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Research Article

Fen Eğitiminde Sistemsel Düşünme Üzerine Yapılan Çalışmaların Meta- Analizi

Meta-Analysis of Systems Thinking Studies in Science Education

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ÖZ

Bu çalışma, fen eğitiminde sistemsel düşünme yaklaşımını benimseyen çalışmaların meta-analizini içermektedir. Araştırmada; Web of Science, SCOPUS, ERIC ve Science Direct veri tabanlarında, "sistemsel düşünme" anahtar kelimesini içeren ve nicel veya karma araştırma yöntemlerinin kullanıldığı nihai olarak 12 makale analize alınmıştır. Araştırmanın güvenilirliğini artırmak amacıyla, çalışma sürecinde Bias Tool ve PRISMA-P protokollerinden yararlanılmıştır. Sistematik derleme sürecinde, PRISMA-P protokolü doğrultusunda makalelerin seçimi, dahil etme ve çıkarma kriterleri ayrıntılı olarak raporlanmıştır. Olası yanlılık risklerini değerlendirmek için Bias Tool, yayın yanlılığını tespit edebilmek amacıyla Funnel Plot görselleştirmesi ve Egger testi analizleri uygulanmıştır. Çalışma, sistemsel düşünmenin fen eğitimindeki akademik çıktılar üzerindeki etkisini öncelikli olarak incelemiş, bu yaklaşımın farklı alt disiplinlerdeki faydalarını ve çeşitli eğitim strateji ve yöntemlerinin etkinliğini değerlendirmiştir. Çalışmalardan elde edilen 26 değişken için etki büyüklükleri ve %95 güven aralıkları hesaplanarak bir orman grafiği ile görselleştirilmiştir. Çalışmalar arasındaki heterojenliği değerlendirmek amacıyla Cochran'ın Q testi ve I^2 istatistiği kullanılmış ve Q değeri ($Q = 1.784$, $p = 1.000$) ile I^2 değeri (%0) hesaplanmıştır. Genel etki büyüklüğü yaklaşık olarak ".47" olarak hesaplanmıştır. Bu sonuç fen eğitimi alanında sistemsel düşünme yaklaşımının orta düzeyde bir etkililiğe sahip olduğunu ve çeşitli alt disiplinlerde avantajlı bir şekilde kullanılabileceğini göstermiştir.

Anahtar Kelimeler:, Fen eğitimi, meta-analiz, sistemsel düşünme.

ABSTRACT

This study presents a meta-analysis of research adopting a systems thinking approach in science education. Academic articles were searched in Web of Science, SCOPUS, ERIC, and Science Direct based on predefined criteria. After removing duplicate studies and applying narrowing criteria, 12 articles were selected for analysis. To enhance study reliability, the Bias Tool and PRISMA-P protocols were used. Article selection and criteria were detailed per PRISMA-P, while the Bias Tool assessed bias risks. Funnel Plot visualization and Egger's test were applied to identify publication bias.. The study primarily examined the impact of systems thinking on science education outcomes and evaluated its benefits across sub-disciplines and instructional methods.. Furthermore, effect sizes and 95% confidence intervals for 26 variables obtained from the studies were calculated and visualized using a forest plot. To assess heterogeneity among the studies, Cochran's Q test and the I^2 statistic were employed, with a Q value (Q =

1.784, p = 1.000) and an I² value (0%) reported. The overall effect size was calculated to be approximately .47. These results indicate that the systems thinking approach in science education demonstrates a moderate level of effectiveness and can be advantageously applied across various sub-disciplines.

Keywords: Meta-analysis, science education, systems thinking.

INTRODUCTION

Science has historically been a pivotal force in human progress and the foundation of societal development and transformation. The advancement of societies largely depends on embracing and meticulously applying scientific principles. Analyzing the accomplishments of advanced societies reveals a strong correlation with their dedication to scientific principles. In today's world, broadening access to information underscores the need for accurate interpretation of this information. The ease of access complicates decision-making processes about its use, highlighting the necessity for effective information utilization and acquiring new information through diverse methods. This demands more intricate and nuanced analytical processes to reevaluate existing data (Bakioğlu & Göktaş, 2018).

One such approach that aligns with this necessity is systematic thinking. Systematic thinking is critical in understanding complex relationships and interdependencies within a system, enabling individuals to view problems and solutions holistically rather than in isolation. This approach fosters the ability to analyze connections between components, anticipate potential outcomes, and make informed decisions. As societies face increasingly multifaceted challenges, the capacity to think systematically becomes indispensable for addressing problems comprehensively and sustainably. By cultivating systematic thinking, individuals are better equipped to generate innovative solutions, adapt to dynamic environments, and contribute meaningfully to scientific and societal progress (Elmes et. al., 2018)

In recent years, numerous studies have highlighted the increasing importance of systems thinking across various disciplines, particularly in understanding and interpreting complex systems. This focus has become more pronounced in science education, with a growing body of research emphasizing integrating systems thinking into teaching and learning processes. Budak and Ceyhan (2024) conducted a systematic review to examine how systems thinking is positioned in empirical, peer-reviewed research articles and to identify trends within the literature. Their review analyzed open-access empirical studies indexed in the Web of Science database, covering publications up to the end of 2022.

The findings revealed a significant rise in systems thinking research in science education, particularly in the United States and Germany. Most studies targeted middle and high school students, with ecosystems being the most frequently addressed domain-specific topic. The review also identified common characteristics of systems thinking, such as complexity, relationships, components, interactions, interrelationships, and dynamics. However, Budak and Ceyhan (2024) noted uncertainty in the consistent use of the terms “characteristics,” “skills,” and “abilities” of systems thinking, as they were often used interchangeably in the literature.

This study underscores the need for further investigation and synthesis of the existing literature, including meta-analyses, to address these inconsistencies and provide a clearer framework for integrating systems thinking into science education. Such efforts could guide future research and practice, ensuring more effective teaching strategies and a deeper understanding of systems thinking among students.

Reviewing scientific literature often reveals multiple studies addressing the same research problem, which is crucial for corroborating a hypothesis and ensuring consistent results across different research efforts. The presence of numerous studies on the same issue is essential for generalization. However, divergent or contradictory findings can emerge within the same research context, a scenario prevalent in social and educational sciences. Elements such as the structure of the research, the traits of the sample, and the characteristics of observations or responses gathered during interviews can impact the results of a study. Furthermore, uncontrollable intermediate variables may also impact the results. This complexity necessitates a careful and comprehensive approach to understanding and interpreting scientific findings, ensuring academic rigor and accuracy in synthesizing research data (Bayraktar, 2020).

The proliferation of scientific research challenges the accessibility of comprehensive knowledge across disciplines. This reality prompts the exploration of methodologies for succinctly summarizing and scrutinizing existing literature. Meta-analysis is an effective statistical technique that amalgamates results from disparate studies to formulate more generalized and substantial conclusions. This method facilitates the discernment of overarching trends, reconciliation of conflicting findings, and a deeper grasp of specific subjects by quantitatively integrating research outcomes, thereby clarifying the issue at hand (Aksoy Kürü, 2021; Bangert-Drowns & Rudner, 1990; Field & Gillett, 2010).

Significant progress has been made in systems thinking, supported by extensive data from various studies. However, the field faces notable challenges. Discrepancies and conflicting results across studies hinder the ability to draw generalized conclusions about the effectiveness and impact of systems thinking in science education. Additionally, systems thinking is inherently suited to qualitative research due to its focus on part-whole relationships, holistic thinking, dynamic complexity, concept mapping, and open-ended inquiry (Ben-Zvi Assaraf et al., 2013; Brandstädter et al., 2012; Bowers et al., 2023; Ghalichi et al., 2021; Orgill et al., 2019; Pazicni & Flynn, 2019), there is a lack of comprehensive meta-analytical studies focusing on quantitative research in this domain. Without such analyses, the potential of systems thinking as a transformative approach in science education remains underexplored and fragmented.

This study seeks to address the identified gaps by conducting a meta-analysis of quantitative research on systems thinking in science education. It aims to integrate existing knowledge and provide a foundation for future research, offering actionable insights for educators and curriculum developers. By aggregating effect sizes and examining methodological variations, the study aims to:

- Evaluate the prevalence and quality of quantitative studies on systems thinking in science education.
- Analyze the methodologies and techniques employed in these studies.
- Assess the impact of systems thinking methodologies across various sub-disciplines of science education.
- Identify the most effective teaching strategies and techniques for promoting systems thinking.

This research adopts a rigorous methodology, incorporating predefined selection criteria and advanced tools, such as PRISMA-P and Bias Tool protocols, to ensure reliability and thoroughness. By focusing on quantitative research in a field traditionally dominated by qualitative studies, this study aims to bridge gaps in the literature and offer a unified understanding of the impact of systems thinking in science education.

