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Ilham Muhammad
Universitas Pendidikan Indonesia, Indonesia

Husnul Khatimah Rusyid
Universitas Pendidikan Indonesia, Indonesia

Swasti Maharani
Universitas PGRI Madiun, Indonesia

Lilis Marina Angraini
Universitas Islam Riau, Indonesia

To cite this article:

Muhammad, I., Rusyid, H.K., Maharani S., & Angraini, L.M. (2024). Computational thinking research in mathematics learning in the last decade: A bibliometric review. *International Journal of Education in Mathematics, Science, and Technology (IJEMST), 12*(1), 178-202. https://doi.org/10.46328/ijemst.3086

International Journal of Education in Mathematics, Science and Technology

2024, Vol. 12, No. 1, 178-202 https://doi.org/10.46328/ijemst.3086

Computational Thinking Research in Mathematics Learning in the Last Decade: A Bibliometric Review

Ilham Muhammad, Husnul Khatimah Rusyid, Swasti Maharani, Lilis Marina Angraini

Article Info

Article History

Received:
05 December 2022
Accepted:
10 August 2023

Keywords

Computational thinking
Mathematics learning
Bibliometric analysis
VOSviewer

Abstract

This study aims to map the landscape of the importance of previous research on computational thinking (CT) in mathematics learning over the last decade. This research is a literature review research, there are 113 publications collected from the Scopus database which are then analyzed using the bibliometric analysis method assisted by the Vosviewer application. The data taken from the Scopus database was refined so that it became 113 publications. The results of the study show that publications are spread across various continents, including America, Asia, Africa, and Europe. The United States and the United Kingdom are the most influential countries and have high cooperation with other countries in this field. The main conclusion from this study is that computational thinking has an important role in learning mathematics and STEM. The integration of computational thinking in the mathematics curriculum can improve students' understanding of mathematics and help them face the challenges of the digital age. In addition, the development of effective training methods for mathematics teachers as well as the assessment of good computational thinking learning tools and platforms can help improve the effectiveness of computational thinking teaching in mathematics contexts. These innovations will help better understand how computational thinking can be effectively integrated in mathematics learning and prepare students for a future filled with digital technologies.

Introduction

Computational Thinking (CT) is an essential ability for all students (Araujo et al., 2019; Deng et al., 2020; Li et al., 2020; Liu et al., 2021; Mohamed et al., 2019; Repenning et al., 2016; Silva et al., 2018; Tofel-grehl & Richardson, 2018; Valovičová et al., 2020; Vinayakumar et al., 2018; Voogt et al., 2015; Yang et al., 2020). According to previous studies Israel et al., (2015); Park & Green, (2019), state that the explicit ability of CT consists of two steps: abstracting the issue; and automating the answer. Furthermore, CT involves abstraction, generalization, decomposition, algorithmic cognition, and debugging (Angeli et al., 2016; Csizmadia et al., 2015; Kale et al., 2018; Lee et al., 2022). In this case, CT is defined as the development of solutions to unsolved problems through a sequence of formal steps (Anderson, 2016; Barr et al., 2011).

CT is strategically vital for resolving a variety of problems and is particularly applicable in mathematics, science, and engineering (Dagienė et al., 2017; Hinterplattner et al., 2020; Taslibeyasz et al., 2020). CT has been described as analogous to mathematical reasoning involving beliefs, problem-solving, and justification (Rich et al., 2020; Shute et al., 2017). Several studies (Mohaghegh & Mccauley, 2016; Nordby et al., 2022) revealed that mathematics activities are broadly related to CT, particularly the skill and process-focused activities. Meanwhile, others (Kallia et al., 2021; Urhan, 2022) highlight three major characteristics of CT that are covered in mathematical education: cognitive processes; problem-solving; and transposition.

CT has been a prevalent topic of study in a variety of scientific fields. Therefore, CT has gained a great deal of interest in recent years and has been the subject of several research investigations aimed at determining its benefits and viability (Roussou & Rangoussi, 2020). Similarly, within the realm of Education, over the past decade, CT has garnered increasing attention in education, spawning a large body of academic literature as well as numerous public and private implementation initiatives (Bocconi et al., 2016).

Diverse literature review techniques may be used to acquire current information (Suseelan et al., 2022). The reported evidence can be exhaustively summarized in a systematic literature review of past studies (Xiao & Watson, 2019). Following the existing research questions, researchers can manually analyze the contents of the literature using qualitative techniques (Funa & Prudente, 2021), which is including a small proportion of previous studies is a form of systematic literature review (Angraini et al., 2023; Snyder, 2019). Meanwhile, a study (Suseelan et al., 2022) revealed that in contrast to a systematic literature review, a meta-analysis quantitatively summarizes the empirical evidence available from previous studies. In this case, a meta-analysis is a statistical technique used to aggregate the findings of several research on the same subject or issue, and it may be used to settle disagreements across studies (Cho, 2020; Dettori et al., 2022; Elyassi Gorji et al., 2021; Helode et al., 2017; Jaspers et al., 2007; K. W. Lee et al., 2020; Y. H. Lee, 2018; Schober & Vetter, 2019; Selim & Mercer, 2018). However, meta-analysis has a drawback that sources of bias are not controlled by the technique, but rather rely on the design and availability of covariate data in the original research (Bocconi et al., 2016). In general, the literature considered in the meta-analysis is less varied (Aguinis et al., 2011).

Furthermore, bibliometric is a statistical method for analyzing publications (Phoong et al., 2022; W. Wang et al., 2021; Zhang et al., 2019; Zyoud et al., 2015). It was stated as well (Zyoud et al., 2022) that bibliometric is the basis for determining the most popular and most significant publications in a particular field. Furthermore, (Zhang et al., 2019) another statement revealed that bibliometric is a research method that combines science, mathematics, and statistics in a quantitative analysis of knowledge that provides extremely comprehensive information. Over the years, bibliometrics has developed and become a general tool for analyzing and mapping concepts and published knowledge in many fields (Rana & Pragati, 2022; Zupic & Čater, 2015). In addition, bibliometric analysis is not much different from a meta-analysis where most of the literature can be included in the review process (Suseelan et al., 2022). Hence, conducting a bibliometric review will be especially useful for researchers in identifying research gaps and research focus (Chen et al., 2019). Therefore, researchers seek to conduct research related to bibliometric analysis in looking at the research landscape from previous studies on CT in mathematics learning from 2011 to 2022.

