



Embedding Computational Thinking in STEM Education: A Comprehensive Literature Review

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Received: January 30, 2025. Revised: February 14, 2025. Accepted: February 18, 2025.

First Available Online: February 26, 2025. Publication Date: February 28, 2025.

DOI: 10.61142/esj.v3i1.203

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Keywords :

Computational thinking,
STEM Education, Literature
Review

ABSTRACT

The study of incorporating computational thinking (CT) into science, technology, engineering, and mathematics (STEM) education has gained interest. We carried out a semi-systematic review of 50 empirical papers on this topic. Our findings highlighted the following crucial points: (a) the majority of research utilized domain-general descriptions for CT, while a few studies suggested domain-specific terms that addressed STEM education; (b) problem-based instruction developed as the most common teaching approach, with popular contextual topics including game design, robotics, and computational modelling; (c) assessments of student learning in combined CT and STEM varied in objectives and formats, with approximately one-third evaluating both CT and STEM integration. Based on our findings, we make recommendations for future study and implementation, with an emphasis on defining and evaluating CT in STEM contexts, developing successful instructional strategies for incorporating CT into STEM, and investigating approaches to promote inclusiveness in integrated CT and STEM education.

INTRODUCTION

Computational thinking (CT) is becoming more widely regarded as a necessary skills in the 21st century (Nouri et al., 2020). It is the process of solving issues using fundamental computer science principles (Günbatır, 2019). CT entails practices such as abstraction (extracting essential information from comprehensive problem contexts), decomposition (breaking down a larger problem into smaller, attainable parts), pattern recognition in data, and algorithm development and application (Ogegbo & Ramnarain, 2022). These skills are widely regarded as necessary for overcoming complex problems across multiple disciplines in modern society. In the recent years, there has been an increasing trend of incorporating computing, and hence CT, into numerous educational subjects, particularly in STEM fields (Basu et al., 2016). Studies show that adding CT into STEM education improves both CT learning and STEM topic comprehension (Wang et al., 2022, Hidayat et al., 2024). This dual benefit stems from the central position of computational procedures and instruments in contemporary STEM disciplines (Bybee, 2013). For instance, the Next Generation Science Standards (NGSS) framework National Research Council (Hoeg & Bencze, 2017) lists "using mathematics and computational thinking" as one of the eight fundamental practices in K-12 science teaching.

Furthermore, incorporating CT within STEM education has the potential to reduce disparities in having access to CT educational possibilities (Wang et al., 2022). The traditional approaches towards CT education are frequently limited to computer science or programming classes, which remain scarce, particularly at the lower grade levels in K-12 settings (Swaid, 2015). Even when such courses are provided, they are frequently voluntary, preventing many students from participating owing to a lack of enthusiasm or programming issues (Çiftçi & Topçu, 2023). STEM courses, on the other hand, are more widely available and often required, giving a more comprehensive and inclusive platforms for introducing CT principles (Weintrop et al., 2014). Despite current discussions about the concept and application of CT in education, agreement on its operationalization remains difficult (Dolgopolas & Dagiene, 2024). For example, the International Society to Technology in Education (ISTE) and the Computing Science Teachers Association (CSTA) identify CT in K-12 education as a problem-solving process that includes formulating a problem, analyzing data, logical grouping, algorithmic thinking, and solution generalizing (Chondrogiannis et al., 2021). Swaid (2015) suggested a CT framework for programming that included fundamental ideas such as sequences of data, loops, parallelism, and conditionals.

When CT definitions cross with other fields, their diversity expands even further (Dolgopolas & Dagiene, 2024), for example, divide CT in mathematics and science education into four categories: data procedures, simulation and modeling practices, computational problem-solving techniques, and systems thinking activities. Similarly, Nouri et al. (2020) define CT in STEM education as elements such as comprehending complex systems, using computing resources, and making data-driven decisions. Nevertheless, integrating CT throughout STEM education offers considerable practical barriers. These include identifying effective instructional strategies, planning appropriate activities, and creating reliable evaluation methods for mixed CT and STEM (Hoeg & Bencze, 2017). Addressing these difficulties is critical for educators to successfully adopt combined CT and STEM curriculum.

The novelty of this review lies in its comprehensive examination of the diverse theoretical and practical dimensions of integrating CT into STEM education. Compared to previous research, this study not only investigates existing definitions and techniques, but it also focuses on equity-related issues, which are sometimes disregarded. It also consolidates results on teaching tactics and evaluation methods, giving a clearer path for educators and researchers to solve ongoing gaps in this field. This paper systematically examines the connection of CT and STEM education to highlight the synergies that enable deeper learning and innovation (Mahardika et al., 2024). It also provides a critical viewpoint on developing comprehensive frameworks which ensure all learners receive the advantages of CT integration across a variety of educational settings. In order to advance research and practice within this essential field, we must analyze how these difficulties have been discussed in the literature. Thus, a systematic review of empirical studies was done to answer the following research questions: (1) How is CT outlined in STEM education? (2) Which teaching strategies are used to embed CT into STEM education? (3) How are CT and STEM materials evaluated in integrated learning environments? (4)

What equity-related concerns are addressed through the combining of CT and STEM education? This review is intended to provide insights and direct future attempts in this crucial sector.