CONCEPTUAL FRAMEWORK

2.1. Science Education and Systems Thinking

In science education, which thrives on continuous research and inquiry, it is vital to stay updated with technological and methodological advancements. This involves crafting lesson plans that engage students, developing projects, enhancing understanding of subjects, making abstract concepts tangible with various tools, and integrating educational content. Furthermore, including sub-disciplines such as chemistry, physics, and biology necessitates that science education programs provide a unified conceptual framework. This framework should enable students to form a comprehensive mental schema of the content (Elmas, Aslan, Pamuk, Pesman & Sözbilir, 2021; Mahaffy, Krief, Hopf & Mehta, 2018). Effective science education requires a deep understanding of the relationships between concepts individually and within a larger framework. It is essential to teach students the unique importance of each concept and its connection to the broader array of scientific knowledge. Systems thinking is gaining acknowledgment as an effective method in science education, providing a holistic viewpoint and a wider understanding. Various scholars have defined this concept diversely. Richmond (1994) characterizes it as the capability to infer system behaviors reliably. Ben-Zvi Assaraf and Orion (2005) describe it as a holistic framework in which interdependent components interact to achieve a purpose. Evagorou, Korfiatis, Nicolaou, and Constantinou (2009) regard systems thinking as a methodology that entails comprehending the dynamics and relationships among system components and examining how these interactions influence the system's collective behavior. Arnold and Wade (2015) describe it as analytical skills for identifying and understanding systems, forecasting their behavior, and effecting changes to achieve desired outcomes. Orgill, York, and MacKellar (2019) interpret systems thinking as a method for analyzing complex events and behaviors from an integrated perspective. This varied understanding underscores its utility in fostering an ability to consider overarching principles in analyzing and predicting interactions within complex systems (Jacobson & Wilensky, 2006). Furthermore, specific sub-parameters of systems thinking are detailed in Table 1.

From Richmond (1993) to the present, various researchers have identified different sub-parameters of systems thinking. These parameters have been developed, changed, or restructured according to the needs. To thoroughly grasp systems thinking, understanding the sub-parameters is essential. Based on the related literature, a table has been developed to determine the sub-parameters of systems thinking. Table 1 chronicles the evolution of systems thinking from historical to modern times, highlighting the fundamental criteria that underpin this analytical approach. Addressing the various dimensions of systems thinking provides a comprehensive summary of the literature in this field. It provides a deep understanding of systems thinking and its sub-parameters. It is posited that Table 1 amalgamates research in systems thinking, aiding researchers, educators, and related professionals in better comprehending its diverse facets and applications across various disciplines. Systems thinking may be characterized as the method of discerning how elements within complex systems interact and assessing the impact of these interactions on the overall functionality. This perspective equips individuals with the analytical and conceptual tools needed to decipher the interconnections among system parts and how these connections influence the collective behavior of the system. The sub-parameters of systems thinking include identifying system elements, understanding the relationships between these elements, monitoring the dynamics of the system over time, and evaluating how the system functions. These parameters develop an individual's ability to analyze complex problems holistically, forming an important basis for academic and practical applications.

2.2. Systems Thinking Teaching Approaches and Techniques

Systems thinking is a crucial skill in science education, aiming to teach students to comprehend the components of a system, the relationships among these components, and the system's overall functioning. Due to its emphasis on part-whole relationships, holistic thinking, dynamic complexity, concept mapping, and open-ended inquiry, systems thinking is inherently aligned with qualitative research methodologies (Ben-Zvi Assaraf et al., 2013; Brandstädter et al., 2012; Bowers et al., 2023; Ghalichi et al., 2021; Orgill et al., 2019; Pazicni & Flynn, 2019).

Table 1

Systems Thinking Sub-Parameters

Study	Thinking sub paramaters							
Richmond (1993, 1994, 1997)	Dynamic thinking	System-as-cause thinking	Forest thinking	Operational thinking	Closed-loop thinking	Quantitative thinking	Scientific thinking	Temporal thinking
Ossimitz (2000)	Thinking in models	Closed loop thinking	Dynamic thinking	Steering systems				
Sweeney & Sterman (2000)	Dynamic complexity	İdentifying and representing feedback processes	Recognizing stock and flow relationships	Understanding the impact of time delays	İdentifying nonlinear dynamics	İdentifying models and limitations of systems thinking		
Kali., Orion & Eylon (2003)	Thinking in models	Closed loop thinking	Dynamic thinking	Steering a system				
Evagorou et. Al. (2009)	Identification of the elements of a system	İdentification of the spatial boundaries of a system	İdentification of the temporal boundaries of a system	İdentification of several subsystems within a single system	İdentification of the influence of specific elements of the system on other elements, or the whole system	İdentification of the changes that need to take place in order to observe certai patterns	İdentification of feedback effects in a system	
Sommer & Luecken (2010)	System organization	System properties	Modelling	Dealing with system properties				
Ben-Zvi-Assaraf & Orion (2005, 2010)	Identifying the components and processes within a system	İdentifying relationships within the system	Organizing the system's components and processes within a framework of relationships	Generalization	İdentifying dynamic relationships within the system	Understanding the hidden dimensions of the system	Understanding the cyclic nature of systems	Temporal thinking: looking at the past and future
Rempfler & Uphues (2012)	System organization	System behavior	System-adequate intention to act	System-adequate action				
Arnold & Wade (2015, 2017)	Feedback loops	Stocks and flows	System structure	Time delays	Nonlinearity	Causal loop diagrams		
Mehren et al. (2017)	System structure	System emergence	System interaction	System dynamics	System prognosis	System regulation		
Pazicni & Flynn (2019)	Systems and system models	Scale, proportion, and quantity	Energy and matter	Stability and change				
Orgill et al. (2019)	The ability to identify the components of a system and processes within the system	The ability to identify relationships among the systems' components	The ability to identify dynamic relationships within the system	The ability to organize the systems' components and processes within a framework of relationships	The ability to understand the cyclic nature of systems	The ability to generalize	Understanding the hidden dimensions of the system	Thinking temporally: retrospection and prediction
Dugan et al. (2022)	Identification of components and connections	Stakeholder needs	Social and environmental context	Potential impacts over time				

Several key approaches are employed in teaching systems thinking in science education:

Concept Mapping: Concept mapping is an effective method for fostering systems thinking skills, as it allows students to visualize and understand the relationships within a system. Through concept maps, students can evaluate systems both at the component level and holistically (Ben-Zvi Assaraf et al., 2013).

Inquiry-Based Learning and Open-Ended Questions: Inquiry-based learning encourages students to generate their own questions and explore the functioning of systems. This approach supports the development of critical thinking and problem-solving skills as students investigate and draw conclusions about complex systems (Brandstädter et al., 2012).

Examining Dynamic Complexity: A central aspect of systems thinking involves understanding the dynamic nature of complex systems. By analyzing the relationships among variables within a system, students learn about feedback loops and processes of change over time (Ghalichi et al., 2021).

Holistic Approach and Part-Whole Relationships: Teaching systems thinking emphasizes analyzing individual components of a system while understanding how these components contribute to the system. This requires students to examine systems at both micro and macro levels, fostering a comprehensive perspective (Orgill et al., 2019).

These approaches provide a robust framework for teaching systems thinking in the context of science education. However, variations in the methods utilized and differences in their effectiveness have been observed in existing studies. Such discrepancies underscore the need for more comprehensive investigations into the teaching practices and trends associated with systems thinking. Research in this area holds significant potential to enable students to develop a critical understanding of complex systems and enhance their ability to engage with such systems within the scope of science education.

This study stands out by conducting a meta-analysis of quantitative research in a field traditionally dominated by qualitative studies. It adopts a rigorous methodology to ensure reliability and thoroughness, including predefined selection criteria and advanced tools such as PRISMA-P and Bias Tool protocols. Furthermore, the study examines the effects of systems thinking across various sub-disciplines of science education, comparing teaching strategies and their outcomes. By aggregating effect sizes and evaluating methodological variations, this research aims to bridge gaps in the literature, offering a unified understanding of the impact of systems thinking in science education. The findings are expected to provide actionable insights for educators and curriculum developers.

The research evaluates the prevalence and quality of quantitative studies on systems thinking in science education. Key objectives include:

- Assessing the extent and availability of quantitative research in this field.
- Analyzing the methodologies and techniques used in these studies.
- Understanding the impact of these studies on our knowledge of systems thinking.
- The specific research questions addressed are:

1. What methodological approaches and techniques are commonly used in studies on systems thinking?
2. What is the overall effect size of systems thinking methodologies in science education?
3. Which teaching strategies and techniques are most effective in systems thinking education?
4. In which sub-disciplines of science education is the systems thinking approach most impactful?

METHOD

This study analyzes the research conducted in the international arena on integrating and applying systems thinking methodologies within science courses in depth, using the meta-analysis method. Meta-analysis can be defined as an advanced statistical method that performs an extensive literature review and systematic synthesis of scientific research (Aksoy Kürü, 2021; Bakioğlu & Göktaş, 2018; Bayraktar, 2020 Karaca et al., 2024). This analytical approach combines the findings from different studies in a consistent and compatible manner, evaluates them under a common criterion, and calculates the effect sizes using statistical methods (Cohen & Manion, 2001). Meta-analysis, defined by Glass (1977), allows a more comprehensive evaluation of scientific evidence in a field by integrating homogeneous or heterogeneous research results. This method facilitates the development of an in-depth and detailed comprehension of a particular subject by enhancing the comparability of research outcomes.

3.1. Data Collection

This research meticulously investigates scholarly work in science education that focuses on the central concept of "systems thinking". The data from internationally recognized academic search engines such as ERIC, SCOPUS, Science Direct, and Web of Science were collected up to 01.11.2023. These databases were preferred because they host high-quality international studies in education. Analyzing these databases is crucial for an exhaustive evaluation of global studies regarding the application of systems thinking in science education. During the review process, 171,881 studies were identified, of which only research articles were evaluated, excluding book chapters, conference proceedings, and review studies. As a result of this selection, the number of research articles included in the analysis was determined as 26,153. The total number of studies, including science and its sub-disciplines, was 429, and the number of studies using quantitative or mixed methods was 31. Articles that appeared across multiple search engines were omitted, resulting in the selection of 12 articles for this study. Special care was taken to confirm that the language of the studies was English. Table 2 presents detailed information on the number of studies obtained from different databases.