Literature Review

Computational Thinking (CT)

CT is a skill that students need in the 21st century (Haseski et al., 2018). The connection between CT and the study of mathematics is crucial for future study (S. W. Chan et al., 2021). In the past, numerous empirical studies on CT have been conducted (Roussou & Rangoussi, 2020). Among them is research that was conducted (Anistyasari et al., 2019) on the factors that influence students' CT abilities to identify CT (Easterbrook, 2014; Gee et al., 2022; Lilly et al., 2022; Weintrop et al., 2021), research on seeing the learning process using CT (Caplan et al., 2021; Hickmott et al., 2018; Lai et al., 2021), and research on evaluating the CT interventions (Christensen & Lombardi, 2020).

Several previous studies have summarized related research in the past. One of those research projects discusses the publication trend in the last 10 years regarding CT research, where CT research are mostly published in Education and Instructional Technology publications (Ilic et al., 2018). In prior research, the theoretical framework and design of the literature review are favored. The most prevalent sample technique is purposive sampling, and the majority of previous CT research participants were high school students. Other related research was also conducted through a meta-analysis of 41 documents to determine the n=magnitude of the influence of CT interventions, which showed large effect sizes on the development of CT in pre-test and post-test comparisons ($g = 1.044$); in this case, programming is the most effective learning tool among different types of interventions (Merino-Armero et al., 2022). In addition, another research (Chen et al., 2018) found that CT, education, k-12, programming, and scratch are the top five keywords with high co-occurrence frequency. In this case, game-based learning, programming and programming languages, k-12 education, and computing is hot topics in CT research, and that the United States, China, and Spain are the most influential countries in the field of CT.

Several related studies were conducted in light of the pertinent literature to answer a number of specific research questions. In this study, the researcher attempted to describe research trends by employing a statistical method, namely bibliometric analysis, to deepen the researchers' understanding of CT in learning mathematics in one of the most recent decades, which will assist or provide an opportunity for future researchers to shape their research.

Purpose of the Study

The purpose of this research was to find out the description of research on CT in mathematics learning in the last decade. The research questions discussed in this study are:

1) What are the current research publication trends related to CT in mathematics learning?
2) What are the research citation trends related to CT in mathematics learning?
3) What is the distribution of journal ranking mapping from publications related to CT in mathematics learning?
4) What is the distribution of publication mapping and relations between countries in research related to CT in mathematics learning?
5) What is the research focus on CT in mathematics learning?

Methodology

Study Design

The design of this study is a bibliometric analysis. Bibliometric analysis is a method used for the statistical study of published materials, like books or articles (Phoong et al., 2022). This method allows researchers to map out the academic landscape of a specific field or topic by assessing the quantity and quality of publications, their origins, key players, and relationships among them. Using tools like Harzing's Publish or Perish programs, VosViewer, and Microsoft Excel allows for a comprehensive analysis of the academic contributions and trends in the field. In the context of this research, the analytical approach applied is descriptive qualitative analysis. The steps of this analysis include identifying and selecting relevant bibliometric data sources, collecting data such as publication title, author, year of publication, institution, etc. Next, the data is collected based on appropriate themes or categories, and the contents of scientific publications are explained in depth to identify patterns, conceptual frameworks, research methods and main findings. The results of the analysis will be interpreted in the context of the research, providing in-depth insight into the topic under study and its significance. With this approach, this research will provide a deeper understanding of academic contributions and trends in scientific literature related to the research topic.

Data Collection

The decision to commence the literature review from 2011 was driven by multiple factors. Around this year, CT emerged as a paramount educational focus, evidenced by its growing prominence as a crucial 21st-century skill (Ezeamuzie & Leung, 2022; Hsu et al., 2018), and the concurrent surge in research on its assimilation into disciplines like mathematics (S.-W. Chan et al., 2023; Lv et al., 2023). This period witnessed the publication of seminal works and the initiation of key educational drives centered on CT. Additionally, the early 2010s experienced a proliferation of digital platforms in education, underscoring the need for skills like CT. Starting from 2011 allowed a decade-long panoramic view of the research landscape, capturing the evolving interplay of CT and mathematics education, and showcasing pivotal studies that have shaped the field.

Researchers searched for data sources related to "CT in mathematics learning" using the Scopus database because of its vast interdisciplinary reach. Several phases were involved in refining the acquired data, as seen in Figure 1. These phases include identification, screening, eligibility, and eventually inclusion (Moher et al., 2009). The first phase, which is the identification of relevant articles used the search term and deleted identical or duplicate publications. The subject and scope is "computational thinking in mathematics education." The searching of "mathematics learning" was carried out by restricting the scope to the subject of mathematics since CT is a study topic inside the discipline of mathematics. This indicated that only articles containing these terms were included in the advanced search. In this case, there were 371 recognized publications and no duplicates have been discovered.

The second phase, screening, involved identifying publications in the relevant language and document type. The language that must meet the requirements of the researchers is English, since it is the worldwide language mostly used for scientific communication. Only journal papers and books were accepted for this research's required documentation. Following the screening procedure, 82 articles were discarded or removed from the data because they did not fulfil the requirements, leaving just 289 publications involved.

