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Exploring Research on Computational Thinking in Mathematics: Trends, Challenges, and Impact on Modern Learning

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Abstract: Computational Thinking (CT) has been recognized as one of the essential skills of the 21st century and is increasingly being integrated into educational curricula in various countries. This study aims to analyze trends, challenges, and the impact of CT in mathematics education through a Systematic Literature Review (SLR) approach of 41 selected articles from the Scopus database covering the period from 2019 to 2024. The analysis results show a significant increase in the number of publications related to CT in mathematics education, with the highest peak occurring in 2023. Scratch technology was identified as one of the most commonly used tools to support CT learning, although there was considerable variation in the types of technology used in the reviewed literature. The most frequently studied mathematics topics were geometry and number patterns, while topics such as trigonometry and measurement were still rarely explored. The findings also indicate that CT has a positive impact on the mathematics learning process, which can be grouped into three main areas: (1) CT's contribution to students' understanding and learning outcomes, (2) the role of digital technology in supporting the implementation of CT, and (3) the relationship between CT and the development of higher-order mathematical thinking skills. However, six categories of challenges in implementing CT in the classroom were also identified, including: (1) barriers to using technology for CT learning, (2) lack of training and guidance for teachers, and (3) limitations in infrastructure and supporting facilities. To address these challenges and optimize the potential of CT in transforming mathematics learning, close collaboration between researchers, educators, and policymakers is required.

Keywords: computational thinking, systematic literature review, mathematics learning.

▪ INTRODUCTION

Computational thinking (CT) is recognized as an essential skill that everyone should learn (Pan, Adams, Ketterlin-Geller, Larson, & Clark, 2024). It has gained prominence as a vital 21st-century competency and is currently being incorporated into school curricula around the world (Nordby, Bjerke, & Mifsud, 2022). As the world becomes increasingly complex, students must be equipped with CT competencies to prepare them for a workforce that increasingly relies on technology and analytical skills (Agbo et al., 2023). For young students, developing CT skills is crucial to prepare them for future job opportunities (Agbo et al., 2023). Therefore, CT is viewed as a key component in helping learners succeed in the digital era (Kite, Park, & Wiebe, 2021). Furthermore, employing CT enables individuals to make informed decisions systematically while utilizing information and communication technology (Haseski, Ilic, & Tugtekin, 2018). Often defined as a cognitive process that involves using computational methods to solve problems, CT is not limited to computer scientists; it should be considered a fundamental competency alongside reading, writing, and arithmetic (J. M. Wing, 2006). It is important that CT is taught as part of children's analytical skill development from an early age, so they are better equipped for an uncertain future (Rodríguez-Martínez et al., 2020; Wing, 2006.). This is because CT

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provides a relevant approach to addressing various types of problems (Ogegbo & Ramnarain, 2022).

The term computational thinking was first introduced by Papert & Seymour (1980), who emphasized its core concept as thinking like a computer scientist (Jeannette M Wing, 2017). Over the past decade, research on computational thinking has evolved in various directions, leading to the development of representative definitions (Selby & Woollard, 2010). Since Jeanette Wing's use of the term computational thinking in 2006, numerous discussions have contributed to the definition of computational thinking (Abdul Hanid, Mohamad Said, Yahaya, & Abdullah, 2022). Operationally, International Society for Technology in Education (ISTE) and the Computer Science Teachers Association (CSTA) (2011) define CT as a problem-solving process that includes several criteria, such as: (1) formulating problems by utilizing tools and computers to find solutions, (2) analyzing and organizing data logically, (3) representing data by abstracting it into models and simulations, (3) representing data by abstracting it into models and simulations, (4) automating solutions through algorithmic thinking, (5) analyzing, identifying, and applying solutions to maximize efficiency, and (6) transferring and generalizing problem-solving processes to various issues. These criteria are essential characteristics that students in the 21st century must acquire. According to CT can be classified into 11 thinking processes, including abstraction, algorithm design, decomposition, pattern recognition, and data representation.

CT is closely related to mathematics, as it integrates mathematical, engineering, and scientific thinking in problem-solving, designing, and evaluating systems, as well as understanding human intelligence and behavior (Wing, 2008). CT skills have become essential competencies for students, enabling them to solve mathematical problems, undertake applied tasks, and make informed decisions (Elicer, Tamborg, Bråting, & Kilhamn, 2023). Both CT and mathematics share common competencies, including problem-solving, modeling, data analysis and interpretation, statistics, and probability (Sneider et al., 2014). Researchers suggest that solving mathematical problems involves various components of computational thinking (Denning, 2017).

The natural and historical connection between CT and mathematics arises from their shared focus on pattern recognition and the generalization of quantitative relationships (Kallia, van Borkulo, Drijvers, Barendsen, & Tolboom, 2021). Integrating mathematics and CT can enhance student reasoning by promoting skills such as abstraction, decomposition, pattern recognition, and algorithm development. This integration ultimately deepens students' understanding of mathematical concepts and skills (Dahshan & Galanti, 2024). Most research on professional development for teachers integrating mathematics and CT focuses on enhancing teachers' knowledge of programming and CT skills, as well as providing strategies for applying this knowledge in the classroom. While professional development can help teachers improve their understanding of CT concepts and practices, research shows that many teachers find it challenging to translate this knowledge into effective CT lessons that enhance the mathematics curriculum and teaching practices (Rich, Yadav, & Larimore, 2020; Smith et al., 2020)

Recently, research on CT has become a major focus of curriculum reform in K-12 schools worldwide (Dong, Li, Sun, & Liu, 2024). Several countries have introduced CT into their curricula, identifying science and mathematics as subjects that can naturally integrate this CT skill (Weintrop et al., 2016). This emphasis on CT highlights its importance as a key competency for the 21st century, equipping students to address complex problems in the world (Li et al., 2020). Schools and teachers need to integrate computational thinking into their teaching practices because it is essential for students to address these challenges effectively (Knie, Standl, & Schwarzer, 2022). Some countries have even started incorporating CT into their curricula (Nordby et al., 2022). For instance, Spain has included the term CT in its curriculum from preschool to university (Dúo-Terrón, 2023). A survey of 21 countries in Europe revealed that 17 of them are actively working to include CT in their educational curricula (Balanskat & Engelhardt, 2015). Therefore, Hunsaker (2020) recommended that students' computational thinking skills be developed and enhanced at every educational level by incorporating CT into teaching and learning practices.