Table 2

Studies in Academic Search Engines

Academic Search Engine	Key Word	Total	Research Article	Science Education / Sub-disciplines	Quantitative / Mixed Study
Web Of Science	Systems thinking	149.651	12.572	86	13
ERIC	Systems thinking	1.028	759	126	10
Science Direct	Systems thinking	11.021	6.877	144	5
Scopus	Systems thinking	10.181	5.945	73	3

The distribution according to search engines is as follows: 149,651 studies were examined from Web of Science, 12,572 of them were evaluated as research articles, 86 of them included science and sub-disciplines, and 13 of them used quantitative or mixed methods. From ERIC, 1,028 studies were analyzed: 759 were research articles, 126 included science and sub-disciplines, and 10 used quantitative or mixed methods. From Science Direct, 11,021 studies were examined, 6,877 of which were research articles, 144 were science and subdisciplines, and 5 included quantitative or mixed methods. Finally, 10,181 studies were examined from Scopus, 5,945 research articles, 73 were in science and subdisciplines, and 3 used quantitative or mixed methods.

In selecting articles, using the word 'systems thinking' in the title, subject, or content that evokes systems thinking was not considered; only the use of 'systems thinking' as a keyword was taken as a criterion. Preferably, the sample consisted of studies involving students, pre-service teachers, or teachers in schools and comparable settings, with particular attention to ensuring that statistical details like counts, means, and standard deviations for experimental and control groups were clear and comprehensible. Studies using ANOVA analyses were not included, and those employing consistent methodologies were preferred to calculate the effect size more accurately.

Narrowing criteria were applied to the extensive collection of studies to align with the research objectives.

- The research was obtained from international indexes such as Science Direct, Scopus, ERIC, and Web of Science.
- The studies should include the keyword "systems thinking",
- The studies must be research articles,
- The studies should involve the discipline of science or sub-disciplines such as chemistry, physics, biology, earth science, environmental science,
- The studies clearly and explicitly use quantitative or mixed methods and use data collection tools appropriate to these methods,
- For calculating the effect size of the studies, it is crucial to specify the sample size, standard deviation, and mean values.

As a result of these narrowing criteria, a total of 12 studies on systems thinking in science education were selected.

3.2. Data Coding

In this study, a coding method designed explicitly for meta-analysis was developed. This method was used to compile the basic information of all the analyzed studies systematically. The coding scheme was structured into two primary sections. The first section encompasses each study's fundamental features and descriptive attributes, systematically organizing this information for coding. The second section contains the critical statistical data that form the basis of meta-analysis. This section carefully recorded important statistical parameters such as the sample sizes of each study, means of control and experimental groups, and standard deviations. Microsoft Excel software was utilized to facilitate data entry and processing in implementing this coding process. Excel is a tool that facilitates orderly data sorting, effective performance of analytical procedures, and visual presentation of results. Thus, the study's data management process became more efficient and less prone to errors. This enhanced coding approach boosts the integrity and reliability of the meta-analysis process and is crucial in addressing the challenges associated with synthesizing the results from diverse studies. The bifurcated structure of the coding scheme facilitates a thorough evaluation of the quantitative elements of the studies, thereby enabling a more detailed and inclusive meta-analytic review.

3.3. Data Analysis

In this study, a meta-analysis evaluation was conducted on 12 independent studies focusing on systems thinking. The data were analyzed using Microsoft Excel for data organization and preprocessing, while the Comprehensive Meta-Analysis (CMA) software was utilized for statistical analyses. The analysis procedures were systematically carried out in accordance with established meta-analytic methodologies, ensuring rigor and reliability in the findings. The procedures performed are given below, item by item, in order.

• Initially, a descriptive analysis of the studies was carried out based on the research questions. This analysis included examining variables such as the methodologies employed in the studies, the years they were conducted, and the sub-disciplines within science education. A table outlining the methods and techniques used in the studies was compiled and subsequently converted into a graph to enhance visual representation. Figure 2 was prepared by marking the intersection points of the methods and techniques used in each study, arranged by the year each study was conducted.

• The number of experimental groups, number of control groups, experimental group averages, control group averages, and standard deviations of each of the 12 meta-analysis studies were noted in the Excel table. From this process, 26 different variables were obtained from the 12 studies.

• The Cohen's d effect sizes of each study were computed using the formulas Cohen's d = (M2 - M1) ⁄ SDpooled and SDpooled = $\sqrt{((SD1^2 + SD2^2)/2)}$.

• The 95% confidence intervals of each study were computed using the formula $\mu 1 - \mu 2 = (M1 - M2) \pm ts\ (M1 - M2)$.

• These computations were depicted in Figure 3 in the form of a forest plot. This graphical representation enables the simultaneous evaluation of effect sizes and confidence intervals across studies, providing a swift assessment of the magnitude and reliability of these effects.

•A heterogeneity test was conducted on the 12 studies using Cochran's Q and I^2 statistics. The test yielded a Q value of 1.784 ($p = 1.000$) and an I^2 value of 0%, confirming the absence of substantial heterogeneity among the studies.

•Given the low heterogeneity observed among the studies, a fixed-effects model was applied in the meta-analysis. The statistical analyses were conducted using Comprehensive Meta-Analysis (CMA) software, ensuring methodological rigor and precision in estimating the overall effect size.

• The fixed effects model assumes that all the studies examined have a common effect size and accepts that the differences in effect sizes between the studies are only random.

• Within the scope of the fixed effects model, the weighting factor was calculated using the formula w=1/ (standard error) ², based on the average standard errors of the experimental (N1) and control (N2) groups, using the Excel application (Bayraktar, 2020).

• The weighting factor was multiplied by Cohen's d values, and the weighted effect sizes were obtained.

• The total of these weighted effects was divided by the total of the weighting factors, resulting in the calculation of the overall effect size as 0.46886119.

• This value signifies the average effect size of all the studies included in the analysis, as determined by the fixed effect model.

• The sum of all weighting factors was calculated, and the standard deviation of the average effect size was determined by taking the square root of the inverse. The value of .28551349 was obtained by using the formula 'SEM = 1/(∑w) ½' in the Excel program.

• Then, the obtained standard deviation value was multiplied by 1.96, resulting in the calculation of the general confidence interval (95%) with a lower limit of -.09074525 and an upper limit of 1.028467629.

• The interpretation of effect sizes was based on the classifications proposed by Thalheimer and Cook (2002) and Cohen (1988).

After completing the statistical analyses, the following parameters were computed for the 26 identified variables: the counts of experimental and control groups, the means and standard deviations for both groups, Cohen's d values, confidence intervals, weighting factors, and weighted effect sizes.

3.4. Validity and Reliability

To eliminate situations that threaten the validity of meta-analysis, Cooper (1998) made the following suggestions.

• Researchers conducting the meta-analysis should consider conceptual or methodological criteria, not the studies' findings, when deciding which studies to include or exclude.
• The weighting scales and their rationale for assigning different weights to the studies included in the meta-analysis should be elucidated.
• Various methods should be employed to access missing data.
• While categorizing research methodologies, it is advisable to encompass a broad spectrum of study design features. Researchers should comprehensively understand the distinct characteristics associated with each study design and meticulously describe and elucidate the effects of these characteristics on the analysis results. It is imperative to conduct precise training and evaluation processes to mitigate the risk of acquiring data with low information reliability.

• Envisioning the involvement of multiple individuals in data coding processes and ensuring a high level of harmonization among them is essential to maintain coding integrity. Meticulous calculation and inter-coder agreement reporting are critical in improving research quality.

Cooper and Hedges (1994) made the following suggestions to ensure reliability in meta-analysis.

• The reliability of the research requires that the coding done by more than one person be in harmony.
• The coding consistency is tested by a pilot coding process, with more than one coder working on the same dataset.
• During pilot coding, coders independently code randomly selected pieces of data.
• Coders compare their coding and evaluate whether they are compatible or not.
• In case of disagreement, discussions are held between the coders to reach a common decision.
• If necessary, pilot coding can be repeated more than once.

The study selection process was conducted in three phases: initial screening, full-text review, and inclusion in the meta-analysis. In the initial screening, titles and abstracts were reviewed by two independent reviewers, and any disagreements were resolved through discussion. The full-text review thoroughly assessed studies for relevance to the research questions, with inclusion and exclusion decisions documented. In the final phase, studies that met the criteria were evaluated for quality and included in the meta-analysis for data integration and analysis.

