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Unpacking research on computational thinking in mathematics education: A systematic literature review

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Abstract

Computational Thinking (CT) is an essential 21st-century skill to prepare students for higher education and future careers. However, comprehensive insights into how CT is effectively implemented in mathematics learning regarding strategies, suitable topics, and integration trends are still limited. This systematic review explores empirical studies on CT in mathematics education from December 2019 to November 2024, sourced from Emerald, EBSCO, and ProQuest databases. Following PRISMA guidelines, 22 articles were selected from an initial 8,518 based on defined inclusion and exclusion criteria. The findings show that CT strongly supports students' problem-solving skills, particularly through Project-Based Learning (PjBL), which fosters engagement, collaboration, and algorithmic thinking. Geometry and statistics emerged as the most effective topics for developing CT, as they promote decomposition, pattern recognition, and abstraction skills aligned with junior high school cognitive development. Although CT-related research varies in focus, integrating CT into mathematics remains vital, especially with the rise of digital tools and interdisciplinary learning. This review provides insight into current research trends, key strategies, and appropriate mathematical content for CT development. Recommendations include providing CT training for teachers, embedding CT into the curriculum, and encouraging interdisciplinary collaboration to equip students with the digital-age competencies needed for real-world problem-solving and conceptual understanding.

Keywords: computational thinking; mathematics education; systematic literature review

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Introduction

Computational thinking (CT) is a person's ability to present a problem and its solution through a specific algorithm, enabling reuse by others and computers to address the same problem. It encompasses problem-solving skills essential to effectively understanding and applying computational concepts (Mukhibin et al., 2024). CT has become integral to mathematics education, equipping students with fundamental problem-solving abilities such as decomposition, abstraction, pattern recognition, and algorithmic thinking. These competencies not only strengthen their mathematical comprehension but also prepare them to tackle real-world challenges and meet the demands of the 21st-century workforce (Hamidi, 2024; Antonella, 2024; Ilham et al., 2023; Marhan et al., 2024).

Research on integrating CT into mathematics education continues to expand. Various instructional approaches, such as project-based learning, digital simulations, and programming, have been shown to effectively enhance students' CT skills (Line et al., 2024). Project-based strategies foster student engagement and deepen their comprehension of both mathematics and CT concepts (Wuwen et al., 2024). This method enables students to interact more actively with mathematical concepts in real-world contexts (Indrajeet et al., 2024). Additionally, programming-based approaches cultivate algorithmic thinking and strengthen students' understanding of the logical processes underlying CT (Dalibor et al., 2022).

Choosing appropriate mathematics content plays a crucial role in enhancing students' CT abilities. Topics such as algebra, geometry and statistics have been shown to be effective for developing these skills (Ilham et al., 2023). Algebra allows students to recognise patterns and perform mathematical modelling, while geometry involves decomposition and analysis of patterns that are suitable for developing CT (Ratih et al., 2019. In addition, materials such as number patterns and systems of linear equations of two variables are also often used to explore CT in mathematics learning because of their relevance to students' daily lives, which helps strengthen their motivation and understanding (Shivaraj et al., 2022; Marhan et al., 2024).

There is a need for clear indicators to assess the success of implementing CT in mathematics learning. Indicators such as analytical skills, problem solving and algorithm design can help evaluate students' CT objectively (Jorge et al., 2024). These indicators allow teachers to provide a more accurate assessment of students' CT development, which includes logical thinking, complex problem solving, and creativity in mathematics (Zhang et al., 2022). Assessing students using clear indicators also enables them to recognize areas for improvement, fostering a deeper understanding of both CT and mathematics. (Solomon et al., 2022).

Several countries have demonstrated measurable improvements in student learning outcomes after integrating CT into their mathematics curriculum. The United States, Singapore, and Finland are among the leading examples, having implemented CT through structured policies and curriculum reforms. In the U.S., CT has been embedded within K-12 education standards, emphasizing algorithmic thinking and real-world problem-solving. Singapore has developed a structured CT framework within its mathematics and science curricula, ensuring early exposure to computational problem-solving strategies. Meanwhile, Finland integrates CT into interdisciplinary learning, fostering creativity and critical thinking across various subjects.

The implementation of these initiatives has led to substantial improvements in students' problem-solving skills and conceptual understanding, fostering deeper engagement with mathematical reasoning and analytical thinking. (Sutama et al., 2024). The success of CT implementation in these countries highlights how well-designed learning strategies and policies can enhance students' comprehensive skill development (Ndudi et al., 2024). Consequently, this study suggests that a CT based approach, when supported by appropriate policies, can serve as a model for other countries aiming to improve the quality of mathematics education (Annie, 2023).