Computational thinking has gained significant research attention, especially in primary and secondary education contexts (Kallia et al., 2021). For instance, a study by Hanid, Mohamad Said, Yahaya, & Abdullah (2022) explored the use of computational thinking elements in geometry learning through augmented reality (AR) technology. Additionally, research by Nordby et al. (2022) examined how mathematics education at the primary level can benefit from CT practices. Despite the rapid development of research on CT in mathematics education in recent years, there are still several gaps that need to be addressed. Some researchers have focused on developing CT frameworks in mathematics; however, there is limited research that systematically examines the challenges of CT in contemporary mathematics education. For example, Kallia et al. (2021) explored what computational thinking is and how it can be applied in mathematics education, using a methodological approach that combined recent literature findings with expert perspectives in the field through a delphi study. Similarly, the study by Irawan, Rosjanuardi, & Prabawanto (2024) merely identified research trends related to CT in mathematics education, without further exploring the impact and challenges of implementing CT in the learning process. Previous studies have focused mainly on the implementation of CT in programming and science education. In contrast, comprehensive studies on integrating CT into mathematics learning remain scarce, particularly those that specifically investigate the impact and challenges of implementing CT in the context of mathematics education. Therefore, this research aims to systematically explore and analyze the development of research on CT in mathematics education, focusing specifically on trends, challenges, and impacts in modern learning. Through a Systematic Literature Review (SLR) approach, this study will identify existing research gaps, analyze best practices for integrating CT into mathematics education, and provide concrete recommendations for future development of CT in mathematics learning. The findings of this study are expected to significantly contribute to the development of effective mathematics learning strategies by integrating CT, as well as serve as a reference for educators and policymakers in developing mathematics curricula relevant to the needs of the 21st century.

Considering the discussion above, this study aims to analyze, present, and visualize the research trends, challenges, and impact of CT in mathematics learning using a Systematic Literature Review. Based on this aim, five questions are addressed in this study, as follows.

1. What are the Emerging Trends in Author Collaboration within CT and Mathematics Learning Publications?
2. What are the trends and developments in CT related to mathematics learning over the publication years?
3. What technologies are used in studies on CT in mathematics learning?
4. What mathematical topics are investigated in research on CT in mathematics learning?
5. What are the challenges in implementing CT in mathematics learning?
6. What impact does the integration of CT have on mathematics learning, particularly in enhancing students' understanding and skills?

▪ METHOD

Research Design

This study utilizes the Systematic Literature Review (SLR) method to examine the trends, challenges, and impact of CT within modern mathematics education. The SLR method was selected for its ability to systematically and comprehensively identify, evaluate, and synthesize findings from prior research. This process adheres to strict protocols to ensure that the obtained results are valid, reliable, and accountable. The process was specific and included the following steps Kitchenham (2004) specifying research questions, searching on databases, inclusion/exclusion criteria, selection of studies, analysis and extraction of data, summary and interpretation of findings, and writing the review report.

Search Strategy

To support the credibility of this study, the researchers primarily used the Scopus database for literature searches. According to Phuong et al. (2023) Scopus is recognized as the most comprehensive and widely used academic database. It was chosen for its reputation as one of the largest and most reliable databases, indexing high-quality, peer-reviewed journals across various disciplines, including mathematics education.

The query string used for the database search was: (TITLE-ABS-KEY ("computational thinking" AND "mathematics")) AND PUBYEAR ≥ 2013 AND PUBYEAR ≤ 2024 AND (LIMIT TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (OPEN ACCESS, "Open access")). The search process is inspired by the approach used by (Irawan et al., 2024). The outcomes of the searches conducted in the Scopus databases were downloaded, and an Excel worksheet was utilized to compute, manually sort duplicate articles, and organize the collected data. The study adhered to the preferred reporting items for systematic literature review and meta-analysis (PRISMA), a widely recognized framework for systematic reviews in the social, education, and health sciences (Elmoazen, Saqr, Tedre, & Hirsto, 2022). Figure 1 presents the PRISMA diagram, illustrating the inclusion process for data extraction.

The article selection process in this study was carried out systematically through several rigorous stages to ensure that only articles that met the inclusion criteria were analyzed further. This approach aimed to collect relevant and credible sources that contributed significantly to understanding the trends, challenges, and impacts of computational thinking in mathematics learning. The article search was conducted on December 1, 2024, through the Scopus database, with the publication year range set between 2013 and 2024.

The initial stage involved the process of identifying relevant articles based on keywords compiled in accordance with the research focus. The results of this process yielded 183 articles that were collected for further evaluation. The next stage was preliminary screening, where the titles and abstracts of each article were reviewed to assess their relevance to the research focus. At this stage, articles that were not relevant were immediately eliminated. One article was excluded because it was not written in English, while 55 articles were removed because they did not discuss computational thinking and were considered irrelevant to the research objectives. Thus, 127 articles remained for further evaluation.