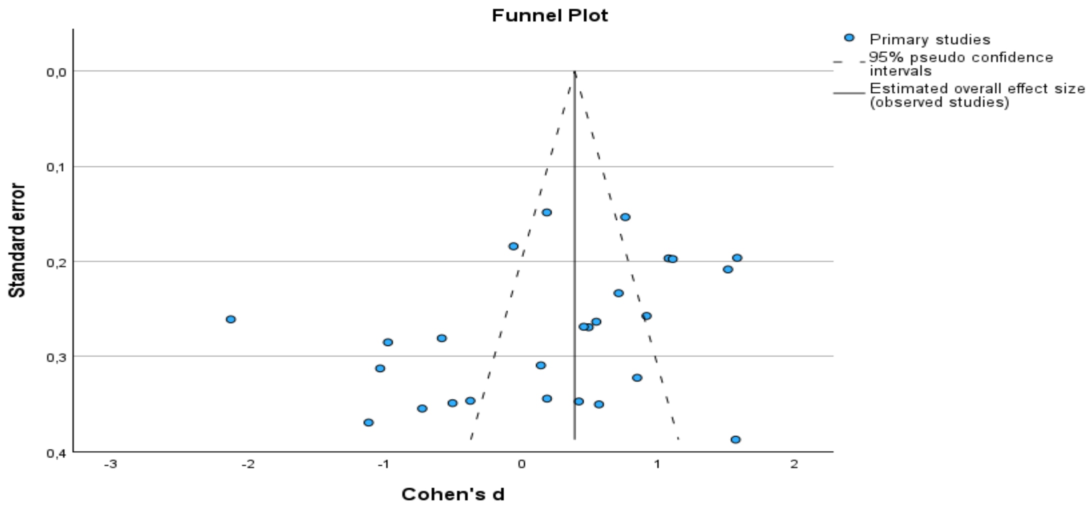
In addition to the above process, the PRISMA-P and Bias Tool Protocol were used during the meta-analysis. PRISMA-P is a set of guidelines that specify protocol reporting requirements for systematic reviews and meta-analyses. In essence, this process serves as a critical tool to ensure that systematic reviews and meta-analyses are meticulously planned, transparent, reproducible, and conducted in adherence to recognized reporting standards (Hür, 2020; Shamseer, Moher, Clarke, Ghersi, Liberati, Petticrew, Shekelle & Stewart, 2015). The PRISMA-P protocol was accessed from its official website, 'http://prisma-statement.org/Extensions/Protocols', and the PRISMA-P checklist, consisting of 17 questions, was completed sincerely. The checklist is provided in detail in Appendix 1.

The bias protocol is a tool to evaluate the risk of bias in studies incorporated into systematic reviews. Bias encompasses any factor that could influence the study's outcomes and potentially compromise its reliability and validity (Hooijmans, Rovers, De Vries, Leenaars, Ritskes-Hoitinga, & Langendam, 2011). Thus, the Bias Tool Protocol was accessed from its official website at 'https://www.riskofbias.info/'. All questions in the Cochrane risk of bias tool (RoB 2) completion template for randomized trials were conscientiously answered. The RobVis tool (McGuinness & Higgins, 2021) was used for data visualization. Robvis is a visualization tool that facilitates the production of high-quality figures summarizing the risk of bias assessments undertaken as part of a systematic review or research synthesis project. Detailed information is given in Appendix 2. Two independent researchers compared the responses to the protocols, and the results and checklists were completed.

Following the completion of the PRISMA-P and Bias Tool protocols, publication bias was further assessed using both Funnel Plot visualization and Egger's regression test. The Funnel Plot allows for a visual inspection of potential publication bias by plotting the effect sizes of included studies against their standard errors. Additionally, the Egger's test provides a quantitative evaluation of the symmetry of the funnel plot, thereby offering further insight into the presence or absence of publication bias within the meta-analysis. The results of the Funnel Plot are presented in Figure 1. These procedures contribute to the methodological rigor of the present study by ensuring that both the internal and external validity of the findings have been critically evaluated.

Figure 1

Funnel Plot



A funnel plot was constructed to assess the presence of publication bias among the included primary studies. The plot demonstrated a generally symmetrical distribution of studies around the estimated overall effect size, as indicated by the vertical line. However, a slight asymmetry was observed, particularly in the lower left region of the plot, where fewer studies with negative effect sizes and larger standard errors appeared. This pattern may indicate the presence of publication bias, with smaller studies reporting negative or non-significant results potentially being underrepresented. Nevertheless, further statistical analyses (e.g., Egger's regression test, Trim and Fill) are recommended to confirm the presence of publication bias (Egger et al., 1997).
Egger's regression test was conducted to assess the presence of publication bias among the included studies. The intercept was not statistically significant (intercept = 0.07, p = .32), suggesting no evidence of significant publication bias in the meta-analysis (Egger et al., 1997).

The combination of visual (Funnel Plot) and statistical (Egger's regression) approaches provides a robust assessment of potential publication bias in meta-analytic studies. While the

Funnel Plot allows for an initial qualitative appraisal, the Egger test offers a more objective statistical evaluation. The results suggest that publication bias is unlikely to have affected the overall findings. Further analyses, such as the Trim and Fill method, were not performed as the primary analyses did not indicate substantial asymmetry.

3.5. Ethical Statement

All the rules specified in the "Directive on Scientific Research and Publication Ethics of Higher Education Institutions" have been complied with in the whole process from the planning of this article to its implementation, from data collection to data analysis. None of the actions specified under "Actions Contrary to Scientific Research and Publication Ethics", the second part of the directive, were carried out. During the writing process of this research, scientific, ethical, and citation rules were followed; No falsification was made of the collected data. As the current study is a meta-analysis, there is no ethics committee report available.

FINDINGS

The findings of this study are presented in alignment with the order of the research questions. Accordingly, the findings for the first research question, "What methodological approaches and techniques are utilized in studies on systems thinking?" are as follows:

The study revealed that the 12 studies analyzed employed experimental, quasi-experimental, and mixed methods. Experimental methods were the most frequently used, focusing on measuring the impact of systems thinking on academic achievement. Quasi-experimental methods were less common but often assessed the effects of systems thinking within disciplines such as environmental sciences. Combining quantitative and qualitative analyses, mixed methods provided comprehensive insights into systems thinking applications.

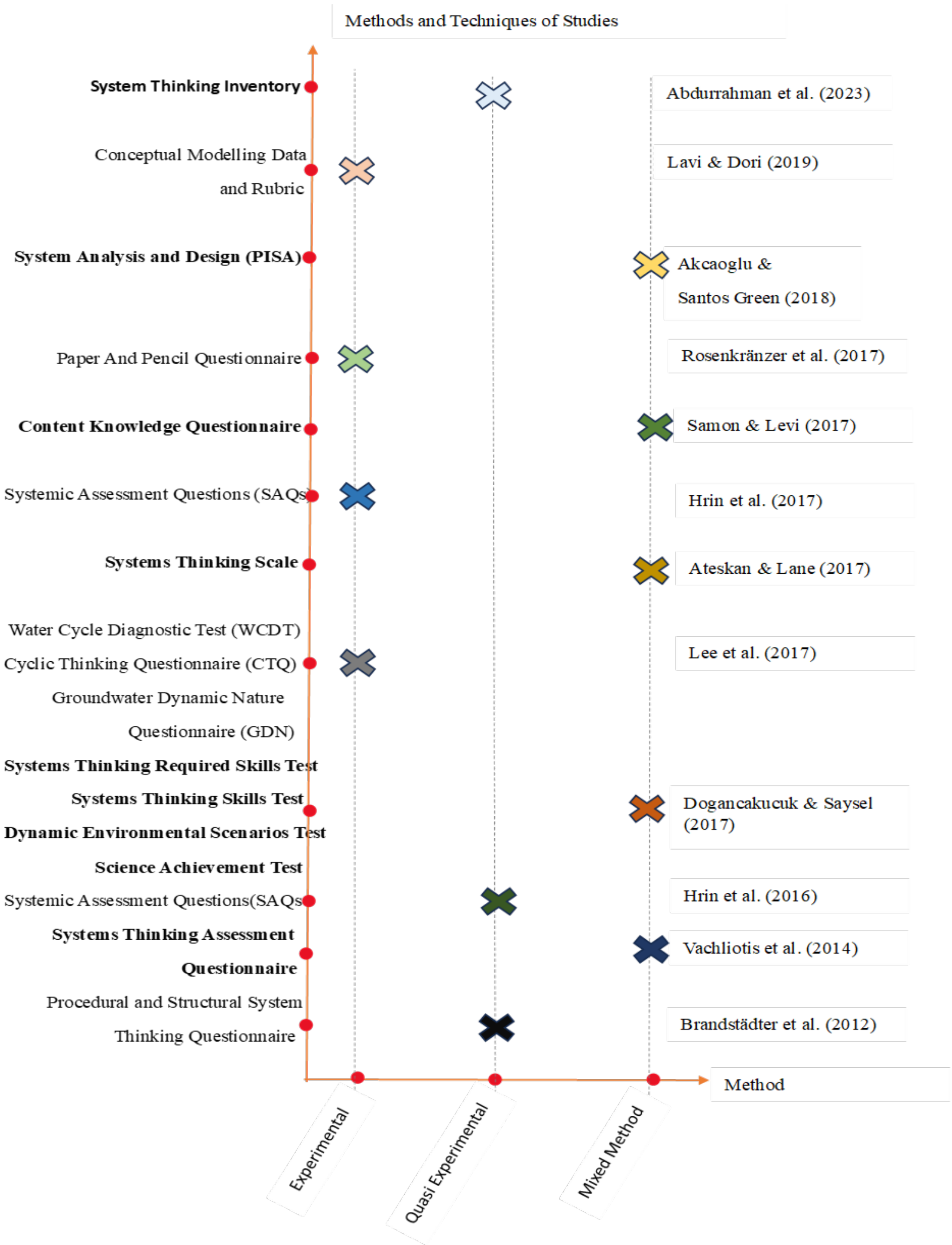
Techniques such as systemic synthesis questions, achievement tests, content assessment tests, and surveys were identified as common tools for evaluating critical thinking and contextual understanding among students. These techniques were represented in a detailed graph illustrating the development and distribution of research methods over time.

The graph displays specific techniques on the left side and the authors and publication years on the right side, arranged chronologically from the oldest to the most recent study. A color gradient highlights the research timeline, with darker shades indicating earlier years. This visual representation underscores the evolution of methodologies used in systems thinking research, offering a clear perspective on how the measurement of these skills has progressed.

These findings provide valuable insights into the diverse methodological landscape of systems thinking research. They highlight the need for continued exploration and refinement of approaches to enhance the impact of systems thinking in science education.