The integration of CT into mathematics instruction has the potential to enhance students' motivation and engagement. By linking mathematical concepts to real-world problems that necessitate CT skills, students are more inclined to develop a genuine interest and enthusiasm for learning mathematics (Lee et al., 2024). These findings align with research highlighting the importance of analytical thinking and problem-solving abilities across various industrial sectors (Anthonysamy et al., 2024). Moreover, project-based problems and programming serve as effective tools to enhance student motivation in learning. When students actively engage in solving authentic problems and designing solutions through CT, they not only gain a deeper understanding of mathematical concepts but also cultivate essential 21st-century skills, including critical thinking, creativity, and advanced problem-solving competencies (Ergin et al., 2023)

The implementation of CT in mathematics education is crucial for enhancing students' preparedness to face future workforce demands, as it enables them to adapt to rapid technological advancements while strengthening their analytical and problem-solving abilities, which are essential across various industrial sectors (Nuzzaci, 2024). However, despite the recognized benefits of CT, its integration in mathematics education still faces significant challenges. Existing studies primarily focus on general frameworks and teaching strategies without providing sufficient empirical evidence on their direct impact on students' problem-solving skills. Additionally, the lack of a standardized assessment model to objectively measure students' CT proficiency further complicates its implementation. This issue is exacerbated by the declining trend of CT-related publications in mathematics education, indicating a need for deeper exploration into effective integration strategies that ensure its long-term sustainability and relevance in addressing the challenges of the digital era.

Computational Thinking is a set of problem-solving skills that emphasize the structured development of algorithms. These algorithms provide repeatable, systematic solutions that are widely applicable without requiring constant reinterpretation. While algorithms have been developed long before the advent of computers (Sabinus et al., 2023), they are now fundamental in programming and computer science. CT has since expanded into various educational disciplines, especially mathematics, where it enhances logical reasoning, structured problem-solving, and analytical thinking (Héctor, 2022).

Papert, in *Mindstorms*, emphasized computing as a tool for knowledge construction and cognitive enhancement (Mehdi, 2023). CT in mathematics is not only about computer skills but also about understanding mathematical concepts through computational approaches (Sobhi, 2024). It enables students to apply logical reasoning and algorithmic processes-such as solving equations step-by-step or recognizing patterns in geometry—which strengthens analytical thinking in both mathematics and real-life situations (Nishant et al., 2024).

According to Antonella (2024), CT involves five core skills: algorithms, abstraction, pattern recognition, decomposition, and evaluation. These components support efficient and structured problem-solving, making CT an essential competency for 21st-century learning. Thus, integrating CT into mathematics education is critical to equip students with adaptable and future-ready thinking strategies (Zuokun, 2024).

CT has garnered increasing attention in mathematics education due to its potential to enhance students' problem-solving abilities and equip them with the necessary skills for future workforce demands. Conducting a comprehensive systematic literature review on CT in mathematics education is crucial, as it facilitates the identification of emerging research trends, key topics, theoretical frameworks, and both practical and theoretical implications that can guide the development of future studies and instructional methodologies (Sabiha et al., 2023). Despite the expanding body of research, significant challenges persist in determining the most effective strategies for integrating CT into mathematics instruction and evaluating its impact on students' problem-solving capabilities. Addressing these gaps is imperative to ensure that CT is implemented in a manner that optimally benefits students. Thus, this study seeks to provide valuable insights for educators and curriculum designers in enhancing students' CT competencies and fostering a more meaningful and applicable mathematics learning experience (Dion et al., 2024).

This systematic review examines the impact of Computational Thinking (CT) integration in mathematics education, highlighting its implications for teaching methodologies and student learning outcomes. Furthermore, the review specifically targets papers with potential for incorporating CT into mathematics content at various educational levels, alongside diverse research methods and learning strategies that can enhance CT integration into mathematics teaching. To assess the current state of the published literature on CT, the following research questions were posed:

1. What are the trends in publications related to CT research in mathematics education from December 2019 to November 2024?
2. What research methods are most frequently used in CT research in learning mathematics?
3. At which level of education is the most CT research in mathematics learning conducted?
4. What mathematics materials are used to develop CT skills?
5. What learning strategies are used to incorporate CT into mathematics education?

Methods

This study employs the Systematic Literature Review (SLR) methodology. As outlined by Santoso and Kurino (2021), SLR is a research approach used to systematically search, review, and synthesize multiple studies relevant to a specific topic. The process follows a structured sequence of steps, beginning with the formulation of the Research Question (RQ). In this study, the RQ focuses on the integration of Computational Thinking (CT) in mathematics education. The next step involves a comprehensive search for relevant literature, ensuring alignment with the research objective. This search was conducted using the Emerald, EBSCO, and ProQuest databases to identify CT-related studies in mathematics education published between December 2019 and November 2024. The final step entails establishing clear inclusion and exclusion criteria to refine the selection of studies for analysis.

In this systematic review, ProQuest was selected as the primary database because of its extensive multidisciplinary coverage and access to peer-reviewed journals, dissertations, and conference papers. ProQuest is particularly relevant for this study, as many articles discussing the integration of CT into mathematics education were found in this database during preliminary searches. To enhance the comprehensiveness and credibility of the review, additional sources were retrieved from Emerald and EBSCO. Both are widely recognized academic databases that consistently index high-quality research in education, technology, and mathematics. According to Gusenbauer (2019), these databases meet important criteria for systematic reviews, such as content quality, search precision, and relevance to academic research in emerging fields like CT.

CT is frequently associated with the capacity to address problems using logical, systematic, and algorithmic approaches. It encompasses key processes such as decomposition, abstraction, pattern recognition, and algorithm design, which serve as fundamental principles for problem-solving in both technology and education. This study aims to examine the application of CT within the context of mathematics education. Accordingly, the search process incorporated key concepts related to CT (Wing, 2006).