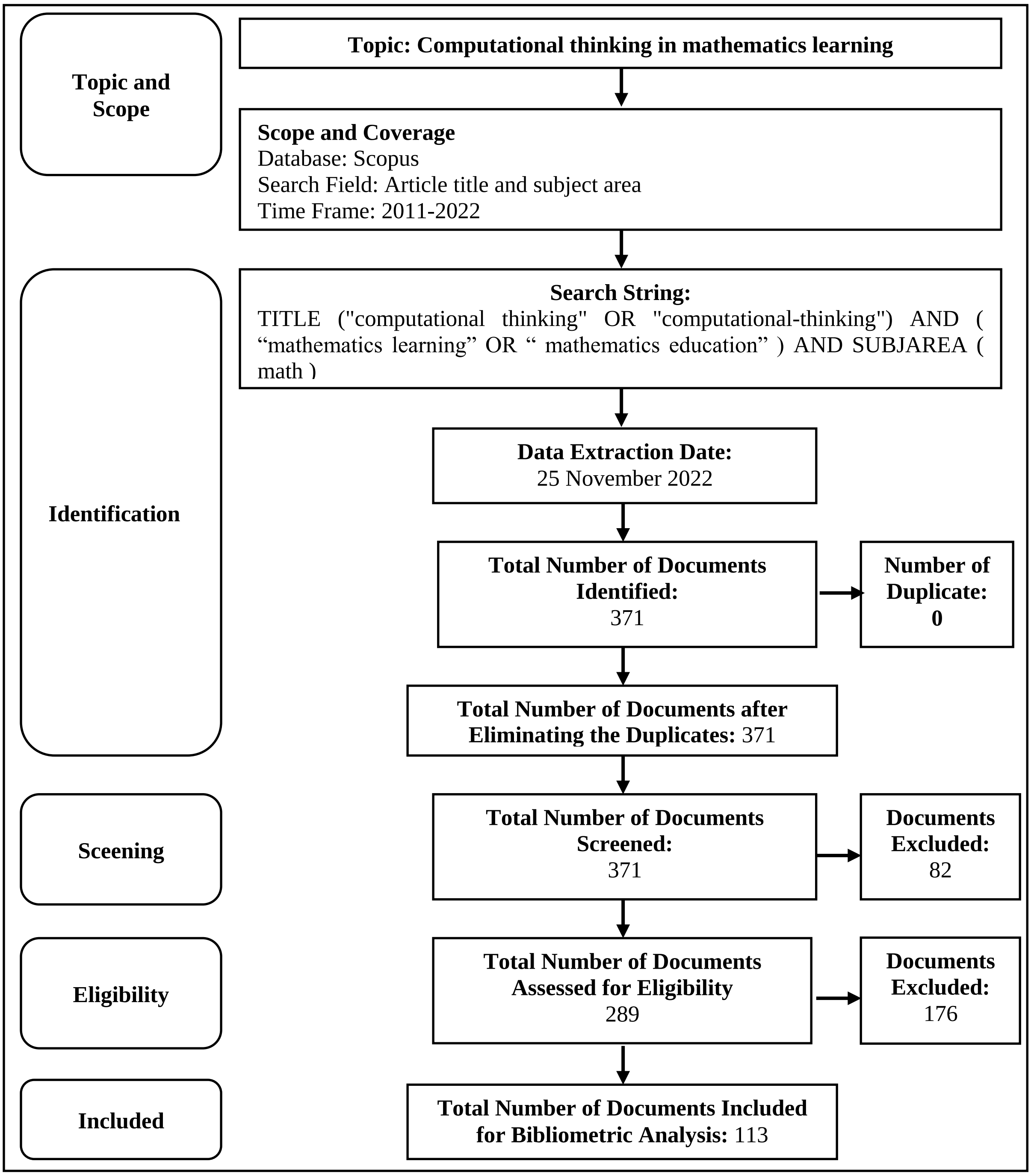

Figure 1. Data Collection Process

In the third step, 289 publications were assessed for their eligibility. Titles and abstracts were manually assessed by researchers to identify which publications met the inclusion criteria, namely research that included CT in mathematics learning. This means that only publications that met the criteria were included in the analysis related to the research discussion. At the end of this stage, 176 publications were deleted because they did not involve

CT in mathematics learning. At the end of this third phase, 113 publications remained. The purpose of this study was to look at trends and the research landscape related to CT in mathematics learning for all publications, namely 113 publications, were included to ensure the objectivity of the interpretation results. These data were retrieved on 25 November 2022 during the inclusion stage.

Data Analysis

Bibliometric and descriptive analysis of the Scopus database were applied to determine publication trends related to CT in mathematics education. The average number of publication citations was also computed using Microsoft Excel. The researcher used the program Harzing's Publish or Perish to determine the h-index and g-index of the paper.

Displaying journal ranking diagrams based on quartile data requires the usage of Microsoft Excel software by researchers. Data acquired from the Scopus database of 113 journals were further categorized according to (Q1), (Q2), (Q3), and (Q4) (Q4). This shows the articles that have been made by researchers have been published in the journal rankings above.

In addition to presenting the distribution of publications by nation using Microsoft Excel, researchers also display the distribution of publications in different countries on a globe map. As with the citation trend, researchers used Harzing's Publish or Perish Software to determine the h-index and g-index of published works. The VOSviewer program was used to generate network visualizations that illustrate the link between nations. Vent analysis with keywords related to CT in mathematics learning was carried out to determine the research focus. The data to be analyzed were taken from the Scopus database, which must be processed first. The research focus can be determined from shared keywords visualized by the VOSviewer Software.

Results

The number of publications obtained at the inclusion stage was 113 selected publications in the last decade, from 2011 to 2022. The data sources were taken from articles by 93.75%, then book chapters by 6.25% and reviews by 2.08%.

Publication Trend

Distribution of publications over the past decade as shown in Figure 2 is ranging from 2011 to 2022. The highest number of publications occurred in 2020 by 26 articles 0r 23%, while the publications in 2021 and 2022 were 19.46% respectively. A significant increase in publications occurred between 2019 and 2020. In 2019, 11 documents were published, while in 2020, the number jumped significantly to 26 documents. This means that the number of publications in 2020 has increased more than 2 times from the previous year, this shows the increasing interest or importance of CT in learning mathematics. The significant increase in the number of publications from 2019 to 2020 reflects important changes in approaches to mathematics learning. This shows that Computational

Thinking (CT) is becoming increasingly important in the world of education. There may be increasing awareness of the importance of CT, which can be used in problem solving and analysis in everyday life and an increasingly digitalized world of work. Another possibility is the implementation of CT in educational curricula, where many schools and educational institutions are starting to incorporate computing concepts into their learning. Research and development may also play a large role in this increase, with researchers increasingly interested in exploring the potential of CT in educational contexts. Other factors that may contribute are the growing impact of technology and the digital era, as well as increasing teacher and student access to resources and training that support the development of computing skills. To better understand the strength and continuation of this trend, further research and observation is needed. However, it should be noted that the lowest number of publications was one publication per year, recorded in 2011, 2012 and 2014.