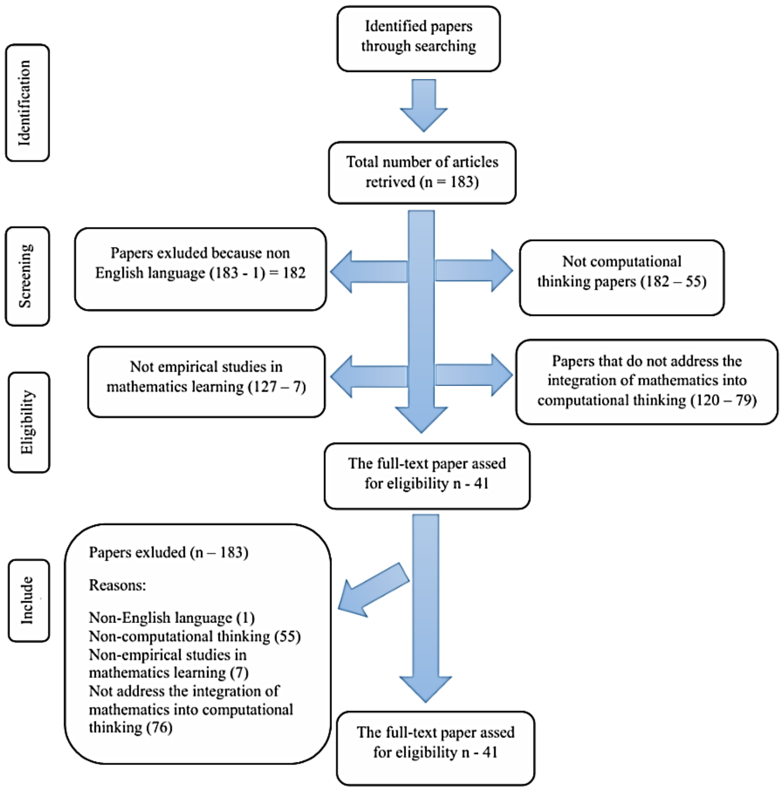


Figure 1. Flow diagram of the review process (Adapted from Sunday, Agbo, & Suhonen (2024))

In the eligibility stage, a comprehensive evaluation of the full content of each article was conducted. Each article was reviewed based on the introduction, methods, results, and conclusions to ensure its suitability with the scope of the research. This evaluation was conducted collaboratively by several authors to maintain objectivity and consistency in assessment. Of the 127 articles reviewed, 79 articles did not discuss the integration of computational thinking in mathematics education and were therefore excluded, and seven other articles were non-empirical articles, such as literature reviews or conceptual articles, that did not contain field research data.

Although the search covered the years 2013 to 2024, the final selection results showed that truly relevant articles began to emerge significantly only from 2019 onwards. Therefore, only articles published between 2019 and 2024 were used in the final analysis.

In total, 41 articles met all inclusion criteria and were deemed suitable for in-depth analysis. These articles form the basis for identifying trends, challenges, and the impact of research related to the integration of computational thinking in mathematics education.

Inclusion and Exclusion Criteria

To ensure the relevance and suitability of the articles analyzed in this study, inclusion and exclusion criteria were systematically established based on the research objectives and scope of the topics studied. These criteria are described in Table 1 below.

Table 1. Inclusion and exclusion criteria

Aspect	Inclusion Criteria	Exclusion Criteria
Publication	Journals indexed by Scopus	Other database
Literature type	Journal Articles	Conference Reviews, Book Chapters, Short Survey, Books, Editorials, Conference Papers, and Reviews
Paper language	English	Other Language
Type of study	Empirical studies	Literature reviews, Theoretical studies
Focus Study	Computational thinking in mathematics learning	Not related to computational thinking in mathematics learning
Research method	Qualitative, Quantitative, Mixed Methods, Research and Development (R&D)	Not using qualitative, quantitative, mixed methods, or R&D approaches
Type of article	Open Access	Not open access

Data Analysis

The analysis of 41 articles was conducted using a qualitative approach through in-depth reading and grouping of information based on similarities in meaning. Each article was thoroughly examined, particularly the introduction, methods, results, and discussion sections, to identify parts relevant to the focus of this study. Relevant information, such as the type of technology used in learning, the mathematics topics under study, challenges in implementing CT, and its impact on students' learning processes and outcomes, was then marked and collected.

After all the information was collected, the researcher developed initial categories based on content similarities, then grouped them into main themes that recurred across various articles. In this process, it was found that 12 articles did not specifically address a particular topic in mathematics, so they were not included in the mathematical topic mapping analysis. One of these was the study of Rafiepour & Farsani (2021), which examined the role of CT in the mathematics curriculum in general, without referring to specific learning materials or content. Nevertheless, these articles were still analyzed to examine the challenges and impacts of CT implementation in mathematics learning.

The analysis process was conducted reflectively and iteratively to ensure that the themes formed were representative and aligned with the research objectives. The final results revealed a general overview of the technological approaches used, the areas of mathematics most frequently studied, challenges in implementing CT, and the tangible contributions of CT to mathematics learning.

▪ RESULT AND DISSCUSSION

In this section, we present the results of our analysis of 41 articles that met the inclusion criteria retrieved from the Scopus database using a Systematic Literature Review framework. We will discuss the development of publication volume on CT in mathematics education during the period 2019–2024, the various technologies serving as CT learning media, and the challenges encountered during implementation. Finally, we will outline how CT contributes to enhancing students' conceptual understanding of mathematics and their critical-thinking skills, based on the findings gathered.

RQ1: What are the Emerging Trends in Author Collaboration within CT and Mathematics Learning Publications?