In order to identify relevant studies for this research, keywords such as "*Computational Thinking", "Mathematics Education"* and *"Students"* were utilized. Additionally, related terms including *"Algorithmic Thinking", "Computational Skills", "Digital Literacy"* and *"STEM Education"* were incorporated to broaden the search scope and ensure comprehensive coverage of key concepts. These terms were strategically combined using the OR operator to capture a wider range of relevant studies. The retrieved articles were evaluated using PRISMA and predefined criteria, with only those meeting the inclusion criteria analyzed further.

Inclusion/exclusion criteria

To conduct research on CT, specific criteria were defined and followed, deemed suitable for the nature of systematic research.

Inclusion:

1. Research on CT that follows a recognised scientific methodology.
2. Research on CT addresses the various learning strategies used.
3. Research on CT related to the field of mathematics education.
4. Research on CT that includes discussions that guide various mathematical materials.
5. Research on CT published or posted between December 2019 and 1 November 2024.

Exclusion

1. Research on CT that is not an article
2. Research on CT that is duplicate.
3. Research on CT other than maths education

Screening process

The search results obtained from the selected databases are presented in Figure 1. Following the screening process, 22 studies were identified, while 8.518 studies were excluded for not meeting the predefined inclusion criteria. These twenty-two studies were then examined in detail to extract specific data related to the application of CT (Kern, 2018). A systematic approach was used to determine the main themes and interpretations of the collected data.

While reviewing and analyzing the content of the selected articles, the researchers made detailed notes of significant findings. The review process was conducted iteratively, meaning that after the initial analysis, articles were reassessed to ensure their relevance in addressing the research questions. The insights obtained during the review prompted a re-evaluation of specific studies, leading to a refinement of thematic categorization and an enhancement of the findings' validity. This iterative process facilitated a more comprehensive synthesis of the literature, ensuring the precise identification of emerging patterns and key themes.

Following the identification of 8,518 articles from three databases (EBSCO, Emerald, and ProQuest), a systematic screening process was implemented in multiple stages. The initial screening applied the open-access and last-five-years criteria, resulting in the exclusion of 4,225 articles. Subsequently title and abstract screening were conducted to remove articles that did not explicitly discuss mathematics in relation to CT, reducing the number of eligible articles to 197. A further manual review was performed to assess the content's relevance to CT in mathematics education, narrowing the selection to 38 articles. At the final stage, review articles and duplicate studies were eliminated, yielding a total of 22 studies for the final analysis. This rigorous selection process ensured that only the most relevant studies aligning with the inclusion criteria were considered for review. The systematic analysis process adhered to the PRISMA stages (Moher et al., 2009), as shown in Figure 1.

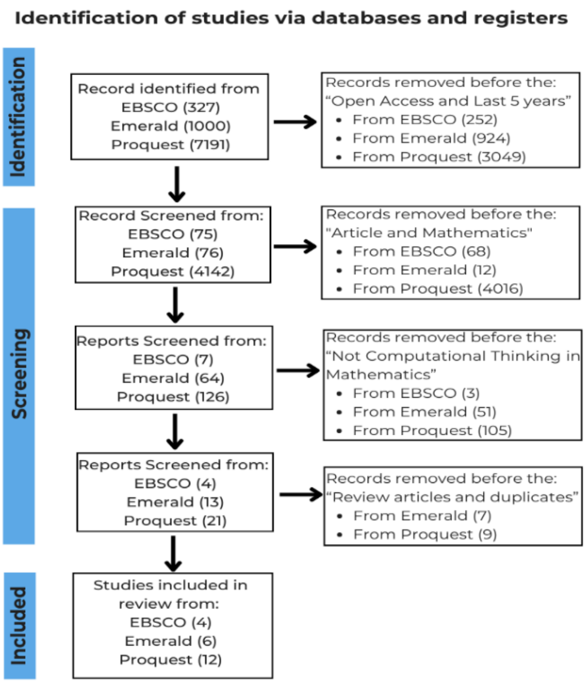

Figure 1. Data collection and screening process using Zotero

Results

The findings of this study are derived from a systematic review of research on Computational Thinking (CT) in mathematics education, utilizing sources from the Emerald, EBSCO, and ProQuest databases. The 22 selected articles are analyzed in the subsequent sections, categorized according to the research questions outlined in the methodology.

Trends in publications related to Computational Thinking (CT) research in mathematics from December 2019 – November 2024

The publication trend of research on CT in mathematics education shows fluctuations over the period from December 2019 to November 2024. In 2019, there was one publication that explored the relationship between creativity, CT, collaboration, and new media literacy in the context of technology-based learning (Tsorantinidou et al., 2019). In 2020, the number of publications increased to two articles discussing the integration of CT with mathematics and technology education, particularly in the context of programming and STEAM education (Bertrand & Namukasa, 2020; Humble et al., 2020). A sharp increase occurred in 2021 with seven publications. This surge was most likely influenced by the rapid shift to online learning during the COVID-19 pandemic, which encouraged the adoption of CT-based learning approaches in mathematics classrooms.