METHOD

Using a semi-systematic approach to the literature review (Zunder, 2021), this study analyzed both qualitative and quantitative research to identify broad trends in the integration of computational thinking (CT) into STEM and science learning (Chondrogiannis et al., 2021). The review employed three main techniques for gathering literature: database searches, citation analysis, and the inclusion of papers already familiar to the authors. The database searches were conducted using Scopus with the following search query: TITLE-ABS-KEY (computational AND thinking AND stem) AND (LIMIT-TO (EXACTKEYWORD , "Computational Thinking") OR LIMIT-TO (EXACTKEYWORD , "STEM") OR LIMIT-TO (EXACTKEYWORD , "STEM (science, Technology, Engineering And Mathematics)")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (OA , "all")). This query ensured the inclusion of peer-reviewed articles and conference proceedings published in English, focusing on CT and its applications in STEM education.

The search terms were specifically chosen to reflect the incorporation of CT into STEM and science learning, using combinations like "computational thinking," "science learning," and "STEM education." These terms were further expanded to include discipline-specific keywords such as "environmental science," "astronomy," and "geology" to capture the science contexts, as well as terms like "coding education" and "educational robotics" for technology-related contexts. Additional searches were conducted on platforms like ResearchGate and Google Scholar to complement the Scopus database. This comprehensive strategy allowed for the identification of a diverse range of studies, ensuring a broad representation of methodologies and perspectives within the field.

The literature review analyzed 156 articles published between 2010 and 2024, providing comprehensive insights into the integration of computational thinking (CT) into science learning. The distribution of articles by year was as follows: 2024 (21 articles), 2023 (24 articles), 2022 (36 articles), 2021 (26 articles), 2020 (14 articles), 2019 (20 articles), 2018 (7 articles), 2017 (1 article), 2016 (3 articles), and 2015 (2 articles). The review was conducted in two phases. The first phase examined articles published between 2010 and 2019, offering foundational perspectives on the application of CT in STEM education. The second phase, conducted from January 2020 to December 2025, emphasized identifying research published after 2020 to capture recent advancements and emerging trends. This phase expanded searches in Scopus-indexed journals and employed citation tracking to locate additional relevant studies. Following the application of inclusion criteria, the final selection retained all 156 articles, focusing on empirical research that demonstrated robust methodologies and meaningful contributions to science learning through CT integration.

Furthermore, in order to ensure consistency and accessibility in the analysis, only English-language articles were taken into consideration. Conference proceedings, book chapters, and duplicate publications that overlapped with journal articles were not included in the review; only journal-published articles were. Only research released in the last ten years were included in the selection process to guarantee the results represented recent developments. Together, these standards made it easier to conduct a thorough and targeted analysis of CT's function in STEM education from the perspective of excellent, empirical research. Every study was thoroughly examined to learn more about the function of computational thinking (CT) in STEM education. The publication year, subject area, participant grade level, study location, and other important information were recorded. Particular remarks regarding CT definitions, teaching strategies, evaluations, and equality issues were also included. WordClouds (<https://www.wordclouds.com/>) was used to assemble theoretical insights after eliminating superfluous terms and standardizing word forms.

RESULTS AND DISCUSSIONS

Geographically, the majority of the studies ($n = 59$) came from the United States, with Spain (10), Austria (8), Italy (8), Greece (7), Germany (6), Indonesia (6), Malaysia (6), and Turkey (6) following closely behind. According to the data, the United States leads the world in computational thinking (CT) research in STEM education, with lesser but noteworthy contributions from other nations. The trend of publications over time indicates a consistent rise, which reflects the growing interest in incorporating CT into STEM education on a global scale. In order to emphasize multidisciplinary linkages and trends in computational thinking (CT) research, the papers were grouped according to their topic matter. There were 156 papers on CT in all, 44 of which were exclusive to STEM settings and 49 of which highlighted computational thinking in general education. Of them, 37 examined how students interacted with CT, 24 with robotics, 23 with education computers, and 21 with engineering education. It is noteworthy that these categories overlap because many studies combine CT with particular STEM fields or contexts, such as engineering and robotics. For example, robotics research usually focuses on real-world applications of CT in STEM learning contexts, overlapping with engineering and computer education. These intersections are illustrated visually with a Venn diagram (Figure 1), which also illustrates the various applications of CT research in STEM education and shows how it crosses several disciplines.