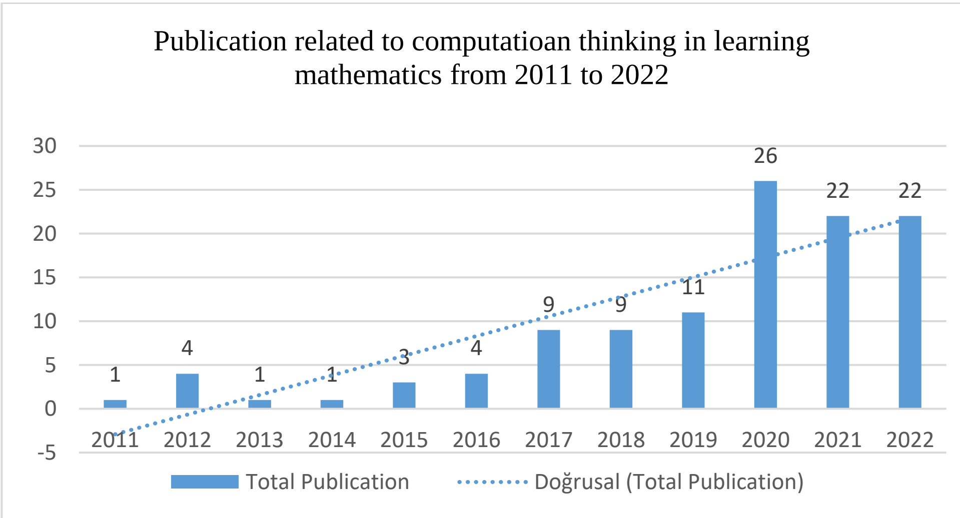

Figure 2. Publications from 2011 to 2022

Citation Trend

In this research, we looked at the trend of citations over the last decade related to CT in mathematics learning in the last decade. Table 1 below presents the number of annual quotations from 2011 to 2022 as follows.

Table 1. Citation analysis of publications

Year	TP (%)	NCP	TC	C/P	C/CP	*h*	*g*
2022	22(19.47%)	3	5	0.23	1.67	1	2
2021	22(19.47%)	8	38	4.75	1.73	4	5
2020	26(23.01%)	14	181	6.96	12.92	7	13
2019	11(9.73%)	5	14	1.27	2.8	2	3
2018	9(7.96%)	9	112	12.44	12.44	6	9
2017	9(7.96%)	9	159	17.67	17.67	6	9
2016	4(3.54%)	3	589	147.25	196.34	2	3
2015	3(2.65%)	3	31	10.34	10.34	2	3

Year	TP (%)	NCP	TC	C/P	C/CP	*h*	*g*
2014	1(0.88%)	1	2	2	2	1	1
2013	1(0.88%)	1	9	9	9	1	1
2012	4(3.54%)	4	78	19.5	19.5	3	4
2011	1(0.88%)	1	22	22	22	1	1

Notes. TP=total of publication, *NCP*=number of cited publication, *TC*=total citations, *C/P*=average citations per publication, *C/CP*=average citations per cited publication, *h*=h-index, *g*=g-index

The table shows that the number of cited paper (NCP) in 2020 is the highest (NCP = 14). The highest total citations were in 2016 with 589 citations, then followed by 2020 with 181 citations. Although the highest number of publications was in 2020, several publications in the previous year had a very large research impact, such as from 2015 which was only 31 quotes rose sharply to 589 citations.

Judging from the g-index and h-index which were calculated annually, the g-index and h-index in 2020 reached the highest with an h-index of 7 and a g-index of 13. This means that in 2020 it had the highest impact on CT in mathematics learning, where in 2020, 26 articles have been published with 181 citations and at least 14 publications have been cited for at least 13 times for each of them.

Journal Rating Mapping Distribution

Based on the Scopus database, a Quartile (Q) value is obtained from a journal. The 113 publications obtained were grouped based on the Q value as follows.

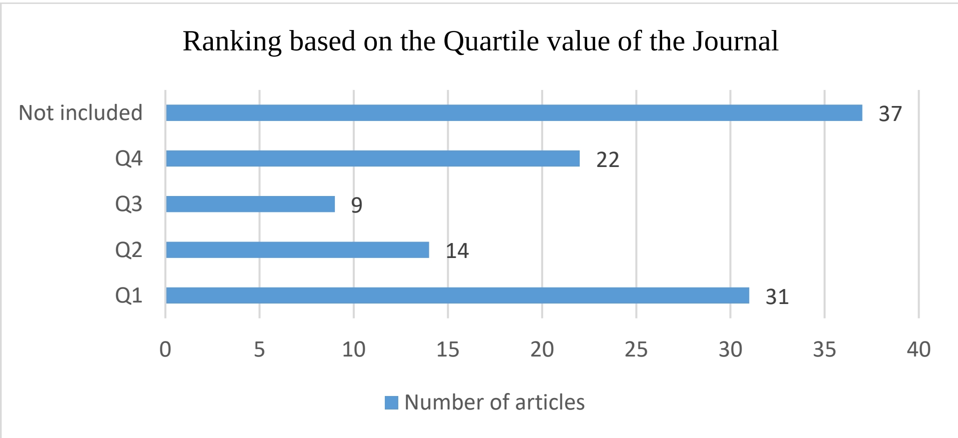

Figure 3. Ranking Based on the Quartile Value of the Journal

Based on the figure above, most articles related to CT in mathematics learning were written in journals that do not yet have a Q value in the journal ranking system, which is by 37 articles. This is because journals that have a Q value are more selective in selecting articles, making it more difficult in terms of publication. This means that the writing of articles related to this field must be further improved so that more articles can be published in journals that have a Q value. Q1 ranks second based on the number of articles, with 31 articles published in Q1 journals.

Geographical Distribution of the Publications

Countries were identified based on the country of origin of the journal. Figure 4 shows the geographic distribution of publications. Based on this figure, a total of 17 countries, were obtained. In this case, countries with more than one publication can be seen in table 2, which is nine countries.