Figure 2

Methods and Techniques Used in Studies



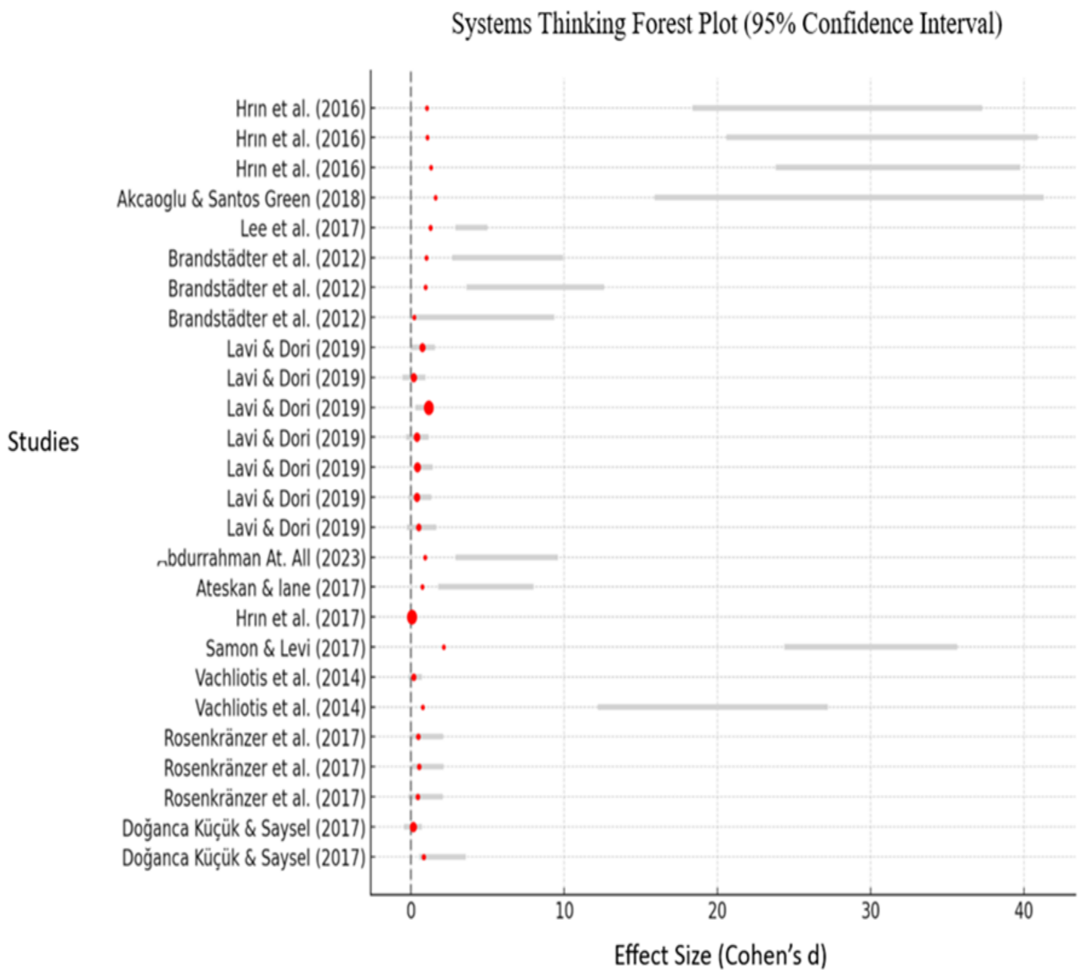
The chart illustrates the distribution of methods and techniques employed in various studies. Experimental methods, shown prominently in darker shades, dominate the research landscape. On the left side, specific techniques like systemic synthesis questions and achievement tests are listed, while the right side provides authors' names and publication years, arranged chronologically. This visualization demonstrates the evolution of methodologies and highlights the increasing use of mixed methods in recent years.

The findings addressing the second research question, "What is the overall effect size of systems thinking methodologies in science education?" are presented systematically below.

First, a forest plot (Figure 3) was generated to visually compare the effect sizes (Cohen's d) and 95% confidence intervals across various studies included in the meta-analysis. This plot highlights the consistency and variability of effect sizes, clearly representing the impact of systems thinking methodologies in science education. A red dot represents each study's effect size, while horizontal lines denote the 95% confidence intervals. The size of the red dots corresponds to the sample size, offering an intuitive view of the weight of each study in the analysis. Subsequently, a heterogeneity test was performed using Cochran's Q test and the I^2 statistic (Table 3) to assess the degree of variability in effect sizes across the studies. This step ensures that the heterogeneity level is appropriately evaluated within the meta-analytic framework and guides the selection of the fixed effects model for further analysis. Finally, the overall effect size was calculated using the fixed effects model, as presented in Table 4. This model assumes all studies share a common true effect size, providing a precise estimate of the mean effect size, standard deviation, and confidence intervals.

Figure 3

Forrest Plot



Cohen's d-effect sizes were calculated using each study's means, standard deviations, and sample sizes. The effect sizes were standardized based on the mean differences between the experimental and control groups and the standard deviations of these groups. For each study, 95% confidence intervals were determined by multiplying the standard error of the effect sizes by 1.96. The forest plot visually represents each study's effect size (denoted by a red dot) and the corresponding 95% confidence intervals (represented by horizontal lines). The size of the dots is proportional to the sample size of the respective studies. The y-axis lists the studies, while the x-axis indicates the Cohen's d values.

To assess the heterogeneity among the studies included in the meta-analysis, Cochran's Q test and the I^2 statistic were used. These measures evaluate the degree of variation in effect sizes across studies and determine the extent of heterogeneity. The results of these tests are presented in Table 3, providing insight into the consistency of the data and guiding the selection of the appropriate meta-analytic model.

Table 3

Heterogeneity and Effect Size Summary

N	Average Effect Size	Q	df	95% CI Lower	95% CI Upper	χ^2 Critical Value	I^2 (%)
26	0.759	1.784	25	0.368	1.150	37.652	0%

Table 3 presents the results of the heterogeneity analysis, which assessed whether variations in effect sizes across studies were significant. The Q statistic and I^2 index indicate the extent to which the observed variability is due to fundamental differences among studies rather than random sampling error. Given that the Q statistic was non-significant and I^2 was 0%, the results confirm that the studies included in the meta-analysis exhibit low heterogeneity. Therefore, the fixed effects model was deemed appropriate for further analysis.

Table 4 summarizes the overall effect size derived from the fixed effects model, employed after assessing heterogeneity through Cochran's Q test and the I^2 statistic. This model assumes a common true effect size across all studies, making it suitable for methodologically similar studies included in the meta-analysis. The table outlines key statistical measures, including the mean effect size, standard deviation, and confidence intervals. It offers a clear and concise overview of the aggregated results for systems thinking methodologies in science education. The overall effect of systems thinking on academic achievement in science education was approximately 0.47. This magnitude suggests that employing systems thinking methodologies in science education results in a medium impact.

To address the questions, "Which teaching strategies and techniques are most effective in systems thinking education?" and "In which sub-disciplines of science education is the systems thinking approach most impactful?" 12 research studies were scrutinized. These studies were assessed using Cohen's d and the weighted factor (w) effect size criteria, allowing for the identification of superior teaching methods and disciplines that benefit most from systems thinking. Effect sizes for each study were computed by dividing the product of Cohen's d and the weighted factor (w) by the number of variables within each study. This methodology ensures uniformity and provides a reliable basis for comparing the studies. Detailed results and comparisons are provided in Table 5.