In 2022, publications slightly declined to six articles. This decrease reflects a shift in focus from general explorations of CT concepts to the use of specific digital tools such as Wolfram Alpha, gamification, and mathematical modeling. The year 2023 recorded only two publications, likely due to changes in educational policies that emphasized national curriculum-based learning and reduced the focus on technology integration. However, in 2024 there was a resurgence with four publications, indicating a renewed interest in algorithmic thinking and the use of interactive platforms such as GeoGebra to enhance mathematical understanding in the classroom.

Overall, the peak of CT-related publications in mathematics education occurred in 2021 as a response to the digitalization of education during the pandemic. The subsequent decline signals a transition from initial exploration to more focused and applied studies, in line with the evolution of educational policies and technological innovations. For further details, please refer to Figure 2.

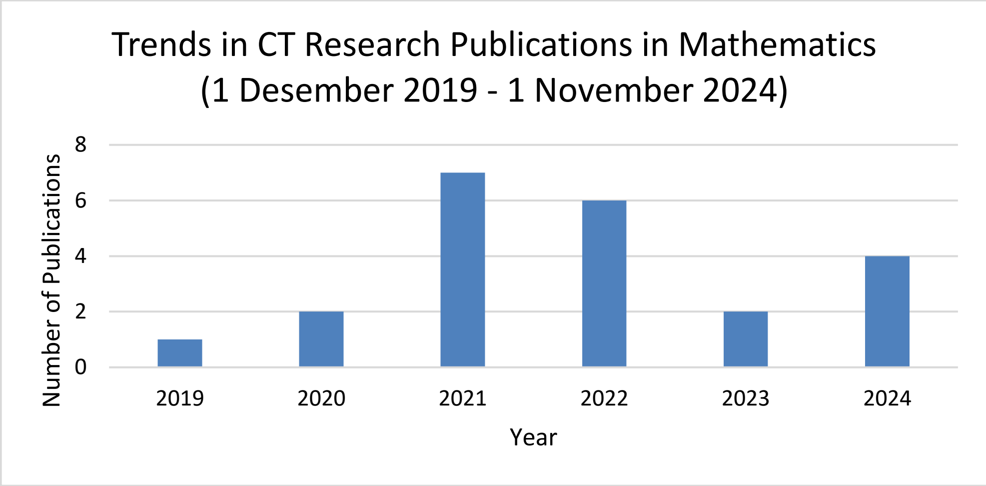

Figure 2. Trends in CT research publications in mathematics education

An analysis of the bar chart and annual publication data reveals a fluctuating trend in CT research in mathematics education over the past six years. In 2019, a single study by Tsorantinidou et al. (2019) linked moments of creativity, CT, collaboration, and new media literacy in technology-enhanced learning. In 2020, two studies explored the integration of CT into mathematics education through STEAM approaches and programming (Bertrand & Namukasa, 2020; Humble et al., 2020).

The year 2021 saw a surge with seven publications addressing various topics, such as mathematical modeling for equitable teaching, the steepest descent algorithm, the role of Wolfram Alpha, and the integration of STEM, robotics, and real-world problem-solving based on CT (Suh et al., 2021; Araya, 2021; Abramovich, 2021; Garcia-Piqueras & Ruiz-Gallardo, 2021; Seckel et al., 2021; Sezer & Namukasa, 2021; Christidou et al., 2021). In 2022, six publications emerged with a focus on algorithmic thinking, gamification in mathematics and physics, project-based learning with educational robotics, and programming as a tool to enhance mathematical understanding (Gonda et al., 2022; Abramovich, 2022; Hilario et al., 2022; Daher et al., 2022; Coufal, 2022; Humble & Mozelius, 2022).

The year 2023 saw a significant drop to just two publications, each addressing the use of BBC micro:bit in statistical reasoning and the role of CT in deepening mathematical understanding (Fojtík et al., 2023; Zunica, 2023). In 2024, four publications indicated renewed interest in the integration of technology and CT, including applications in urban schools, secondary mathematics education, debugging strategies in GeoGebra, and the relationship between CT and cognitively demanding mathematics teaching (Silver et al., 2024; Looi et al., 2024; Yunianto et al., 2024; Rich et al., 2024). In summary, although the peak occurred in 2021, the body of research from 2019 to 2024 reflects an evolving trajectory. The focus has shifted from initial explorations of CT concepts toward more specific applications within pedagogical frameworks, educational technologies, and deeper mathematical problem-solving approaches.

Research methods of computational thinking in learning mathematics

The diversity of research methods employed in this study reflects various approaches to understanding and analyzing CT in mathematics education. Three studies utilized quantitative methods, emphasizing objective measurement, hypothesis testing, and statistical analysis to assess the effectiveness of CT implementation (Araya, 2021; Gonda et al., 2022; Fojtík et al., 2023). In contrast, qualitative research dominated the field, with 12 studies employing interviews, observations, and descriptive analysis to explore experiences, perceptions, and challenges related to CT integration in mathematics education (Tsortanidou et al., 2019; Bertrand & Namukasa, 2020; Humble et al., 2020; Seckel et al., 2021; Christidou et al., 2021; Abramovich, 2022; Daher et al., 2022; Coufal, 2022; Zunica, 2023; Silver et al., 2024; Yunianto et al., 2024; Rich et al., 2024).