A collaboration network analysis was conducted to identify patterns of scientific collaboration among researchers who published scientific works related to CT in mathematics education. This network visualization was constructed using VOSviewer software based on 41 articles that met the inclusion criteria. The visualization results show that 107 authors are distributed across 31 collaboration clusters, each represented by a different color. These clusters reflect collaborative relationships based on joint involvement in one or more publications. In general, the collaborative network that has formed remains fragmented, with some large clusters showing high connection density, while others appear more isolated. For more in-depth analysis, this study focuses on the three most significant clusters. The first cluster, marked in red, consists of seven authors; the second cluster, marked in green, consists of six authors, dominated by contributions from Indonesian researchers; and the third cluster, marked in light blue, shows a more evenly distributed collaboration structure, with six authors. The visualization of the authors' collaboration network is shown in Figures 2, 3, 4, and 5 to clarify the patterns of relationships among researchers in CT research in mathematics learning.

Figure 3 focuses on Cluster 1, marked in red and consisting of 7 authors. In this cluster structure, Annette Hessen Bjerke occupies a central position with the highest number of connections, indicating her dominant role in building research collaboration in this field. The high level of connectivity among authors in this cluster indicates the presence of an active and organized research community.

Furthermore, Figure 4 depicts Cluster 2, marked in green and consisting of 6 authors. This cluster shows close collaboration, particularly in the national context in Indonesia. Among the cluster members, Neneng Aminah and Adi Nur Cahyono appear to have the widest connections, indicating their position as a center of collaboration. The high intensity of connections between authors in this cluster indicates progress in CT research collaboration at the local or national level.

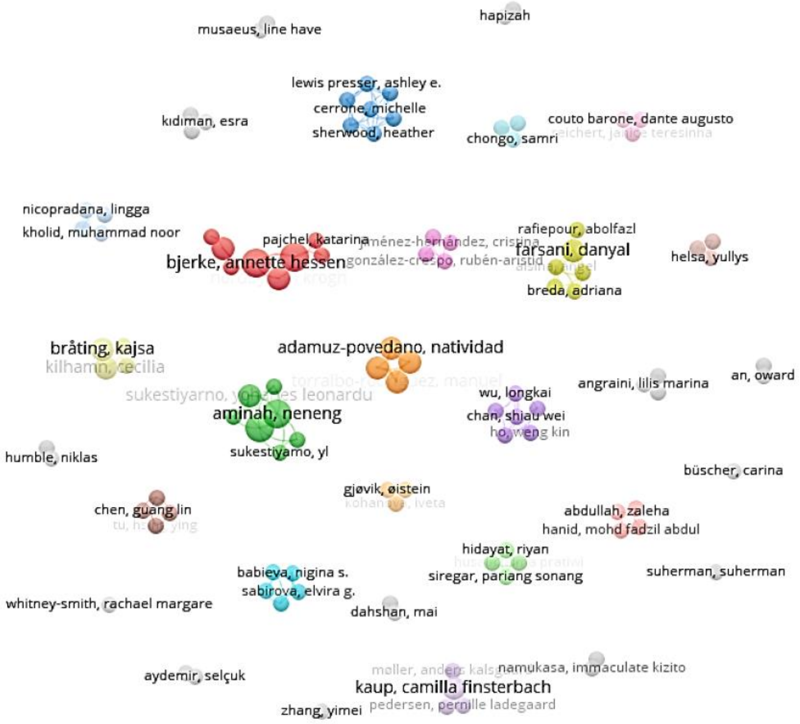


Figure 2. Collaborative network between authors on CT in mathematics learning

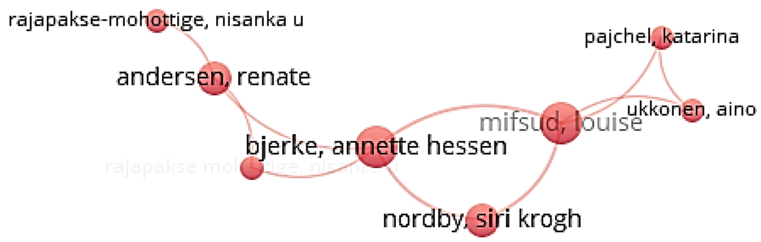


Figure 3. Collaborative network between authors on computational thinking in mathematics learning in cluster 1

Figure 4. Collaborative network between authors on computational thinking in mathematics learning in cluster 2

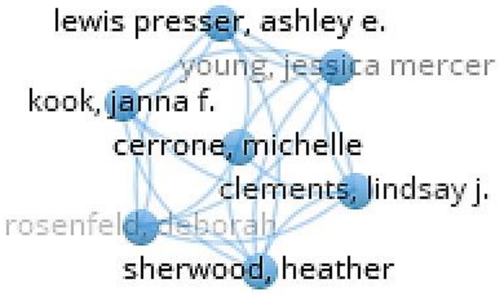


Figure 5. Collaborative network between authors on computational thinking in mathematics learning in cluster 3

Figure 5 shows Cluster 3, marked in light blue. Unlike the previous two clusters, the collaborative relationships in this cluster appear to be evenly distributed and not centered on any one individual. The six authors show balanced connections with each other, indicating a pattern of egalitarian cooperation in their publications.

In addition to these three main clusters, several authors appear as independent entities in the network, such as Suherman Suherman, Carina Büscher, and Yimei Zhang. These authors do not show any connection to any cluster, indicating individual contributions or the absence of documented scientific collaboration in the dataset. The existence of these independent authors reflects a great opportunity to expand cross-institutional and cross-national collaboration in the development of CT research in the future.

RQ2: What are the Trends and Developments in CT Related to Mathematics Learning Over the Publication Years?

This article is part of a growing research trend over the past decade that focuses on the application of CT in mathematics education. Out of 183 articles identified, only 41 met the relevance and quality criteria for further analysis. This indicates a rising interest in CT as an innovative approach, but it also highlights the need for more targeted and high-quality studies to support the development of effective learning methods. To illustrate this analysis, data on the number of identified publications that met the criteria are presented in a graph. This graph will provide a visual overview of the distribution of these articles, making it easier to identify trends and developments in research related to CT in mathematics education.