Table 4

Fixed Effects Model Effect Size

Studies	n1	n2	m1	m2	S. E1	S. E2	Cohen's d	CI	Weighting Factor (w)	Cohen's d*w effect
Hrın, Mılenković, Segedınac & Horvat (2016)	65	54	86.25	58.43	14.71	34.93	1.038056	18.3736, 37.2664	0.001623291	0.001685
Hrın, Mılenković, Segedınac & Horvat (2016)	65	54	84.44	53.7	15.54	37.68	1.066592	20.5868, 40.8932	0.001412246	0.001506
Hrın, Mılenković, Segedınac & Horvat (2016)	65	54	58.17	19.89	26.4	24.09	1.314133	23.7867, 39.7533	0.001569095	0.002062
Akcaoglu & Santos Green (2018)	19	16	50.72	19.89	22.13	16.34	1.584956	15.9144, 41.2656	0.002702811	0.004284
Lee,Jones & Chesnutt (2017)	67	69	11.63	7.68	3.73	2.27	1.279336	2.9062, 4.9938	0.111111111	0.142148
Brandstädter, Harms & Großschedl (2012)	35	17	22	28.29	5.82	6.58	1.012616	2.6836, 9.8964	0.026014568	0.026343
Brandstädter, Harms & Großschedl (2012)	34	23	12.76	20.87	7.36	9.51	0.953756	3.6262, 12.5938	0.014054967	0.013405
Brandstädter, Harms & Großschedl (2012)	33	22	13.52	18.32	7.14	9.61	0.212626	0.2686, 9.3314	0.014257073	0.003031
Lavi & Dori (2019)	16	18	1.1	1.9	1.12	1.08	0.727153	0.031, 1.569	0.826446281	0.600953
Lavi & Dori (2019)	16	18	2.1	1.9	0.96	1.18	0.185936	-0.558, 0.958	0.873438728	0.162404
Lavi & Dori (2019)	16	18	1.6	2.4	0.5	0.86	1.1373	0.3, 1.3	2.162629758	2.459559
Lavi & Dori (2019)	16	18	1.2	1.6	0.85	1.22	0.380444	-0.344, 1.144	0.9335107	0.355149
Lavi & Dori (2019)	16	18	1.8	1.4	1	0.92	0.416305	0.179, 1.421	1.085069444	0.45172
Lavi & Dori (2019)	16	18	1.3	0.7	1.03	1.09	0.392614	-0.143, 1.343	0.88999644	0.349425
Lavi & Dori (2019)	16	18	1	1.7	1.44	1.33	0.505017	-0.268, 1.668	0.521315278	0.263273
Abdurrahman vd. (2023)	31	36	81.42	75.18	5.6	7.74	0.923722	2.8948, 9.5852	0.022477517	0.020763
Ateskan & lane (2017)	39	39	72.8	67.9	6.92	6.91	0.721619	1.781, 8.019	0.020912966	0.015091
Hrın, Mılenković, Segedınac & Horvat (2017)	65	54	4.38	4.42	0.63	0.7	0.060067	-0.2016, 0.2816	2.261292329	0.135829
Samon & Levi (2017)	47	45	45	75	12	16	2.12132	24.35, 35.65	0.005102041	0.010823
Vachliotis, Salta & Tzougraki (2014)	91	91	3.54	3.27	1.32	1.61	0.183404	-0.1607, 0.7007	0.465934373	0.085454
Vachliotis, Salta & Tzougraki (2014)	91	91	72.3	52.6	25.2	26.8	0.757334	12.198, 27.202	0.00147929	0.00112
Rosenkränzer, Hörsch, Schuler & Riess (2017)	23	37	2.17	1.17	2.22	1.93	0.480755	-0.0869, 2.0869	0.232254318	0.111657
Rosenkränzer, Hörsch, Schuler & Riess (2017)	25	37	2.26	1.17	2.1	1.93	0.540462	0.0544, 2.1256	0.24629177	0.133111
Rosenkränzer, Hörsch, Schuler & Riess (2017)	23	37	2.12	1.17	2.34	1.93	0.442928	-0.1635, 2.0635	0.219383642	0.097171
Doğanca Küçük & Saysel (2017)	22	20	3.11	2.98	0.84	1.02	0.139135	-0.4506, 0.7106	1.156203029	0.160868
Doğanca Küçük & Saysel (2017)	22	20	6.84	4.78	1.96	2.88	0.836266	0.536, 3.584	0.170753364	0.142795
Totals									12.26723643	5.751631066
Fixed Effects Model Mean Effect Size									0.46886119	
Mean Effect Size Standard Error									0.28551349	
Mean Confidence Interval for Effect Size (%95)									-0.09074525	1.028467629

Upon examining Table 5, the average weighted effect sizes of the analyzed studies reveal notable variations across sub-disciplines. For example, Hrin, Milenković, Segedinac, and Horvat (2016) focused on organic chemistry with an effect size of 0.00175, while Akcaoglu and Santos Green (2018) explored STEM education, reporting an effect size of 0.00428. Similarly, Lee, Jones, and Chesnutt (2017) investigated science education with an effect size of 0.142. Studies such as Brandstädter, Harms, and Großschedl (2012) emphasized biology education with an effect size of 0.01426, while Lavi and Dori (2019) addressed science and engineering education, achieving a higher effect size of 0.663. Additionally, Doğanca Küçük and Saysel (2017) reported a notable effect size of 0.151 in environmental education. These results highlight the diversity and effectiveness of systems thinking methodologies across educational contexts.

Table 5

Weighted Effect Averages of Studies by Variables and Disciplines Included

Studies	Cohend's d * w effect	Disciplines
Hrın, Mılenkovıć, Segedınac & Horvat (2016)	0.001751119	Organic Chemistry
Hrın, Mılenkovıć, Segedınac & Horvat (2016)		
Hrın, Mılenkovıć, Segedınac & Horvat (2016)		
Akcaoglu & Santos Green (2018)	0.004283836	STEM Education
Lee,Jones & Chesnutt (2017)	0.142148	Science Education
Brandstädter, Harms & Großschedl (2012)	0.014259734	Biology Education
Brandstädter, Harms & Großschedl (2012)		
Brandstädter, Harms & Großschedl (2012)		
Lavi & Dori (2019)	0.663211706	Science Education / Engineering Education
Lavi & Dori (2019)		
Lavi & Dori (2019)		
Lavi & Dori (2019)		
Lavi & Dori (2019)		
Lavi & Dori (2019)		
Lavi & Dori (2019)		
Abdurrahman At. All (2023)	0.020763	Science Education / STEM Education
Ateskan & lane (2017)	0.015091	Environmental Education

Other studies, including those by Abdurrahman et al. (2023), observed an effect size of 0.02076, focusing on science education/STEM education. Ateskan and Lane (2017) examined environmental education with an effect size of 0.01509, while Hrin, Milenković, Segedinac, and Horvat (2017) revisited organic chemistry with a higher effect size of 0.135. Studies such as those by Samon and Levi (2017) calculated an effect size of 0.01082, centering on chemistry education. Vachliotis, Salta, and Tzougraki (2014) focused on organic chemistry with an effect size of 0.04328. Finally, Rosenkränzer, Hörsch, Schuler, and Riess (2017) emphasized science and geography education with an effect size of 0.113, and Doğanca Küçük and Saysel (2017) recorded an effect size of 0.151 in environmental education. These findings provide a detailed comparison of the weighted effect sizes, highlighting the diverse applications and effectiveness of systems thinking approaches across various sub-disciplines in science education.

DISCUSSION AND CONCLUSION

Science education is inherently interdisciplinary, integrating concepts from chemistry, physics, biology, and environmental sciences. However, traditional science curricula often compartmentalize knowledge into discrete units, limiting students' ability to recognize the interconnectedness of scientific concepts (Elmas et al., 2021; Mahaffy et al., 2018). This reductionist approach can hinder students' ability to engage in complex problem-solving, as real-world scientific challenges require an integrative understanding of dynamic systems. Systems thinking addresses these limitations as a cognitive framework by enabling learners to analyze interdependent relationships within complex systems, fostering holistic reasoning and conceptual understanding (Ben-Zvi Assaraf & Orion, 2005; Jacobson & Wilensky, 2006).

5.1. The Role of Systems Thinking in Science Education

Systems thinking has been increasingly recognized in science education for cultivating higher-order thinking skills, enhancing problem-solving abilities, and promoting deep conceptual understanding (Orgill et al., 2019; Pazicni & Flynn, 2019). Unlike traditional linear and reductionist perspectives, systems thinking encourages students to recognize feedback loops, cause-and-effect relationships, and emergent properties within scientific phenomena (Arnold & Wade, 2015; Sweeney & Sterman, 2000). Furthermore, it helps students develop a deeper understanding of part-whole relationships, allowing them to see how individual components contribute to the functioning of a more extensive system. Several studies have demonstrated that students who develop systems thinking skills exhibit an improved ability to construct integrative explanations, apply scientific reasoning across disciplines, and engage in meaningful knowledge transfer (Brandstädter et al., 2012; Evagorou et al., 2009).

Despite these advantages, integrating systems thinking into science education remains inconsistent across disciplines and instructional methods. Prior research suggests that systems thinking is particularly effective in ecology, environmental sciences, and engineering education, where complex systems and interdependencies are fundamental (Ben-Zvi Assaraf & Knippels, 2022; Doğanca Küçük & Saysel, 2017). However, systems thinking studies in science education have predominantly been conducted using qualitative research methods due to the nature of the approach. While qualitative studies provide valuable insights into students' cognitive processes, they often lack generalizability in larger educational contexts. This study addresses this gap by conducting a meta-analysis of quantitative studies incorporating systems thinking, offering a broader, data-driven perspective on its effectiveness in science education and addressing a significant gap in the literature. In contrast, organic chemistry and physics fields have shown lower adoption rates, likely due to the traditionally reductionist approach in these disciplines (Vachliotis et al., 2014). These findings underscore the need for instructional scaffolding and interdisciplinary approaches to facilitate the incorporation of systems thinking in science curricula.

5.2. Findings from the Meta-Analysis: Evaluating the Impact of Systems Thinking

This meta-analysis quantitatively synthesized research on systems thinking in science education and assessed its overall impact. The analysis of 12 studies revealed an overall effect size of 0.47, indicating a moderate effect according to Cohen's (1988) classification. This effect size is comparable to other widely implemented instructional strategies in science education (Lipsey & Wilson, 2001), highlighting the pedagogical value of systems thinking.

Cochran's Q test and the I^2 statistic were applied to assess the variability among included studies. The results indicated that the Q statistic was non-significant ($Q = 1.784$, $p = 1.000$) and I^2 was 0%, suggesting negligible heterogeneity. According to Borenstein et al. (2009), an I^2 value of 0% indicates that observed variation in effect sizes is attributable solely to sampling error rather than methodological or contextual differences across studies. This supports using a fixed effects model, assuming that all included studies estimate a common true effect size (Hedges & Vevea, 1998).

5.3. Variability Across Disciplines and Instructional Strategies

A closer examination of effect sizes across sub-disciplines revealed notable variations:

Lavi & Dori (2019) reported the highest weighted effect size (0.663) in science and engineering education, suggesting that systems thinking methodologies are particularly impactful in problem-based learning environments, emphasizing design thinking and complex systems analysis.

Studies in environmental and sustainability education (e.g., Doğanca Küçük & Saysel, 2017; Ateskan & Lane, 2017) exhibited moderate effect sizes (0.151 and 0.015, respectively), indicating that systems thinking enhances students' ability to analyze ecological interdependencies and long-term environmental impacts.

Research in organic chemistry and physics (e.g., Vachliotis et al., 2014) demonstrated smaller effect sizes, suggesting that these fields may require additional instructional scaffolding and interdisciplinary connections to facilitate the adoption of systems thinking.