Figure 4 shows that America and United Kingdom are the most influential countries in this field. The United States has published 25 articles, while the United Kingdom has published 20 articles. When the publications from these two countries are combined, it has more than 50 percent of the total publications.

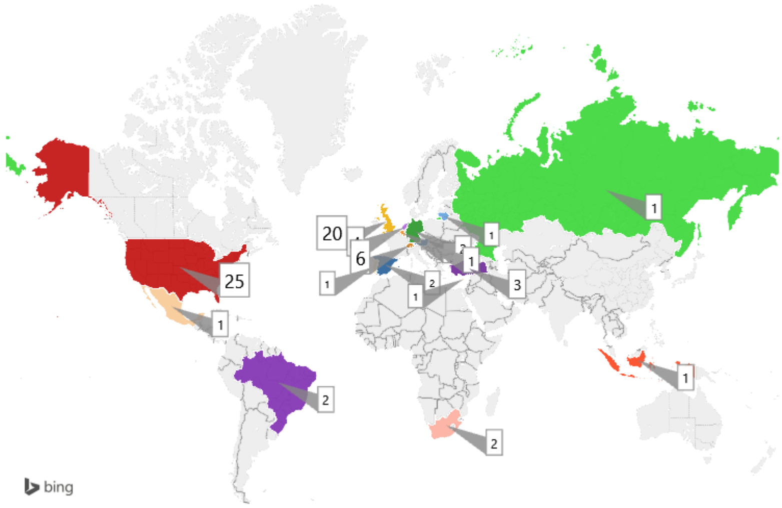

Figure 4. Geographical Distribution of Publications

The Americas, Asia, Europe, and Africa have published articles, while the Australian continent has not published any articles related to CT in mathematics learning. The Americas and Europe are the continents that publish the most articles, because countries in the Americas and Europe, namely the United States and United Kingdom, have 25 and 20 publications, respectively.

Countries with more than one publication are listed in Table 2. Based on the table, there are nine countries that have more than one publication. The United States has a number of publications of 37.88 percent of the total, with 210 citations. The Netherlands, with 6 publications, has the highest number of citations, with 631 citations. Although the number of publications is not as high as that of the United States, the Netherlands is listed as the country with most cited publications.

Furthermore, affected countries were calculated based on the g-index and h-index values. The United States is the country with the largest research impact with g-index =14; h-index = 7. The second place is occupied by the United Kingdom with g-index = 12; h-index = 12. Next is Switzerland with 1 g-index and 1 h-index. Although the number of publications in Switzerland is higher than the Netherlands, the g-index and h-index of Switzerland (g-index = 1; h-index = 1) are lower than the Netherlands (g-index = 4; h- index =3) and the NCP Switzerland (NCP=6) less than Netherlands (NCP=4).

Table 2. Countries with more than One Publications

Country	TP (%)	NCP	TC	C/P	C/CP	*h*	*g*
United States	25(37.88%)	14	210	8.4	15.0	7	14
United Kingdom	20(30.30%)	12	167	8.4	13.9	6	12
Switzerland	6(9.09%)	1	7	1.2	7.0	1	1
Netherlands	4(6.06%)	4	631	157.8	157.8	3	4
Turkey	3(4.55%)	3	24	8.0	24.0	3	3
Brazil	2(3.03%)	1	1	0.5	1.0	1	1
Germany	2(3.03%)	1	11	5.5	11.0	1	1
South Africa	2(3.03%)	1	1	0.5	1.0	1	1
Spain	2(3.03%)	1	1	0.5	1.0	1	1

Notes. TP=total of publication, *NCP*=number of cited publication, *TC*=total citations, *C/P*=average citations per publication, *C/CP*=average citations per cited publication, *h*=h-index, *g*=g-index

Global Collaboration Pattern

Among the 17 existing countries, the United States has the most relationships with other countries, as shown by the number of links emanating from the United States. The number of links emanating from the United Kingdom is comparable to that of the United States. However, not all countries are directly related to the United Kingdom, such as Switzerland, Lithuania, and Estonia. This indicates that the United States and the United Kingdom have formed cooperative relationships with several nations.

Austria, Lithuania, Switzerland only have cooperation with two other countries. Meanwhile, the Russian state is a country that has the fewest relations with other countries, with only one relationship with another country, namely the United States. Among these 17 countries, there are 6 clusters, in which the largest cluster is in the red circle. Meanwhile, the other clusters were given other colors such as blue, yellow, green, orange and purple.

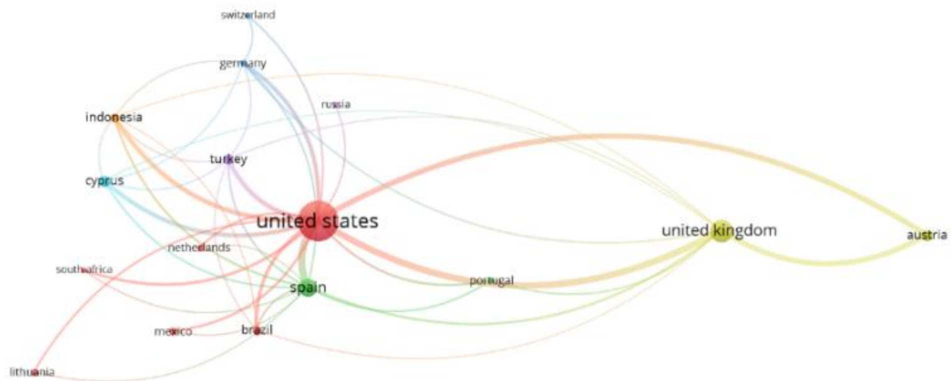

Figure 5. The Collaboration between Countries

Research Focus

The analysis of events with keywords was carried out to determine the research focus on CT in mathematics learning. Researchers set a threshold that was at least 2 publications that contain the same keywords. Based on these results, 325 keywords were reduced to 38 keywords.