The development of research related to computational thinking in mathematics education from 2019 to 2024 is illustrated in Figure 6. In 2019, the number of studies was relatively low, with only about 1 study conducted. However, there was a significant increase in 2020, with the total rising to 3 studies. In 2021, this figure remained stable at around five studies. In 2022, the number of studies was the same as the previous year, namely five studies. A substantial surge occurred in 2023, with the number of studies sharply increasing to a peak of 16. Despite differences with the study by Irawan et al. (2024), which analyzed 276 English-language journal articles from Scopus and indicated a peak in publications in 2022, these divergent findings reflect the impact of applying stricter inclusion criteria in our study.

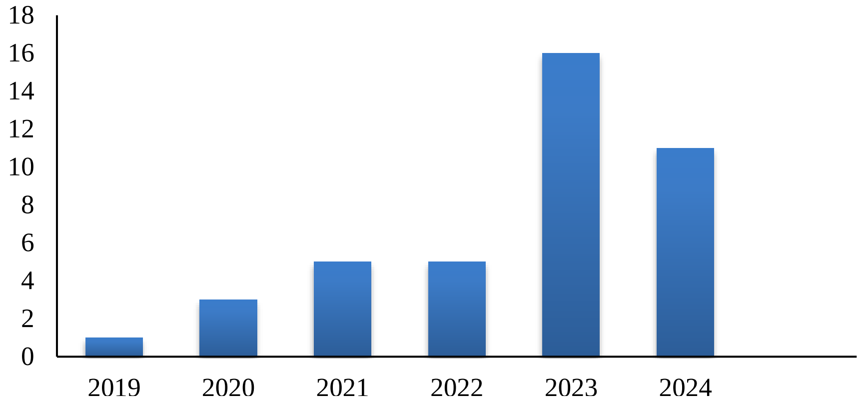


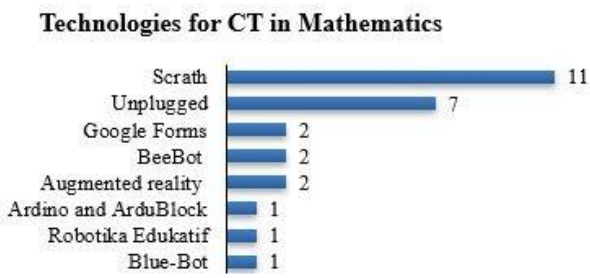
Figure 6. Progression of the number of publications on CT in mathematics learning from 2019 to 2024 (Source: Authors' elaboration)

Nevertheless, in 2024, the number decreased slightly to about 11 studies compared to the previous year. Overall, this trend reflects a growing interest in the topic of computational thinking in mathematics education over the past six years, with the highest level of research activity occurring in 2023.

RQ2: What Technologies are Used in Studies on CT in Mathematics Learning?

With the rapid advancement of information and communication technology (ICT) and the dynamics of current global needs, there is a demand to prepare individuals with skills relevant to the 21st century (Cırıt & Aydemir, 2023). In the context of education, technology is not merely a tool but has become a central element in the teaching and learning process, particularly in the field of mathematics education (Valtonen et al., 2020). The use of ICT in learning activities is considered capable of enhancing the effectiveness of learning itself (Aulia & Utami, 2021). Even the application of digital technology in mathematics education is crucial to support and enhance students' CT skills (Helsa et al., 2023).

To strengthen understanding of technology's contribution to CT development, the following section will present visual data illustrating the types of technology used and their roles within the CT research context. This visualization aims to highlight trends in technology utilization to support CT skill development while facilitating analysis of technology's strategic role in achieving learning objectives.



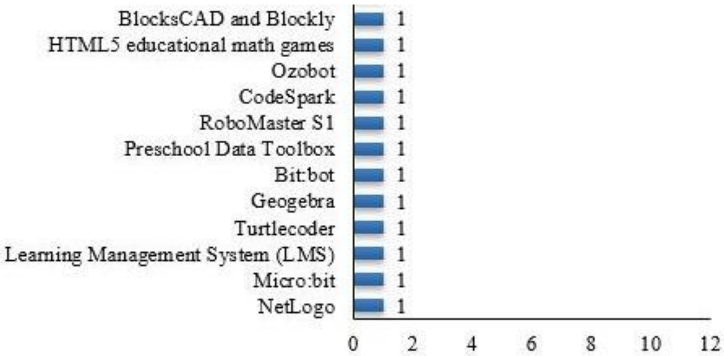


Figure 7. Technologies for CT in mathematics (source: authors' elaboration)

Based on the findings, Scratch is the most widely used technology for CT learning in mathematics, with 11 studies reporting its use. This finding aligns with the study by Barcelos, Munoz, Villarroel, Merino, & Silveira (2018), whose systematic literature review also identified Scratch as the most dominant technology used in integrating CT into mathematics. Scratch is a visual programming environment designed to help children and teenagers, particularly those aged 8 to 16, learn computer programming through personal and meaningful projects, such as creating animated stories and interactive games (Maloney, Resnick, Rusk, Silverman, & Eastmond, 2010). One of the main objectives of developing Scratch is to encourage self-directed learning through creative exploration (tinkering) and collaboration with peers. In this process, users are not only trained to think creatively, design systematically, and collaborate, but are also introduced to basic concepts in computer science while they create and share their work (Karen Brennan, Monroy Hernández, & Resnick, 2009). In line with this, various research findings indicate that consistent use of Scratch can support the development of CT skills in students (Cırıt & Aydemir, 2023; Ibrohim, Siregar, & Chaeruman, 2023; Nordby, Mifsud, & Bjerke, 2024a; Piedade & Dorotea, 2022).