These findings align with prior research indicating that disciplines inherently involving dynamic complexity—such as ecology and engineering—are more conducive to systems thinking approaches (Ben-Zvi Assaraf & Orion, 2005; Orgill et al., 2019). In contrast, more reductionist disciplines may necessitate targeted pedagogical strategies to foster integrative reasoning.

5.4. Implications for Science Education and Future Research Directions

The findings of this meta-analysis underscore the need for systematically integrating systems thinking into science curricula to enhance conceptual understanding and problem-solving skills. Moving forward, several key recommendations emerge:

Science curricula should explicitly incorporate systems thinking components, ensuring consistent exposure to interconnected scientific concepts.

Inquiry-based and model-based learning approaches should be prioritized, as they align well with systems thinking principles (Ben-Zvi Assaraf & Orion, 2010; Kali et al., 2003).

Teacher education and professional development programs should emphasize interdisciplinary teaching strategies, equipping educators with the skills to integrate systems thinking into their instructional practices (Sommer & Lücken, 2010).

Future research should focus on comparative studies examining different instructional strategies for teaching systems thinking, including experimental studies that compare inquiry-based learning, computational modeling, and project-based approaches (Schraw et al., 2006; Slavin, 2002).

Longitudinal studies should assess how students retain and apply systems thinking skills over time, contributing to a more comprehensive understanding of its long-term impact on scientific literacy (Slavin, 2002).

5.5. Conclusion

This study contributes to the growing body of research emphasizing the importance of systems thinking in science education. The findings indicate that systems thinking methodologies have a moderate yet stable effect on students' academic achievement, problem-solving skills, and conceptual understanding across multiple scientific disciplines. Given the increasing complexity of global challenges, such as climate change, sustainability, and technological advancements, integrating systems thinking into science education is not merely beneficial but essential (Ben-Zvi Assaraf & Knippels, 2022; Sweeney & Sterman, 2007).

By fostering students' ability to analyze interconnected systems and dynamic interactions, systems thinking prepares future scientists, engineers, and decision-makers to tackle real-world scientific and societal challenges. As science education evolves, embracing systems thinking as a core pedagogical framework will be essential for developing scientifically literate, systems-oriented thinkers (Jacobson & Wilensky, 2006; Ben-Zvi Assaraf & Orion, 2010).

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APPENDIX 1

PRISMA-P 2015 Checklist
This checklist has been adapted for use with protocol submissions to Systematic Reviews from Table 3 in Moher D et al: Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Systematic Reviews 2015 4:1

Section/topic	#	Checklist item	Information reported		Line number(s)
			Yes	No	
ADMINISTRATIVE INFORMATION					
Title					
Identification	1a	Identify the report as a protocol of a systematic review	X		
Update	1b	If the protocol is for an update of a previous systematic review, identify as such		X	
Registration	2	If registered, provide the name of the registry (e.g., PROSPERO) and registration number in the Abstract		X	
Authors					
Contact	3a	Provide name, institutional affiliation, and e-mail address of all protocol authors; provide physical mailing address of corresponding author	X		
Contributions	3b	Describe contributions of protocol authors and identify the guarantor of the review	X		
Amendments	4	If the protocol represents an amendment of a previously completed or published protocol, identify as such and list changes; otherwise, state plan for documenting important protocol amendments		X	
Support					
Sources	5a	Indicate sources of financial or other support for the review	X		
Sponsor	5b	Provide name for the review funder and/or sponsor	X		
Role of sponsor/funder	5c	Describe roles of funder(s), sponsor(s), and/or institution(s), if any, in developing the protocol	X		
INTRODUCTION					
Rationale	6	Describe the rationale for the review in the context of what is already known	X		
Objectives	7	Provide an explicit statement of the question(s) the review will address with reference to participants, interventions, comparators, and outcomes (PICO)	X		

Section/topic	#	Checklist item	Information reported		Line number(s)
			Yes	No	
METHODS					
Eligibility criteria	8	Specify the study characteristics (e.g., PICO, study design, setting, time frame) and report characteristics (e.g., years considered, language, publication status) to be used as criteria for eligibility for the review	X		
Information sources	9	Describe all intended information sources (e.g., electronic databases, contact with study authors, trial registers, or other grey literature sources) with planned dates of coverage	X		
Search strategy	10	Present draft of search strategy to be used for at least one electronic database, including planned limits, such that it could be repeated	X		
STUDY RECORDS					
Data management	11a	Describe the mechanism(s) that will be used to manage records and data throughout the review	X		
Selection process	11b	State the process that will be used for selecting studies (e.g., two independent reviewers) through each phase of the review (i.e., screening, eligibility, and inclusion in meta-analysis)	X		
Data collection process	11c	Describe planned method of extracting data from reports (e.g., piloting forms, done independently, in duplicate), any processes for obtaining and confirming data from investigators	X		
Data items	12	List and define all variables for which data will be sought (e.g., PICO items, funding sources), any pre-planned data assumptions and simplifications	X		
Outcomes and prioritization	13	List and define all outcomes for which data will be sought, including prioritization of main and additional outcomes, with rationale	X		
Risk of bias in individual studies	14	Describe anticipated methods for assessing risk of bias of individual studies, including whether this will be done at the outcome or study level, or both; state how this information will be used in data synthesis	X		
DATA					
Synthesis	15a	Describe criteria under which study data will be quantitatively synthesized	X		

Section/topic	#	Checklist item	Information reported		Line number(s)
			Yes	No	
	15b	If data are appropriate for quantitative synthesis, describe planned summary measures, methods of handling data, and methods of combining data from studies, including any planned exploration of consistency (e.g., I^2, Kendall's tau)	X		
	15c	Describe any proposed additional analyses (e.g., sensitivity or subgroup analyses, meta-regression)	X		
	15d	If quantitative synthesis is not appropriate, describe the type of summary planned		X	
Meta-bias(es)	16	Specify any planned assessment of meta-bias(es) (e.g., publication bias across studies, selective reporting within studies)	X		
Confidence in cumulative evidence	17	Describe how the strength of the body of evidence will be assessed (e.g., GRADE)	X		

APPENDIX 2

Risk of bias domains

Study	D1	D2	D3	D4	D5	Overall
Hrın, Mılenković, Segedınac & Horvat (2016)-a	+	+	+	+	+	+
Hrın, Mılenković, Segedınac & Horvat (2016)-b	+	+	+	+	+	+
Hrın, Mılenković, Segedınac & Horvat (2016)-c	+	+	+	+	+	+
Akcaoglu & Santos Green (2018)	+	+	-	+	+	-
Lee,Jones & Chesnutt (2017)	+	+	+	+	+	+
Brandstädter, Harms & Großschedl (2012)-a	+	+	+	+	+	+
Brandstädter, Harms & Großschedl (2012)-b	+	+	+	+	+	+
Brandstädter, Harms & Großschedl (2012)-c	+	+	+	+	+	+
Lavi & Dori (2019)-a	+	+	+	+	+	+
Lavi & Dori (2019)-b	+	+	+	+	+	+
Lavi & Dori (2019)-c	+	+	+	+	+	+
Lavi & Dori (2019)-d	+	+	+	+	+	+
Lavi & Dori (2019)-e	+	+	+	+	+	+
Lavi & Dori (2019)-f	+	+	+	+	+	+
Lavi & Dori (2019)-g	+	+	+	+	+	+
Abdurrahman At. All (2023)	+	+	+	+	+	+
Ateskan & lane (2017)	+	+	-	+	+	-
Hrın, Mılenković, Segedınac & Horvat (2017)	+	+	+	+	+	+
Samon & Levi (2017)	+	+	+	+	+	+
Vachliotis, Salta & Tzougraki (2014)-a	+	+	+	+	+	+
Vachliotis, Salta & Tzougraki (2014)-b	+	+	+	+	+	+
Rosenkränzer, Hörsch, Schuler & Riess (2017)-a	+	+	+	+	+	+
Rosenkränzer, Hörsch, Schuler & Riess (2017)-b	+	+	+	+	+	+
Rosenkränzer, Hörsch, Schuler & Riess (2017)-c	+	+	+	+	+	+
Doğanca Küçük & Saysel (2017)-a	+	+	X	+	+	X
Doğanca Küçük & Saysel (2017)-b	+	+	X	+	+	X

Domains:
D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended intervention.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement
X High
- Some concerns
+ Low

GENİŞLETİLMİŞ ÖZ

Giriş

Bilginin geniş erişilebilirliği, bu bilgilerin doğru yorumlanmasını zorunlu kılmakta ve bireylerin bilgiyi etkili bir şekilde değerlendirme ihtiyacını artırmaktadır (Bakioğlu ve Göktaş, 2018). Aynı araştırma problemini ele alan birçok çalışmada çelişkili bulgular ortaya çıkabilir; bu durum, özellikle sosyal ve eğitim bilimlerinde yaygındır (Bayraktar, 2020). Bu karmaşıklık, bulguların akademik titizlikle yorumlanmasını gerektirmektedir. Meta-analiz yöntemi, farklı çalışmaların sonuçlarını birleştirerek daha genel ve güvenilir sonuçlar elde etmeye olanak sağlamaktadır (Aksoy Kürü, 2021; Bangert-Drowns ve Rudner, 1990; Field ve Gillett, 2010). Fen eğitimi, öğrenci ilgisini çekmek ve soyut kavramları somut hale getirmek için çeşitli araçların kullanımını gerektiren dinamik bir alandır (Elmas ve diğerleri, 2021; Mahaffy ve diğerleri, 2018). Sistemsel düşünme de fen eğitiminde giderek önem kazanan bir yaklaşımdır ve karmaşık sistemlerin bileşenleri arasındaki etkileşimleri anlamayı amaçlamaktadır (Richmond, 1994; Ben-Zvi Assaraf ve Orion, 2005; Evagorou ve diğerleri, 2009; Jacobson ve Wilensky, 2006; Arnold ve Wade, 2015; Orgill ve diğerleri, 2019). Bu meta-analiz çalışması, fen eğitiminde sistemsel düşünmenin yerinin derinlemesine anlaşılmasına katkı sağlamayı ve gelecek araştırmalara temel oluşturmayı hedeflemektedir. Araştırmanın hedefleri arasında aşağıdaki sorulara yanıt aranmıştır.

