahmad Mudzakir; formal analysis: Nisyya Syarifatul Husna; investigation: Nisyya Syarifatul Husna; resources: Nisyya Syarifatul Husna; data curation: Nisyya Syarifatul Husna; writing—original draft preparation: Nisyya Syarifatul Husna; writing—review and editing: Nisyya Syarifatul Husna; visualization: Nisyya Syarifatul Husna; supervision: Ahmad Mudzakir, Hernani; project administration: Ahmad Mudzakir.” All authors have read and agreed to the published version of the manuscript.

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The authors declare that there are no conflicts of interest. There are no personal or professional interests that could influence

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