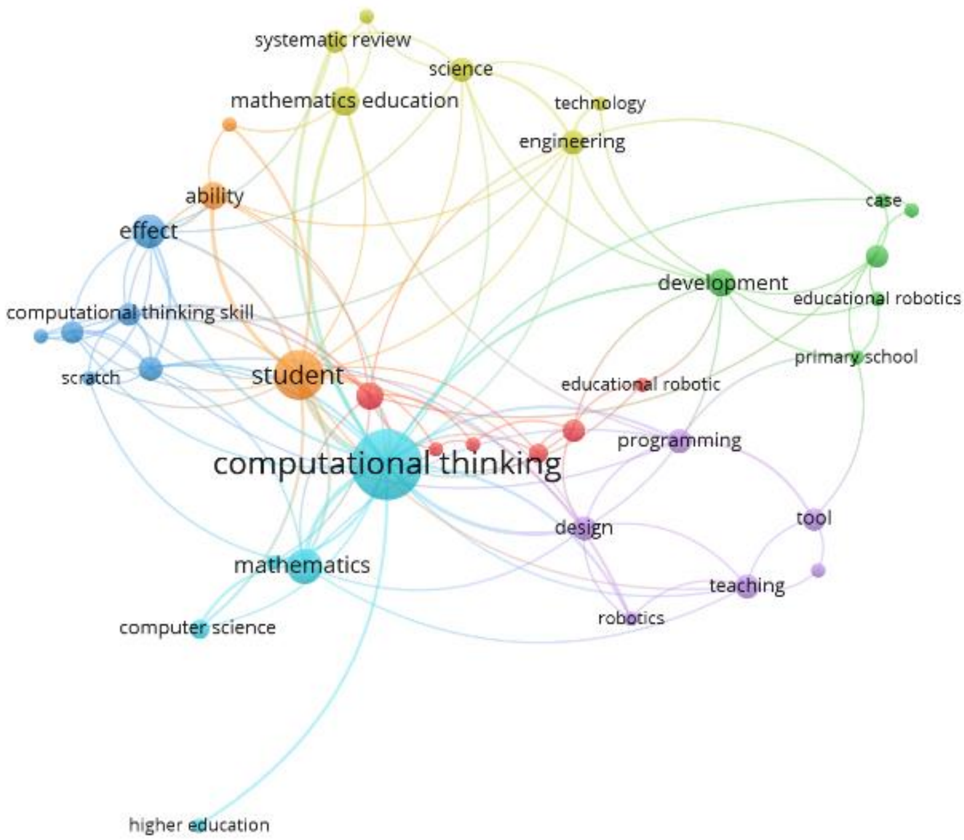

Figure 6. Keyword Co-Occurrence Network (Occurrence Threshold ≥ 2)

Figure 6's network visualization reveals that there are seven clusters containing a total of 38 elements pertaining to CT in mathematics education. The first cluster (red) is the largest cluster and consists of six items (computational, educational robotic, mathematical thinking, relationship, stem education, and study). In this case, the keywords of study, stem education, and mathematical thinking have the largest circles among the other first cluster keywords, indicating that these keywords share a research focus with CT. The second cluster (green) has seven items, with the keywords of development, case, and educational robotics having bigger circles than others, indicating that these keywords show a shared research emphasis with CT. The third cluster (dark blue) consists of 4 items, with the largest circle on the keyword effect, primary school student, indicating that the keyword reflects the focus of research along with CT. The fourth cluster (yellow) consists of 6 items with the keywords of computational literacy and mathematics education, indicating that these keywords reflect the focus of research along with CT. The fifth cluster (purple has six keywords, with programming and teaching being the majority of the cluster, indicating that these keywords represent a shared research emphasis with CT. The sixth cluster (light blue) contains 5 items, with mathematics and computer science being the largest, indicating that these keywords reflect the joint research focus with CT. Meanwhile, the last one, the seventh cluster (orange) contains 3 items, including with mathematical problem being the largest, indicating that the keyword reflects the joint research focus with CT.

Discussion

This study aimed to present the landscape of computational-related research in mathematics learning in the last decade. The following section discusses the research questions.

What is the current publication trend of research related to CT in mathematics learning?

Publication statistics connected to CT in mathematics education over the last decade indicate that the number of publications has grown from 2019 to 2020, with a peak of 26 publications in 2020. According to a statement (Roussou & Rangoussi, 2020), CT has lately gained a great deal of interest and has been the subject of several research papers aiming at demonstrating its benefits and viability.

The number of publications in 2020 totaled 26, but only 14 have been cited at least once, meaning that there are 12 publications that have not been cited at all. Nearly half of the total number of journals have never been cited. These 14 journals are as follows.

Table 3. List of Documents Published in 2020 at least one citations

No	Author	Title	Sources	Citation
1	Rodríguez-Martínez, 2020	CT and mathematics using Scratch: an experiment with sixth-grade students	Interactive Learning Environments	53
2	I. Lee, 2020	CT from a Disciplinary Perspective: Integrating CT in K-12 Science, Technology, Engineering, and Mathematics Education	Journal of Science Education and Technology	43
3	Israel, 2020	From classroom lessons to exploratory learning progressions: mathematics + CT	Interactive Learning Environments	14
4	Lavigne, 2020	An exploratory approach for investigating the integration of CT and mathematics for preschool children	Journal of Digital Learning in Teacher Education	11
5	Sung, 2020	Factors to consider when designing effective learning: Infusing CT in mathematics to support thinking-doing	Journal of Research on Technology in Education	10
6	Voskoglou, 2020	Benefits and limitations of the artificial with respect to the traditional learning of mathematics	Mathematics	7
7	Stigberg, 2020	Teaching programming and mathematics in practice: A case study from a Swedish primary school	Policy Futures in Education	6
8	Reichert,	CT in K-12: An analysis with mathematics	Eurasia Journal of	4