Additionally, seven mixed-method studies illustrate an effort to leverage the strengths of both quantitative and qualitative approaches by integrating diverse data sources to achieve a more comprehensive analysis (Suh et al., 2021; Sezer & Namukasa, 2021; Garcia-Piqueras & Ruiz-Gallardo, 2021; Hilario et al., 2022; Humble & Mozelius, 2023; Looi et al., 2024; Abramovich, 2021). The distribution of these research methods underscores the complexity of CT studies in mathematics education and highlights the necessity of examining various dimensions from a broader analytical perspective.

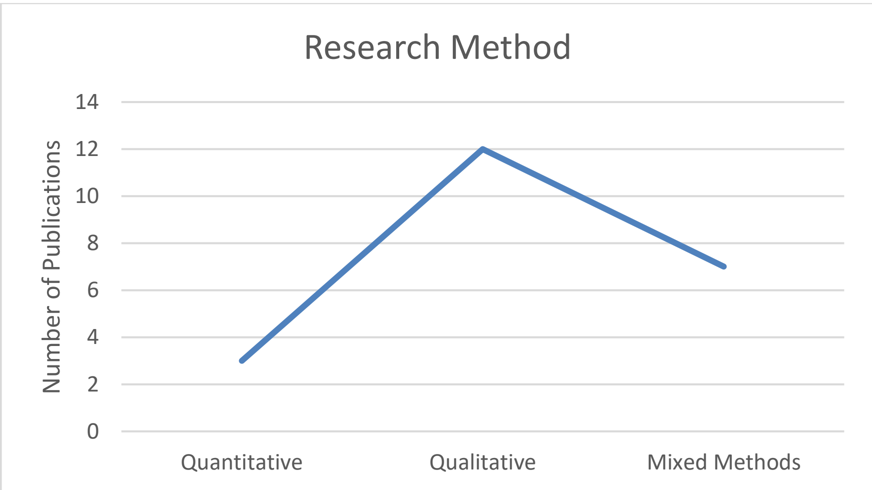

Figure 3. Data based on research method

Level of education/subject of computational thinking research in mathematics learning

Figure 4 illustrates that research on CT in mathematics education is most concentrated at the junior high school level, accounting for 37.5% (9 articles). This prevalence may be due to early adolescence being a critical stage for cognitive development, where students transition from concrete to more abstract reasoning. At this stage, CT can be effectively introduced to enhance problem-solving skills and logical thinking (Purwasih et al., 2024). Additionally, middle school curricula often integrate STEM-related subjects, aligning with educational policies that promote CT at this level (Cheng et al., 2023).

At the elementary school level, 29.2% (7 articles) emphasize the importance of establishing a strong foundation in CT. Research indicates that early exposure to CT fosters problem-solving abilities and computational fluency, essential for later learning in mathematics and science (Pramudiani et al., 2024). The relatively high research focus on elementary education reflects the growing recognition that introducing CT at a young age enhances long-term cognitive skills.

In contrast, only 12.5% (3 articles) address CT at the high school level. One possible reason for this lower proportion is that high school mathematics curricula become increasingly specialized, with CT often integrated into subjects such as computer science or physics rather than being examined as a standalone competency (Huang & Looi, 2021). At the university level, research on CT in mathematics education is even less prevalent, with only 8.3% (2 articles). This may stem from the assumption that university students are already capable of self-directed learning and problem-solving. Additionally, CT at this stage is frequently embedded within discipline-specific courses rather than being the central focus of pedagogical studies.

These trends suggest that researchers prioritize studying CT education at early and middle school levels due to its foundational role in cognitive development and its alignment with national and international STEM education initiatives. Future research should examine the long-term impact of early CT education and assess how these foundational skills contribute to advanced academic achievement and professional success.