Interestingly, the unplugged approach was also found in 7 studies that showed that this method is still relevant and effective for teaching CT concepts without relying on digital devices. Research by (Busuttil & Formosa, 2020) concluded that unplugged computing is an effective pedagogical strategy because it enhances active student engagement and promotes collaboration among them. Activities used in this approach are typically conducted without computers or screens, but rather through simple media such as cards, classroom or outdoor games, and mechanical toys (Zapata-Ros, 2019). These activities are interactive and engaging, while also contributing to the development of logical thinking and problem-solving skills in students (Triantafyllou, Sapounidis, & Oikonomou, 2024; Vazquez-Uscanga, Nussbaum, & Naranjo, 2025).

In addition to Scratch and unplugged approaches, several other technologies are beginning to be used in CT learning in mathematics, although with fewer findings. Google Forms, BeeBot, and Augmented Reality were each reported in 2 studies, indicating that although their use is not yet as widespread as Scratch, all three are beginning to gain attention as potential learning tools. Meanwhile, several other technologies appeared in only one study each. This suggests that the adoption of technology in CT development in mathematics remains highly varied and largely limited to specific contexts or exploratory stages in research.

RQ3: What Mathematical Topics are Investigated in Research on CT in Mathematics Learning?

In this study, various mathematical topics are used to explore the application of CT in mathematics education, with a focus on how mathematical concepts can be integrated to develop students' computational thinking skills. To provide a clearer overview of the relationship between the mathematical topics discussed, a diagram will be presented below, illustrating the application of CT within the context of mathematics.

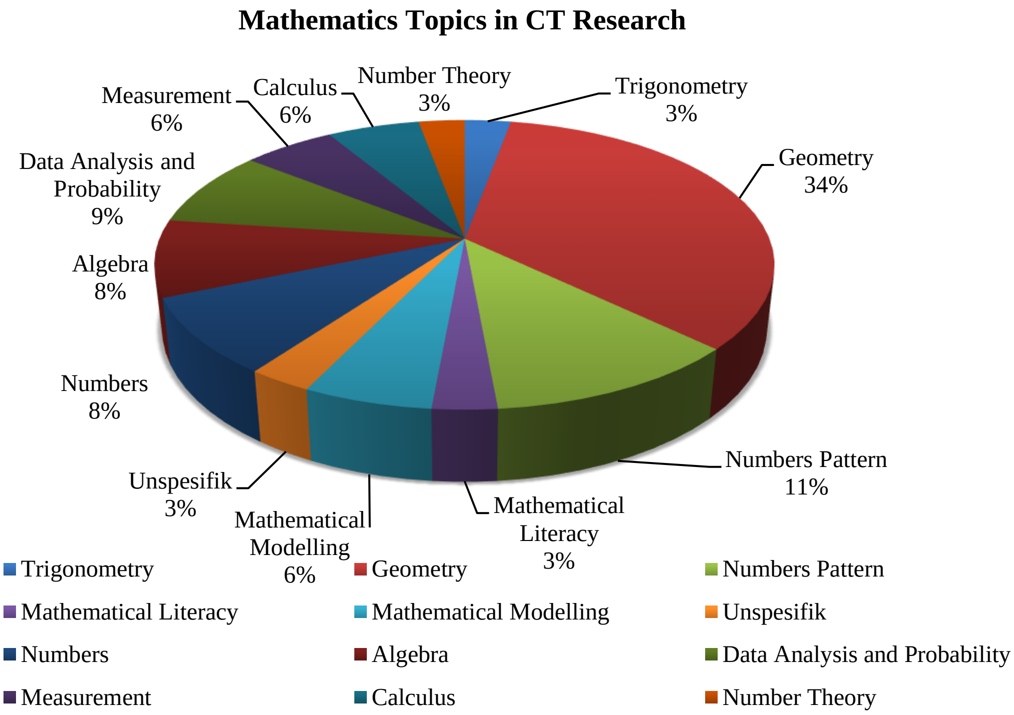


Figure 8. Mathematics topics in CT research (source: authors' elaboration)

A systematic analysis of the existing literature reveals a diverse distribution of mathematics topics integrated with CT. The distribution of mathematical topics in CT research reveals a notable imbalance. The most frequently studied topics are geometry, 12 studies. Geometry is a very important field of mathematics (Galitskaya & Drigas, 2020). According to Sung & Black (2020) CT has a relation with problem solving in Geometrical topic. Engaging with geometric problems enhances critical thinking and problem-solving abilities, key components of computational thinking (Moita & Viana, 2019). Another topic that has been widely studied is number patterns (4 studies). The high level of interest in this topic is inseparable from its strong connection to basic computational thinking skills, such as pattern recognition and abstraction. Richardo (2023) shows that students' CT skills can be effectively developed through learning sequences and series. The ability to recognize patterns is a key component in CT and mathematical reasoning, as it enables students to identify regularities and relationships in a sequence of numbers (Nurlaelah, Usdiyana, & Fadilah, 2024).

Furthermore, several other topics such as algebra, data analysis, probability, and basic numbers were found in three studies. Meanwhile, topics such as measurement, calculus, and mathematical modeling only appeared in two studies. Topics such as number theory, mathematical literacy, and trigonometry were only mentioned in one study each. This uneven distribution indicates that the application of CT in mathematics education remains concentrated in certain areas and has not yet reached the entire spectrum of mathematical content evenly. In the case of trigonometry, one reason for the limited exploration of this topic is that many educators still face conceptual and pedagogical challenges in teaching it (Fernando Tercero Vitola de la Rosa, 2023).