No	Author	Title	Sources	Citation
	2020	teachers	Mathematics, Science and Technology Education	
9	Ahmed, 2020	Didactic Methods of Integrating Programming in Mathematics in Primary School Findings from a Swedish National Project	SIGCSE 2020 - Proceedings of the 51st ACM Technical Symposium on Computer Science Education	4
10	Seidametova, 2020	Combining programming and mathematics through computer simulation problems	CEUR Workshop Proceedings	3
11	Rich, 2020	Teacher implementation profiles for integrating CT into elementary mathematics and science instruction	Education and Information Technologies	2
12	Sinkovits, 2020	Introducing Computing and Technology through Problem-Solving in Discrete Mathematics	ACM International Conference Proceeding Series	1
13	Fofang, 2020	Mutually supportive mathematics and CT in a fourth-grade classroom	Computer-Supported Collaborative Learning Conference, CSCL	1
14	Majumder, 2020	A study of common concerns inhibiting teacher enactment of CT into project-based mathematics and career technical education	CSEDU 2020 - Proceedings of the 12th International Conference on Computer Supported Education	1

The publication in 2020 that has the highest number of citations is research conducted by (Rodríguez-Martínez, 2020) regarding CT and mathematics using scratch on elementary school students with a total of 53 citations. Meanwhile, the second place is occupied by the research conducted by (I. Lee, 2020) which integrated CT with STEM in K-12 with a total of 43 citations. Among the 14 documents displayed related to CT in mathematics learning, CT is present at almost all levels of education.

What is the citation trend of research related to CT in mathematics learning?

The publication that has the highest number of citations is in 2016, as shown in table 2, with a total of 589 citations. Meanwhile, there were only three published articles in 2016. Furthermore, a previous research project was conducted (Weintrop, 2016) with the title of "Defining CT for Mathematics and Science Classrooms" has been cited 564 times, meaning that the number of citations in one article has exceeded 95% of the number of citations in that year. Article written by (Weintrop, 2016) widely cited because the article presents a response to the challenge by proposing a definition of CT for mathematics and science in the form of a taxonomy consisting of four main categories: data practice, modelling and simulation practice, computational problem-solving practice, and systems thinking practice.

Meanwhile, another article (Sung, 2017) written in 2017 it became the publication with the second most citations with 57 citations. This article has been widely cited because it contains recommendations on how to make CT processes more concrete and relevant in the context of the standard curriculum, especially mathematics. Judging from the g-index and h-index, which were calculated annually, it shows that the g-index and h-index in 2020 reached the highest with an h-index of 7 and a g-index of 13. This means that in 2020 it will have the highest impact on CT in mathematics learning, where in 2020, 26 articles have been published with 181 citations, and at least 14 publications have been cited each at least 13 times. The year of 2020 also has a publication with the third highest number of citations, namely research conducted by (Rodríguez-Martínez, 2020) discussed in the publication trends above.

What is the distribution of journal rankings from publications related to CT in learning mathematics?

The ranking of the journal that has the highest number of articles is based on the Q value from the Scopus database, where there are still many articles that have not been published in Q1-Q4, as many as 37 articles published in journals that have not been indexed by Scopus. Meanwhile, the second rank is Q1, with a total of 31 articles. The journals that entered Q1 are as follows.

Table 4. List of Journals with Q1 Ratings

Name of journal	Number of articles
Eurasia Journal of Mathematics, Science and Technology Education	3
Interactive Learning Environments	2
Journal of Science Education and Technology	2
Mathematical Thinking and Learning	2
Research in Mathematics Education	2
British Journal of Educational Technology	1
Cognitive Systems Research	1
Education and Information Technologies	1
Education Inquiry	1
Educational Technology Research and Development	1
Interdisciplinary Journal of Problem-based Learning	1
International Journal of Information and Learning Technology	1
Journal for Research in Mathematics Education	1
Journal of Chemical Education	1
Journal of Digital Learning in Teacher Education	1
Journal of Educational Computing Research	1
Journal of Engineering Education	1
Journal of Neurolinguistics	1

Name of journal	Number of articles
Journal of Research on Technology in Education	1
Journal of Special Education Technology	1
Journal on Mathematics Education	1
Learning and Instruction	1
Teacher Education and Special Education	1
Technology, Knowledge and Learning	1
ZDM - Mathematics Education	1

Eurasia Journal of Mathematics, Science and Technology Education is the entry journal (Q1) with the highest number of articles. The journal originates from Turkey with Modestum Ltd. as the publisher. Furthermore, judging from the number of articles, "Journal of Physics: Conference Series" is the journal that has the most articles, where the journal which is ranked Q4 has a total of 7 articles.

What is the geographical distribution of the publication and the collaboration pattern among countries in research related to CT in mathematics learning?

The three countries with the highest number of publications related to CT in mathematics learning are the United States, United Kingdom, and Switzerland. These three countries are spread over two continents, namely the American continent and the European continent. The country with the top order based on the number of publications is the United States, in which the total number of publications from the United States is 25% of the total in the last decade.

The connection or cooperation between nations is also controlled by the United States, where practically all countries who published studies connected to CT in mathematics learning work with the United States. The United Kingdom is the nation with the second-highest number of publications, with a total of 20 articles having been published. After the United States, the United Kingdom has the second greatest degree of cooperation. These two nations, the United States and the United Kingdom, accounted for 55% of the total number of publications.

What are the focus of the research on CT in mathematics learning?

The researcher identified a research focus related to CT in mathematics learning based on the clusters shown. The research focus was divided into seven namely, 1) CT which involves stem study and mathematical thinking; 2) CT with case and development; 3) computational effects involving primary school students; 4) CT involving computational literacy in mathematics education; 5) teaching CT with programming; 6) CT in mathematics and computer science; and 7) about math problems.

The main research focus is CT which involves stem methods in mathematical thinking. Research focusing on the integration of computational (CT) thinking into science, technology, engineering, and mathematics (STEM) education is emerging (C. Wang et al., 2021). This finding is in line with another study (Swaid, 2015) that one of the main approaches to support STEM education is embedding CT elements in STEM topics. Then, it was also stated previously (Černochová & Selcuk, 2022) that teacher students reported CT close to mathematical thinking. The second research focus is CT with cases and development. Four concepts comprise the design approach for the advancement of CT: offering challenging computational tasks in phases at all levels of the curriculum in order to improve computer technology (CT) abilities; reviewing each level of the curriculum by generating a sample of final assignments to ensure comprehensive coverage of CT knowledge; designing interesting computational tasks for target learners to foster interest-driven creators; and establishing appropriate assessment criteria for the final project and displaying the students' creations to foster the learners' creativity (Kong, 2016).