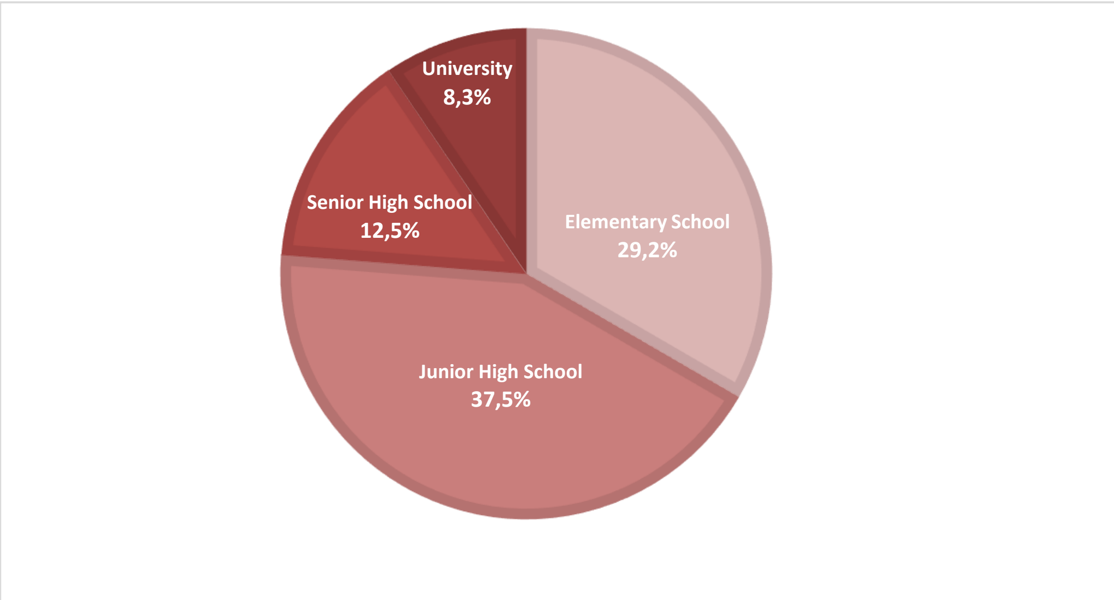

Figure 4. Data based on level of education

Maths used to develop computational thinking skills

Out of 22 articles, 19 mentioned the mathematics materials selected to assess CT ability in this study, as shown in Table 1. The remaining three articles focused on evaluating digital tools and analyzing teacher perspectives on CT integration rather than applying specific mathematics content

Table 1. Materials selected in the study of learning mathematics to look at computational thinking skills

No	Content	Research Results
1	Statistics	The findings indicate that incorporating statistical concepts into CT creates a meaningful and engaging learning experience. This integration strengthens several essential aspects, including an interdisciplinary approach, the enhancement of critical thinking skills, and increased student engagement in the learning process (Fojtík, 2023).
2	Geometry Concepts	Geometric concepts, including comparability and trigonometry, are applied in CT) research to address real-world problems. This approach not only reinforces students' understanding of geometry but also cultivates essential CT skills such as abstraction, decomposition, and automation, resulting in a more relevant and applicable learning experience (Valovičová, Ľ., 2020; Suh, J., 2021; Daher, W., 2022; Coufal, P., 2022; Humble, N., 2022)
3	Graph Theory and Combinatorics	The findings indicate that incorporating graph theory and combinatorics into CT research establishes a robust learning framework, fostering students' conceptual understanding of algorithms rather than mere procedural application. Additionally, this integration equips students with essential problem-solving and critical thinking skills, preparing them to navigate complex challenges in the technological era (Gonda, 2022)
4	Numbers	Number concepts in CT research are employed to represent real-world attributes, aiding students in grasping mathematical abstractions, enhancing their modelling abilities, and fostering STEM integration (Araya, R. 2021; Abramovich, S. 2021; Seckel, M. J., 2021; Rich, K. M., 2024).
5	Rows and Sequences	The concept of rows and sequences in CT research is used to promote deep learning through computational experimentation. By utilising properties such as the convergence ratio of the Fibonacci sequence, this research confirms the importance of technology integration to develop logical, reflective and creative thinking skills while facilitating in-depth exploration of mathematical patterns. (Abramovich, 2021)
6	Parametric Curve	The integration of parametric curves in CT research bridges mathematical theory with practical applications, such as robot navigation. Utilizing Bézier curves through GeoGebra and MATLAB enhances CT development while fostering students' motivation and comprehension of real-world mathematical applications (Hilario, L., 2022).
7	Matrix	The concept of matrices in CT research functions as a fundamental tool for analyzing and processing digital data, including image pixels and geographical coordinates. The application of matrices enhances students' CT skills by bridging mathematical logic with software development, establishing a

No	Content	Research Results
		crucial foundation for integrating mathematics and technology in education (Garcia-Piqueras, M., 2021).
8	Angle and Distance	The concepts of angle and distance in CT research serve as a bridge between mathematical understanding and real-world problem-solving skills. This approach enables students to apply abstract concepts in practical scenarios, such as designing robot trajectories or solving navigation challenges, thereby enhancing critical, algorithmic, and collaborative thinking skills. The integration of these concepts not only deepens students' mathematical comprehension but also fosters essential 21st-century competencies necessary for addressing real-world challenges (Bertrand, M. G., 2020).
9	Positive and Negative Slope	The integration of positive and negative slope concepts in this study demonstrates that applying CT through interactive technologies, such as Google Earth and coding, enhances students' ability to visualize and comprehend abstract mathematical concepts more effectively. This approach not only strengthens their understanding of slope in real-world contexts but also fosters critical and collaborative thinking skills, particularly in solving technology-based problems (Silver, P., 2024).
10	Circle	Circle concepts such as determining area by Archimedes' exhaustion method and estimating π through polygons are used in this study as ideal contexts to train CT. (Yunianto, W., 2024)
11	Mathematical Modelling	The concept of mathematical modelling in CT research is used to develop complex problem solving skills. With steps such as decomposition, abstraction and algorithmic thinking this modelling integrates mathematical thinking and CT to improve concept understanding as well as student engagement in learning. (Looi, C. K., 2024)
12	Surd Simplification	The concept of surd simplification in Computational Thinking-based research helps students understand the steps deeply and systematically. By turning the process into a structured algorithm, students develop conceptual understanding, analytical skills and sustainable problem-solving abilities and make this material effective for modern maths learning. (Zunica, B. 2023)

Learning strategies used to incorporate computational thinking into maths education

There were 22 articles that mentioned learning strategies used in CT research on mathematics learning. The following will present the articles of learning strategies used in CT research, as for the information can be seen in Table 2.