RQ4: What are the Challenges in Implementing CT in Mathematics Learning?

The integration of CT into mathematics learning has been a significant focus of research in recent years (Kallia et al., 2021). To better understand the challenges involved in this process, it is essential to identify the various obstacles faced by educators and educational institutions. In this study, challenges in applying CT in mathematics learning are classified into three main categories, namely: (1) barriers to the use of technology for CT, (2) lack of training and guidelines for teachers, and (3) limitations in infrastructure and facilities supporting CT. This classification provides a systematic overview of the various barriers that slow down or hinder the implementation of CT in various educational environments.

The first category relates to difficulties in using technology in CT-based learning. Teachers often encounter obstacles in integrating programming tools such as Scratch, BlocksCAD, and Bee-Bot into mathematics contexts, either due to technical complexity or incompatibility with previous teaching practices (Magreñán-Ruiz, González-Crespo, Jiménez-Hernández, & Orcos-Palma, 2024; Nordby et al., 2024a; Turgut, Kohanová, & Gjøvik, 2024). The use of tools like Scratch is also challenging for participants without prior experience, although their understanding improves once they become accustomed to it (Molina-Ayuso, Adamuz-Povedano, Bracho-López, & Torralbo-Rodríguez, 2022a). Other technical barriers arise from the students' side, such as limitations in visualization and slow device responses (Yunianto, Bautista, Prasetyo, & Lavicza, 2024), as well as difficulties in adapting tools like the preschool data toolbox to children's developmental levels (Lewis Presser et al., 2023). Chan et al. (2021) also noted that students are not accustomed to using spreadsheet tools, while institutional support for teachers remains limited. Common challenges include gaps in teacher readiness and resistance to changing methods (Magreñán-Ruiz et al., 2024).

The second category highlights the lack of training and guidelines for teachers in understanding and teaching CT effectively. Many teachers do not have a background in computer science or programming, so they need additional training, both in cognitive and technical aspects (Molina-Ayuso, Adamuz-Povedano, Bracho-López, & Torralbo-Rodríguez, 2022b). Teachers also face difficulties in designing appropriate CT assessments (Ukkonen, Pajchel, & Mifsud, 2024) and there remains a gap in understanding regarding the importance of algorithmic representation in instructional design (Sala-Sebastià, Breda, Seckel, Farsani, & Alsina, 2023). Aminah, Sukestiyarno, Wardono, & Cahyono (2022) show that prospective mathematics teachers tend to only describe the thought process without truly understanding the concept of CT in depth. Rajapakse-Mohottige, Andersen, & Bjerke (2024) note that the absence of national guidelines causes uncertainty regarding the extent to which CT should be integrated into the curriculum. Nordby et al. (2022) adds that misunderstandings of the meaning of CT associated with standard mathematical algorithms also contribute to confusion. Other barriers include a lack of concrete examples, inappropriate evaluation methods, and uneven teacher understanding (Elicer et al., 2023; Mumcu, Kıdıman, & Özdinç, 2023).

The final category is limitations in CT infrastructure and facilities, particularly in schools with limited resources. These barriers include a lack of hardware such as computers, tablets, and AR or educational robotics tools (Reichert, Couto Barone, & Kist, 2020; Soboleva, Sabirova, Babieva, Sergeeva, & Torkunova, 2021). (Aminah, Sukestiyarno, Cahyono, & Maat, 2023) notes that support for the use of Scratch and similar technologies remains insufficient, including in measuring the long-term impact of CT implementation. Logistical challenges and the need for additional training are also reported, both from the teachers' and students' perspectives, to utilize tools like Bee-Bot and micro :bit effectively (Kaup, Pedersen, & Tvedebrink, 2023).

Overall, these challenges indicate that the implementation of CT in mathematics education requires not only technical mastery but also systemic support through training, clear policy guidelines, and adequate infrastructure. Understanding these various constraints is key to designing more realistic and contextual CT implementation strategies, especially in efforts to drive 21st-century mathematics education transformation.

RQ5: What Impact does the Integration of CT have on Mathematics Learning, Particularly in Enhancing Students' Understanding and Skills?

The development of CT in education has attracted the attention of researchers, particularly in the context of mathematics learning. CT is considered capable of supporting various aspects of the learning process, not only in terms of conceptual understanding but also in developing logical and analytical thinking skills (Wing, 2008). To identify the impact of CT research in mathematics learning, we categorized them into three categories: (1) the contribution of CT to student understanding and achievement, (2) the role of digital technology in supporting CT, and (3) the relationship between CT and higher-order mathematical thinking skills.

In the first category, several studies indicate that CT contributes to enhancing students' understanding of mathematical concepts, learning outcomes, and problem-solving strategies. (Maharani, Kholid, Pradana, & Nusantara, 2019) found that integrating computational thinking into mathematics lessons increases student engagement and improves problem-solving skills. The integration of CT has been shown to enhance students' understanding and teachers' interest in using it (Chongo, Osman, & Nayan, 2020; Salwadila & Hapizah, 2024). The use of CT-based augmented reality is also effective in improving geometry understanding and learning motivation (Abdul Hanid et al., 2022). It has proven to be superior to traditional methods, especially for students with low mathematical ability (Angraini, Yolanda, & Muhammad, 2023). CT skills are positively correlated with students' mathematical academic achievement (Chongo et al., 2020), and specifically, they help students with high CT skills solve exponential problems more effectively (Salwadila & Hapizah, 2024). CT-based activities, including unplugged methods, promote students' analytical skills, creativity, collaboration, and motivation (Mumcu et al., 2023). At the early childhood level, Lewis Presser et al. (2023) show that preschoolers can already think critically and analytically through computational tools. Computational representations in the form of flat shapes, angles, rotations, and symmetries support interactive learning and strengthen students' digital literacy (Molina-Ayuso, Adamuz-Povedano, Bracho-López, & Torralbo-Rodríguez, 2024; Musaeus & Musaeus, 2024). The application of CT through Scratch significantly improves mathematical problem-solving skills (Aminah et al., 2023). CT interventions also enhance mathematical understanding (Kaup et al., 2023) and support a deeper understanding of geometric concepts (Büscher, 2024). For prospective teachers, CT has been shown to improve teaching skills and effective learning strategies (Aminah, Sukestiyamo, Wardono, & Cahyono, 2022; Dahshan & Galanti, 2024), as well as help them solve non-routine problems, such as linear Diophantine equations (Aminah, 2022). Even outside formal contexts, CT-based learning activities also help families understand mathematical and programming concepts (Møller & Kaup, 2023).