The third research focus is the effect of CT in learning in primary school students. According to a study (Xu et al., 2022), the training effect of CT cannot be properly measured, and the characteristics of students in primary school students cannot be explored further. The fourth research focus is computational literacy and mathematics education. The principles that define computational literacy are useful in analyzing and considering the possibilities, strengths, and limitations in computation-centered mathematics education, especially CT (Li et al., 2020).

The fifth research focus is programming and teaching. This is in line with what was conveyed previously (Papadakis et al., 2016) that in recent years, the teaching of programming, the development of basic concepts of programming, and CT at preschool age have attracted the interest of the educational and scientific community. Not just for preschool age, according to (Kong, 2016), in response to the growth of digital technology integration in all fields, one way to achieve the goal in response to the growth of digital technology integration in all fields is to design a curriculum in K-12 to promote CT through programming. The next research focus is CT which involves mathematics and computer science. Connecting Mathematics and Computer Science has strived to inform and inspire middle school math teachers (Allan et al., 2010). According to (Pollock et al., 2019), replacing the general education math and computer science requirements with new courses focused specifically on CT for all Bachelor of Science degrees.

The last research focus is the CT mathematical problem in CT. In research conducted previously (Cui & Ng, 2021) exploring the challenges of students experience when solving problem in mathematics on block-based programming, these challenges are analyzed according to a taxonomy that focuses on CT in mathematics. The challenges experienced by students were compounded by having to learn CT-based environments and apply mathematical concepts and problem solving in that environment. The seven research focuses above are the current research focus related to CT in mathematics learning.

There are several innovations that can be proposed for further research in the field of CT in mathematics learning. First, curriculum development that is fully integrated between CT and STEM (Science, Technology, Engineering, and Mathematics) can be the main focus. This includes developing course materials that integrate CT concepts in math, science, and engineering topics, with an evaluation of their impact on students' mathematical understanding and CT. Second, research can explore effective teacher training methods for teaching CT in the context of mathematics. The development of special training programs for mathematics teachers can help them better integrate CT concepts into their teaching. Third, evaluation of CT learning tools and platforms in the context of mathematics can provide insight into which tools are most effective. Fourth, longitudinal studies that monitor the development of students' CT from elementary school to advanced levels may provide a better understanding of how CT evolves over time. Fifth, the development of a valid and reliable assessment instrument to measure students' CT understanding and mathematical ability is an important step. Sixth, special CT programs for early childhood can help build a strong foundation in CT from an early age. Seventh, collaboration between mathematics and computer science departments at universities can enhance mathematical understanding and CT among students. Altogether, these innovations will help us better understand how CT can be effectively integrated into mathematics learning, enhance math understanding, and prepare students for the challenges of the digital age.

Conclusion

The trend of publications related to CT in mathematics learning increased in 2020. The highest number of citations was in 2016, with 589 citations. Among the 113 journals published in the last decade, 31 of them have been ranked in the Q1 journal ranking. Articles about CT seen from a geographical distribution based on a wide country have a high impact on learning mathematics. The focus of research in this field is as follows: 1) Stem education and mathematical thinking; 2) development and cases; 3) effects and primary school students; 4) computational literacy and mathematics education; 5) programming and teaching; 6) mathematics and computer science; and 7) mathematical problems. The seven research focuses are gaps and research landscapes that encourage future researchers to conduct relevant research in CT in mathematics learning. The delineation of these seven themes provides an invaluable roadmap for future researchers.

There's a clarion call for more in-depth investigations into each focus, understanding the dynamic evolution of CT within mathematical pedagogy. Furthermore, with the rapid advancements in technology and pedagogical methodologies, the integration of CT in math learning will likely evolve, necessitating continuous research updates. The trends and gaps identified in this study underscore the vast potential for groundbreaking research, driving innovation in both CT and mathematics education.

There are several innovations that can be proposed for further research in the field of CT in mathematics learning. First, curriculum development that is fully integrated between CT and STEM (Science, Technology, Engineering, and Mathematics) can be the main focus. This includes developing course materials that integrate CT concepts in math, science, and engineering topics, with an evaluation of their impact on students' mathematical understanding and CT. Second, research can explore effective teacher training methods for teaching CT in the context of mathematics. The development of special training programs for mathematics teachers can help them better integrate CT concepts into their teaching. Third, evaluation of CT learning tools and platforms in the context of mathematics can provide insight into which tools are most effective. Fourth, longitudinal studies that monitor the development of students' CT from elementary school to advanced levels may provide a better understanding of how CT evolves over time. Fifth, the development of a valid and reliable assessment instrument to measure students' CT understanding and mathematical ability is an important step. Sixth, special CT programs for early childhood can help build a strong foundation in CT from an early age. Seventh, collaboration between mathematics and computer science departments at universities can enhance mathematical understanding and CT among students. Altogether, these innovations will help us better understand how CT can be effectively integrated into mathematics learning, enhance math understanding, and prepare students for the challenges of the digital age. These innovations will help fill existing research gaps and drive further developments in the integration of CT in mathematics education. Future endeavors in this field should prioritize bridging these gaps and aligning with the evolving educational paradigms.

Limitations and Suggestions for Future Studies

The limitations of this research are as follows: 1) the data analyzed comes from the Scopus database, so there are many other databases that can be used, such as WoS and others; 2) this research only discusses CT in mathematics learning, so many other fields of education can be investigated further; and 3) the data in this study taken on November 25 cannot reflect research conducted after that date, so there may be slight differences.

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Author Information

Ilham Muhammad
https://orcid.org/0000-0002-6124-774X
Universitas Pendidikan Indonesia
Indonesia

Husnul Khatimah Rusyid
https://orcid.org/0000-0002-8667-4000
Universitas Pendidikan Indonesia
Indonesia

Swasti Maharani
https://orcid.org/0000-0002-5792-2933
Universitas PGRI Madiun
Indonesia

Lilis Marina Angraini
https://orcid.org/0000-0003-1328-5466
(Corresponding Author)
Universitas Islam Riau
Indonesia
Contact e-mail: *lilismarina@edu.uir.ac.id*