Table 2. Learning strategies used in the research Computational Thinking in Mathematics learning

No	Model/Strategy	Research Results
1	Use-Modify-Create	The findings suggest that the Use-Modify-Create learning strategy effectively cultivates various CT skills within mathematics education. This approach not only enhances students' comprehension of mathematical concepts but also equips them with practical computational skills relevant to real-world applications. By engaging students in utilizing pre-existing programs, modifying them, and ultimately generating new solutions, this strategy fosters the progressive development of CT competencies (Fojtík, M., 2023; Valovičová, Ľ., 2020).
2	Backtracking	The findings indicate that the implementation of the backtracking strategy significantly enhanced students' understanding of algorithmic steps, improved their ability to adapt algorithms to different tasks, and increased their awareness of the importance of developing their own algorithms for solving mathematical problems. This approach notably strengthened students' cognitive abilities, shifting their learning process from rote memorization to a deeper comprehension and flexible application of algorithms across various mathematical contexts (Gonda, D., 2022).
3	Project Based Learning	The findings suggest that students engaged in Project-Based Learning (PjBL) not only develop a deeper understanding of mathematical concepts but also acquire essential 21st-century skills. Tsortanidou et al (2019) observed that the Project-Based Learning model has proven effective in enhancing problem-solving skills, collaboration, interdisciplinary integration, creativity, reflection, and the professionalism of pre-service teachers. Suh (2021) and Araya (2021) observed that PjBL enhances mathematical problem-solving abilities by immersing students in real-world applications, bridging theoretical knowledge with practical implementation. Hilario et al. (2022) and Daher et al. (2022) emphasized that PjBL fosters collaboration and communication skills by encouraging teamwork and solution-oriented discussions. Additionally, Coufal (2022) and Garcia-Piqueras & Ruiz-Gallardo (2021) demonstrated that incorporating robotics and computational tools within PjBL reinforces CT) through hands-on learning experiences. Furthermore, Seckel et al. (2021) and Bertrand (2022) highlighted that PjBL cultivates creativity and critical thinking by enabling students to engage with open-ended problems and devise innovative solutions. Collectively, these findings underscore PjBL as an effective instructional approach for enhancing both mathematical proficiency and essential 21st-century competencies.
4	Problem-based Learning	The findings of this study suggest that the Problem-Based Learning (PBL) model plays a significant role in enhancing

No	Model/Strategy	Research Results
		students' CT skills in mathematics education. This approach effectively integrates problem-solving, technology utilization, and collaborative learning, all of which are essential for developing key CT competencies (Abramovich, S., 2021).
5	Model Susceptible-Infected-Recovered (SIR)	The results show that the SIR model in mathematics education can be an excellent strategy for implementing and developing students' CT skills. By connecting mathematical concepts with the real world and technology, students not only learn the mathematical theory but also how the theory can be applied in solving larger problems. (Sezer, H. B., & Namukasa, I. K. 2021)
6	Teaching modules in the context of Professional Development School (PDS)	The research results from the implementation of the strategy with teaching modules in the context of the Professional Development School (PDS) highlighted several important findings related to enhancing teachers' ability to integrate technology and CT in mathematics education. The study demonstrated that this approach successfully improved teachers' skills in using technology and CT, which, in turn, had a positive impact on student learning experiences and outcomes. (Silver, P., 2024).
7	*Video-based Learning*	The results showed that Video-based Learning not only helped students understand CT concepts, but also encouraged them to actively engage in mathematics learning, thus improving their overall CT ability. (Looi, C. K., 2024)
8	*Hypothetical Learning Trajectory* (HLT)	The findings indicate that the implementation of the Hypothetical Learning Trajectory (HLT) strategy in mathematics education significantly enhanced students' CT skills. This approach reinforced conceptual understanding, improved problem-solving abilities, and fostered active engagement in learning. Through this strategy, students developed the ability to reflect on errors, adapt to feedback, and collaborate effectively, resulting in a deeper and more sustainable learning experience (Yunianto, W., 2024).
9	Integrating Computational thinking practices into mathematics learning tasks	The results show that this strategy successfully integrates CT principles into mathematics education, improving the quality of learning tasks and the cognitive demands placed on students. However, the success of this integration requires effective teacher training and consistent implementation in the classroom. (Rich, K. M., 2024).

Discussion

Findings on the definition of Computational Thinking (CT) in mathematics education indicate a general consensus on its broad conceptual framework. Most reviewed studies define CT as a collection of essential problem-solving skills, including abstraction, decomposition, generalization, and algorithmic thinking (Nouri et al., 2020; Kallia et al., 2021; Tsai et al., 2022; Ye et al., 2023). This definition aligns with the theoretical foundation outlined in the introduction and highlights CT's contribution to enhancing students' analytical reasoning and logical thinking in mathematics.

From the publication trend analysis, there is a significant increase in research interest related to CT in mathematics education from December 2019 to November 2024. This growth reflects a global awareness of the importance of integrating CT into mathematics instruction as part of the broader movement toward 21st-century skills. The peak in publications during 2023 suggests that CT has gained momentum as a key focus area in education research, particularly in response to the rapid adoption of digital technologies in learning environments.