1-Sistemsel düşünme üzerine yapılan çalışmalarda hangi metodolojik yaklaşımlar ve teknikler kullanılmaktadır?

2-Fen eğitiminde sistemsel düşünme yaklaşımını kullanan çalışmaların genel etki büyüklüğü nedir?

3-Sistemsel düşünme yaklaşımında en etkili öğretim stratejileri ve teknikleri nelerdir?

4-Fen eğitiminin hangi alt disiplinlerinde sistemsel düşünme yaklaşımı daha etkilidir?

Yöntem

Bu çalışmada meta-analiz yöntemi kullanılmıştır. Meta-analiz, geniş bir literatür taraması yaparak bilimsel araştırmaları sistematik bir şekilde sentezleyen gelişmiş bir istatistiksel yöntemdir (Aksoy Kürü, 2021; Bakioğlu & Göktaş, 2018; Bayraktar, 2020; Karaca ve diğerleri, 2024). Bu yöntemin amacı, farklı çalışmalardan elde edilen bulguları tutarlı bir şekilde bir araya getirmek, ortak bir ölçüt altında değerlendirmek ve bu süreçte etki büyüklüklerini hesaplamaktır (Cohen & Manion, 2001). Bu doğrultuda verilerin toplanması, toplanan verilerin kodlanması, verilerin analizi başlıklarında süreç ayrıntılı biçimde ele alınmıştır.

Araştırmada, fen eğitiminde "sistemsel düşünme" anahtar keliimesini kullanan çalışmaları incelemiştir. Veriler, ERIC, SCOPUS, Science Direct ve Web of Science akademik veri tabanlarından 01.11.2023 tarihine kadar olan sürede toplanmıştır. Bu veri tabanları, eğitim alanında yüksek kaliteli uluslararası çalışmaları barındırmaları nedeniyle tercih edilmiştir. Toplamda 171,881 çalışma taranmış ve yalnızca araştırma makaleleri değerlendirilmiştir. Bu inceleme sonucunda 12 makale meta-analize dahil edilmiştir. Çalışmaların dilinin İngilizce olması ve örneklem gruplarının net istatistiksel detaylara sahip olması önemsenmiştir.

Bu çalışmada meta-analiz için özel olarak geliştirilmiş bir kodlama yöntemi kullanılmıştır. Kodlama şeması iki ana bölüme ayrılmıştır: birinci bölüm, her bir çalışmanın temel özelliklerini ve tanımlayıcı niteliklerini içerirken; ikinci bölüm, meta-analiz için gerekli olan istatistiksel verileri içermektedir. Bu süreçte Microsoft Excel ve CMA programı kullanılarak verilerin düzenli bir şekilde işlenmesi sağlanmıştır. Ek olarak her bir çalışmanın deney ve kontrol gruplarına ait ortalama ve standart sapmalar kullanılarak Cohen's d etki büyüklükleri hesaplanmış, %95 güven aralıkları belirlenmiştir. Çalışmalarda heterojenlik testi yapılmış ve elde edilen sonuç neticesinde sabit etkiler modeli kullanılmıştır. Yapılan istatistiksel hesaplamalar sonucunda ortalama etki büyüklüğü 0.468 olarak hesaplanmıştır.

Meta-analizin geçerliliğini artırmak için Cooper (1998) ve Hedges'in (1994) önerileri dikkate alınmıştır. Çalışma seçim süreci, iki bağımsız gözlemci tarafından gerçekleştirilmiş ve PRISMA-P protokolü kullanılmıştır (Hür, 2020; Shamseer ve diğerleri, 2015). Ayrıca, Robvis aracı kullanılarak yanlılık riski değerlendirilmiş ve sonuçlar görselleştirilmiştir.Çalışmada protokollere ek olarak, yayın yanlılığının değerlendirilmesi amacıyla Funnel Plot ve Egger’s regresyon testi analizleri gerçekleştirilmiştir. Funnel Plot, dahil edilen çalışmaların etki büyüklükleri ile standart hatalarının dağılımını görselleştirerek olası yayın yanlılığının nitel olarak incelenmesine olanak sağlamıştır. Buna ek olarak, Egger’s regresyon testi ise funnel plot’un simetrisini istatistiksel olarak değerlendirerek yayın yanlılığı olup olmadığına dair nicel bir kanıt sunmuştur. Analiz sonuçları, meta-analiz bulgularının yayın yanlılığından anlamlı düzeyde etkilenmediğini göstermiştir. Bu yöntemlerin birlikte kullanılması, çalışmanın metodolojik sağlamlığını artırarak elde edilen sonuçların güvenilirliğini desteklemiştir.

Sonuç, Tartışma ve Öneriler

Taranan 12 çalışmanın yöntem ve teknikleri incelendiğinde, fen eğitiminde sistemsel düşünme yaklaşımının araştırılmasında dört çalışmanın deneysel yöntemi, üç çalışmanın yarı deneysel yöntemi ve beş çalışmanın karma yöntemi benimsediği görülmüştür. Çalışmalarda en çok tercih edilen yöntem olan karma yöntemin sistemsel düşünmenin kapsamlı ve derinlemesine analiz edilmesini sağladığı düşünülmektedir. Bunun temel nedeni, sistemsel düşünmenin yalnızca akademik başarıya değil aynı zamanda öğrencilerin bilgiyi nasıl yapılandırdığı ve anlamlandırdığına da odaklanmasıdır. Karma yöntemin, bu bağlamda hem nicel hem de nitel verilerin birlikte kullanılarak daha kapsamlı bir analiz yapılmasını mümkün kıldığından dolayı tercih edildiği anlaşılmaktadır. Özellikle mülakatlar, görüşmeler ve gözlemler gibi nitel veri toplama teknikleri, öğrencilerin sistemsel düşünme süreçlerini ve kavramsal anlamlandırmalarını derinlemesine incelemek için önemli bir araç olarak kullanılmaktadır.

Yapılan istatistiksel analizler sonucu fen eğitiminde sistemsel düşünme yaklaşımını kullanan çalışmaların genel etki büyüklüğü yaklaşık 0.47 olarak çıkmıştır. Bu sonuç, Cohen’in (1988) etki büyüklüğü sınıflandırmasına göre orta düzeyde bir etkiye işaret etmektedir. Bu büyüklük, sistemsel düşünmenin öğrencilere kavramsal ve analitik beceriler kazandırma potansiyelini ortaya koymaktadır (Cohen, 1988; Thalheimer ve Cook, 2002). Orta düzeyde bir etki büyüklüğünün gözlemlenmesi, sistemsel düşünme yaklaşımının fen eğitiminde belirgin bir fark oluşturduğunu ancak bu etkinin tüm öğrenci grupları üzerinde eşit düzeyde olamayabileceğini göstermektedir. Bu sonucun birkaç olası nedeni olabilir. Sistemsel düşünme becerileri, öğrencilerin mevcut bilgi düzeylerine ve bilişsel gelişim aşamalarına bağlı olarak değişkenlik gösterebilir. Özellikle karmaşık sistemleri anlamak ve bu sistemler arasında ilişki kurabilmek, öğrencilerin zihinsel modellerine dayanan üst düzey bilişsel süreçler gerektirir. Bu nedenle, sistemsel düşünme etkinliklerinin başarısı öğrencilerin önceki bilgi birikimi ve deneyimleriyle yakından ilişkili olabilir (Elmas ve diğerleri, 2021; Jacobson ve Wilensky, 2006). İkinci olarak, araştırmacıların bu yaklaşımı uygulamadaki kullandıkları metotlar ve veri toplama araçları etki büyüklüğünü doğrudan etkileyebilir (Arnold ve Wade, 2015; Evagorou ve diğerleri, 2010). Son olarak, eğitim ortamının ve kullanılan materyallerin niteliği de bu sonuca etki etmiş olabilir. Özellikle sistemsel düşünme becerilerini geliştirmeye yönelik zengin görsel ve dijital araçların kullanımının öğrencilerin kavramsal öğrenmelerini destekleyici bir unsur olduğu bilinmektedir (Kali, Orion ve Eylon, 2003). Öğrenme ortamlarının bu tür araçlarla desteklenmesi, öğrencilerin karmaşık sistemler ve ilişkiler arasında bağlantı kurma yetilerini daha ileri düzeyde geliştirebilir.

Çalışma bulgularına göre, sistem düşüncesi becerileri fen eğitiminin her aşamasına entegre edilmeli ve bu beceriler öğrencilere somut ve anlamlı bağlamlarda sunulması (Elmas ve diğerleri, 2021; Sweeney ve Sterman, 2000), öğretmenlerin sistem düşüncesini öğretme becerilerinin geliştirilmesi (Sommer ve Lücken, 2010), sistemsel düşünme yaklaşımı, öğrencilerin farklı öğrenme stillerine ve kültürel arka planlarına uygun bir şekilde sunulması (Arnold ve Wade, 2015; Ben-Zvi Assaraf ve Orion, 2005) önerilmektedir.