The second category discusses the role of digital technology in supporting CT and mathematics learning. The use of tools such as Scratch, BlocksCAD, Blockly, and augmented reality not only strengthens computational thinking skills but also enhances mathematical understanding in a more visual and interactive way. The use of Scratch enables the exploration of CT concepts through instructions, directional movements, and loops, and receives positive feedback from prospective teachers (Molina-Ayuso et al., 2022a). Technology-based educational games have proven effective in enhancing CT aspects such as abstraction, decomposition, generalization, and pattern recognition (Elicer et al., 2023). The integration of BlocksCAD and Blockly strengthens students' creativity, CT, and problem-solving skills (Magreñán-Ruiz et al., 2024). Tools such as Bee-Bot, Scratch Jr, and AR have also been shown to improve spatial reasoning and teachers' insights into integrating CT (Angraini et al., 2023; Nordby, Mifsud, & Bjerke, 2024b). Additionally, math-based gamification and online Scratch encourage increased creativity and CT integration in math and science education (Cırıt & Aydemir, 2023; Soboleva et al., 2021).

The third category highlights the relationship between CT and higher-order thinking skills in mathematics. Improvements in critical and computational thinking are significantly correlated with mathematical modeling abilities (Kannadass, Hidayat, Siregar, & Husain, 2023). CT also acts as a positive mediator in the relationship between problem confidence, cognitive stress, and mathematical creative thinking abilities (Suherman, 2024). Students' attitudes toward mathematics influence their CT skills and mathematical literacy (Lee, Tu, Chen, & Lin, 2023). Additionally, the connection between CT and algebraic thinking enhances a deeper understanding of mathematical concepts through programming practice (Bråting & Kilhamn, 2021).

Overall, these findings indicate that CT has a significant positive impact on mathematics learning, both cognitively, affectively, and pedagogically, and is highly relevant for application in 21st-century mathematics education.

▪ CONCLUSION

This study aims to explore trends, challenges, and the impact of CT in mathematics learning through a Systematic Literature Review (SLR) approach. A total of 183 articles were retrieved from the Scopus database, and 41 articles that met the selection criteria were analyzed in depth. The findings indicate that research on the integration of CT in mathematics education is growing rapidly, although there are still challenges related to research quality that need to be addressed. Publication trends show a significant surge, peaking in 2023, reflecting increasing interest in the application of CT in mathematics education. From the analysis of author collaboration networks, 107 authors involved in the 41 articles formed 31 collaborative clusters. These findings indicate that although there are interconnected research communities, collaboration networks remain fragmented and dispersed. Only a few large clusters show strong connections between authors, while the majority remain isolated. This indicates the need to strengthen scientific networks among researchers, both nationally and internationally, in order to build a more integrative CT research ecosystem. Technologies such as Scratch have become the dominant platform in CT integration due to their accessibility, visual nature, and support for the development of CT skills. Although alternative approaches such as unplugged activities show promising potential, their use is still relatively limited. The distribution of mathematical topics studied is also uneven. Most studies focus on geometry and number patterns, while topics such as trigonometry and number theory still receive little attention. This imbalance indicates broad research opportunities in areas that are still rarely touched upon. In addition, the implementation of CT in mathematics learning faces various challenges, such as limited digital infrastructure, low teacher readiness, and the need for ongoing professional training. Nevertheless, the positive impact of CT integration is clear, including improved conceptual understanding, problem-solving skills, and student motivation. Overall, this study emphasizes the importance of developing a more comprehensive framework for CT integration in mathematics education, improving infrastructure and policy support, and strengthening collaboration among researchers. Further research is recommended to expand the scope to less-studied mathematical topics and combine empirical and conceptual approaches to achieve a more holistic understanding. Additionally, more precise and more structured national guidelines are needed for the systematic implementation of CT in mathematics curricula across various educational levels.

▪ LIMITATION

This study has several limitations that need to be explained in detail to provide a comprehensive understanding of the scope and potential limitations of the findings. First, the literature search was conducted exclusively through the Scopus database, meaning that relevant studies from other databases such as Web of Science, Dimensions, and Google Scholar may have been overlooked. Second, only English-language articles were analyzed, potentially excluding important findings from publications in other languages. Third, the selection criteria were limited to open-access articles, so high-quality articles behind paywalls could not be included in this review. Additionally, this study focused solely on empirical articles, excluding conceptual or theoretical studies that could provide important insights, particularly regarding challenges, frameworks, or pedagogical approaches in the development of computational thinking in mathematics education.

For future research, it is recommended that the literature search be expanded to include various academic databases, cover articles in multiple languages, and consider studies with different access models. Additionally, including both empirical and non-empirical articles would result in a more comprehensive and in-depth review of the development, challenges, and trends of CT in mathematics education. Future research is also expected to examine changes in research methodology trends and the development of the focus on aspects of CT being studied, in order to obtain a more complete picture of the progress of this field, both methodologically and conceptually.

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