The research also reveals that CT has been studied across multiple educational levels, with secondary education being the most frequently targeted. This can be attributed to students at this level being developmentally ready to grasp abstract concepts and engage in problem-solving tasks. However, there is also a growing number of studies focusing on primary education, emphasizing the importance of early CT skill development to build strong foundational thinking habits.

In terms of research methodologies, the reviewed studies employed a diverse range of approaches. Quantitative methods dominate the field, often used to measure students' CT skills and academic performance through tests and statistical analysis. Qualitative studies, on the other hand, provide insights into students' thought processes, learning experiences, and teachers' instructional strategies. Mixed-method approaches offer a holistic view by combining measurable outcomes with in-depth contextual understanding, thus enriching the quality of findings.

Regarding instructional strategies, Project-Based Learning (PjBL) emerges as a consistently effective model for integrating CT into mathematics education. Studies such as those by Saad et al. (2024), Hsieh et al. (2022), Jalinus et al. (2024), and Anuar et al. (2020) demonstrate how PjBL fosters deeper student engagement, promotes collaboration, and enables students to apply mathematical concepts in real-world contexts. PjBL naturally supports CT indicators-particularly abstraction, algorithmic thinking, and problem decomposition-by allowing learners to navigate complex challenges and design their own solutions.

The review also highlights commonly addressed mathematical topics in CT-based interventions, including geometry, number systems, number patterns, and statistics. These topics are selected due to their relevance in daily life and strong potential to develop CT skills. For instance, geometry supports spatial reasoning and visualization, while number patterns train students in recognizing and formulating rules-core aspects of algorithmic thinking.

Finally, the thematic analysis of the reviewed studies reveals recurring patterns and gaps in the literature. While many studies focus on measuring CT skills and their impact on learning outcomes, fewer explore the longitudinal effects of CT-based interventions or the role of teacher professional development in sustaining these practices. Furthermore, research in non-Western contexts remains limited, indicating a need for more culturally responsive studies that consider diverse educational systems and student populations.

In conclusion, the findings from this review contribute to a clearer understanding of how CT is conceptualized, applied, and studied within the context of mathematics education. They underscore the importance of aligning instructional strategies with CT components and adapting them to students' developmental levels. The identified trends and gaps serve as a valuable guide for future research directions and policy development aimed at enhancing computationally enriched mathematics instruction.

Conclusion

Systematic research on Computational Thinking (CT) in mathematics education underscores its essential role in addressing the challenges of the digital era. The findings affirm that CT fosters students' problem-solving abilities, critical thinking, and creativity through innovative instructional approaches such as Project-Based Learning (PjBL) and Problem-Based Learning (PBL). Additionally, mathematics topics such as geometry, statistics, and number patterns have been particularly effective in cultivating CT skills, especially at the junior secondary level.

An analysis of publication trends from December 2019 to November 2024 indicates an initial increase in CT-related research, followed by a decline in recent years. This pattern suggests a shift from the broad integration of CT toward more specialized applications, particularly in the utilization of digital tools and interdisciplinary approaches. The prevalent use of mixed-methods research highlights the need for comprehensive investigations that integrate qualitative and quantitative perspectives to assess the effectiveness of CT-based learning interventions.

Despite the increasing recognition of CT in mathematics education, several challenges persist. A key limitation lies in the inconsistency of assessment models for measuring CT competencies, which hinders the comparability of research findings. Additionally, the integration of CT into mathematics curricula varies across regions, underscoring the need for standardized frameworks and pedagogical guidelines. Future research should prioritize longitudinal studies to assess the long-term impact of CT on students' mathematical proficiency and problem-solving skills. Moreover, further exploration is required to investigate how emerging technologies, such as artificial intelligence and adaptive learning systems, can be utilized to enhance CT-based instruction

From a practical standpoint, this study offers valuable insights for educators, curriculum designers, and policymakers. To optimize the benefits of CT in mathematics education, it is essential to integrate CT training into teacher professional development programs, ensuring that educators acquire the necessary skills to effectively implement CT in their classrooms. Additionally, curriculum developers should establish structured pathways for CT integration, embedding computational skills within existing mathematics curricula rather than treating CT as an independent competency. Policymakers should support initiatives that foster interdisciplinary collaboration between mathematics and computer science education, creating a holistic learning environment that equips students with the competencies required to meet the demands of the 21st-century workforce

By addressing these aspects, CT can be more effectively embedded in mathematics education, ensuring that students not only develop stronger mathematical competencies but also acquire essential skills for navigating an increasingly technology-driven world. However, this study is not without its limitations. The scope of the literature reviewed is limited to publications indexed in selected databases and confined to the period of December 2019- November 2024, which may not capture all relevant research developments. Furthermore, the variability in research methodologies and CT assessment criteria across studies poses challenges in drawing generalized conclusions. Despite these limitations, the implications of this study are significant: it highlights the urgent need for standardized CT assessment models, targeted teacher training, and integrated curriculum development. These findings can inform future research and policymaking aimed at optimizing the role of CT in mathematics education.

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Conflicts of Interest

The authors affirm that there are no conflicts of interest associated with the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, research misconduct, data fabrication, falsification, duplicate publication, submission, and redundancies, have been thoroughly addressed in accordance with academic integrity standards.

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