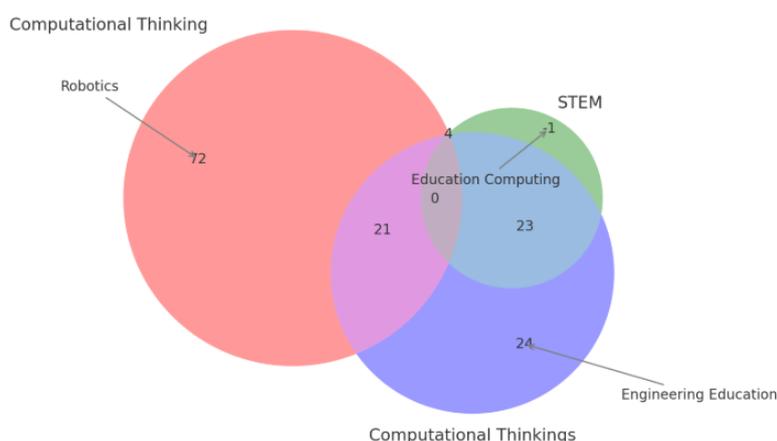


Fig 1. Venn diagram of STEM and CT

A word cloud analysis provides a brief summary of the terms commonly used to define or interpret computational thinking (CT) in the literature collection. Figure 2 provides a word cloud visualization. Key terms like “problem” ($f = 170$), “computer” ($f = 107$), “student” ($f = 107$), “solve” ($f = 102$), “programming” ($f = 98$), and “skill” ($f = 95$) highlight the fundamental role that CT plays in promoting problem-solving skills, particularly in STEM education. In CT-related learning, computers continue to be the major tool, but programming becomes a central activity. The interdisciplinary character of CT integration in STEM education is demonstrated in Figures 1 and 2, which display the quantity of research conducted in fields including science (19 publications), mathematics (9 papers), and technology and engineering (17 papers). The connections between these domains highlight the need for a comprehensive strategy to integrate CT into various educational systems. The theoretical underpinnings of integrating CT into STEM education are highlighted by these findings, which demonstrate how it can help students develop essential 21st-century abilities including creativity, logical reasoning, and the capacity to methodically examine and resolve complicated issues.

programming activities, contextualized subjects, and instructional models. The variety of methods highlights CT education's complexity and its capacity to help STEM students develop essential problem-solving abilities. These tactics support the main objective of integrating CT as a crucial skill for handling challenging problems in the twenty-first century.

In order to provide a comprehensive understanding of how Computational Thinking (CT) is incorporated into STEM education, this systematic review examines four key research questions. First, the definition of CT within STEM education varies across different frameworks and interpretations. Some studies adopt discipline-specific taxonomies, such as Weintrop et al. (2016), which outline CT practices like data analysis, modeling, problem-solving, and systems thinking. Others use broader conceptualizations, like Wing's (2006) perspective on CT as a fundamental competency akin to writing and mathematics. Many researchers adapt established frameworks—such as those from CSTA and ISTE—to align with the unique requirements of specific STEM disciplines, reflecting the ongoing effort to refine and expand CT definitions.

The second aspect of this review focuses on instructional strategies for integrating CT into STEM education. Activity-driven methods, including robotics, game design, and computational modeling, are commonly employed, alongside problem-based learning approaches. Programming activities, particularly block-based programming, are frequently used for younger students, while scaffolding techniques—such as collaborative problem-solving and step-by-step guidance—enhance engagement and comprehension. Additionally, some studies explore non-programming activities, like maker-based learning, which fosters CT skills through hands-on experimentation with abstraction, decomposition, and algorithmic thinking. Assessment methods in CT-integrated STEM learning also vary, aiming to evaluate students' problem-solving abilities, understanding of CT concepts, and application of STEM knowledge. Tools such as project-based evaluations, quizzes, and rubrics are widely used, though a lack of standardized frameworks highlights the need for more comprehensive assessment tools.

Finally, this review addresses equity-related concerns in CT-integrated STEM education. Ensuring broader participation and accessibility for underrepresented groups remains a key challenge. While some studies focus on interventions for female students and economically disadvantaged learners, there is a significant research gap in this area. Efforts to promote inclusivity include designing equitable curricula, providing affordable learning resources, and fostering collaborative learning environments. However, further research is necessary to identify and eliminate barriers to equitable participation. Overall, this study offers an in-depth analysis of CT frameworks, teaching strategies, assessment methods, and equity considerations, laying the groundwork for future research aimed at refining assessment techniques, developing inclusive practices, and strengthening CT integration within STEM education.

CONCLUSION AND SUGGESTION

Several important conclusions can be drawn from our analysis of 156 empirical research on the incorporation of computational thinking (CT) into STEM education. The contextualization of CT within particular domains has been emphasized in efforts to create domain-specific definitions of CT that are suited to STEM subjects. The most popular methods for integrating CT into STEM are problem-based learning techniques like game design, robotics, and computational modeling. Although assessments of student learning in STEM and CT integrated contexts have been carried out with a variety of goals and approaches, their reach is still restricted. Furthermore, there is a conspicuous dearth of research on pedagogical approaches intended to promote equity and inclusivity in CT-integrated STEM education, despite the fact that several studies have looked at learning performance and processes across various populations. Even though this field is still in its infancy, these findings provide a useful basis for future study and application, especially in the areas of operationalizing CT in various STEM contexts, creating reliable assessments for integrated learning, and addressing equity to increase enrollment in STEM education that incorporates CT.

ACKNOWLEDGMENTS

The authors would like to express their deepest gratitude to the Department of Science Education, Faculty of Teacher Training and Education, Universitas Sebelas Maret, for their invaluable support and encouragement throughout the course of this study. The resources, guidance, and collaborative environment provided by the department were instrumental in the completion of this research.

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