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Research trends of computational thinking in mathematics learning: A bibliometric analysis from 2009 to 2023

Edi Irawan [1], Rizky Rosjanuardi [1,2], Sufyani Prabawanto [1,2*]

[1] Faculty of Mathematics and Science Education, Universitas Pendidikan Indonesia, Bandung, West Java, INDONESIA
[2] Indonesian DDR Development Center, Bandung, West Java, INDONESIA

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Abstract

This study presents a comprehensive overview of computational thinking (CT) research trends in mathematics learning from 2009 to 2023. To reach this aim, a bibliometric approach was used in this study to analyze the publication distribution pattern on CT focused on the following categories: research development, the most productive journals and countries, highly cited references, topic network, and thematic evolution map. A total of 276 articles retrieved from the Scopus database were analyzed and visualized through the Bibliometrix analysis package from R and VOSviewer software. The finding shows that since 2009, CT has been the subject of mathematics learning research, which has grown significantly since 2013. Regarding total publication in CT, Education and Information Technologies contributes as the most productive journal, and the United States places first among all countries. The article 'computational thinking' appears as the most widely referenced source. Moreover, the frequent topics network with CT are the integration of CT with programming, STEM, and coding. This result is analyzed further by the thematic evolution map showing CT research in STEM education, including mathematics, exhibits promising prospects for future development.

Keywords: computational thinking, bibliometric analysis, mathematics learning

INTRODUCTION

In recent decades, a major transformation has occurred in mathematics education, primarily encouraged by the growing integration of information and communication technology (ICT) into our daily activities. Subsequently, not only does the learning of mathematics need to help students construct mathematical concepts, but it also accommodates them with the necessary ability to apply the concepts with ICT. One of the abilities students require is computational thinking (CT), which has become a fundamental aspect of learning mathematics nowadays (Li et al., 2020; Weintrop et al., 2015). CT is a cognitive process involved in formulating problems and expressing their solutions in a way that computers, humans, or machines can effectively carry out (Wing, 2017). According to Dong et al. (2019), CT involves solving problems through PRADA's five phases: *pattern recognition, abstraction, decomposition,* and *algorithm*. Integrating CT into mathematics learning has emerged as a transformative approach, promising to enhance students' understanding of mathematical concepts while simultaneously fostering their problem-solving abilities (Khoo et al., 2022; Ramaila & Shilenge, 2023). At its core, the integration of CT into mathematics learning empowers students by harnessing the power of programming-like steps, equipping them with invaluable tools for solving complex problems (Subramaniam et al., 2022).

Although the importance of CT has been widely discussed in literature, recent studies have reported some educational issues concerning to the development of CT in mathematics learning. In higher education, prospective mathematics teacher candidates encounter challenges applying CT to solve Diophantine linear equation problems (Aminah et al., 2022). The integration of CT into the curriculum poses risks of causing obstacles in learning (Kite et al., 2021). Furthermore, many educators face difficulties associating CT with

✉ nawariide@upi.edu ✉ rizky@upi.edu ✉ sufyani@upi.edu **(*Correspondence)**

Contribution to the literature

- This article provides an alternative approach to visualizing and presenting research trends of CT in mathematics learning using bibliometric analysis.
- The result of this study contributes to a better understanding of recent publication distribution related to CT in mathematics learning from diverse aspects such as productive journals, authors, countries, topic networks, and thematic evolutions.
- A growing number of studies on CT and the integration of CT in the STEM field, including mathematics, bring possible further research and international collaboration in this area.

their curriculum and instructional practices in their fields (Ciftci & Topcu, 2023). Educators' challenges in integrating CT into their classrooms stem from a dearth of skills, time, and professional development (Bati & Ikbal Yetisir, 2021). Therefore, as a newly emerging research field, the dynamics surrounding the integration of CT in mathematics education will continue to evolve.

A growing number of studies investigated the implementation of CT in mathematics learning. Previous studies reported their findings on potential ways of integrating CT in mathematics learning, namely through the utilization of block-based programming languages (such as Scratch) (Rodríguez-Martínez et al., 2020; Tan et al., 2021), digital tools and algorithms (Abramovich, 2023), educational computer games (Soboleva et al., 2021), problem-solving modules rooted in CT (Subramaniam et al., 2023), and even through unplugged methods (Mumcu et al., 2023). As an emerging field, studies on CT are anticipated to escalate further, employing more varied approaches, methods, and topics (Chen et al., 2023). Efforts to integrate CT into mathematics learning are intrinsically tied to the close interrelation between CT and mathematics (Irawan & Herman, 2023). Integrating CT into mathematics education has at least three benefits: fostering a mutually beneficial relationship between mathematics and CT, addressing practical problems for all students while enhancing teachers' skills, and aligning mathematical education more closely with current professional practices (Weintrop et al., 2015). Therefore, exploring the progression of themes while synthesizing the outcomes of various studies regarding the integration of CT in mathematics education holds the promise of significant results.

Nevertheless, few studies were carried out to explore the research development on CT. In this study, we attempt to present, visualize, and analyze previous CT studies by using a methodological approach named Bibliometric analysis. Bibliometric studies have been prominent in literature, owing to the state of the art's contribution to many research interests (Cancino et al., 2017). This study extensively examines publications sourced from prominent academic databases, including Scopus, Web of Science, and others. Its primary objective is to elucidate the current intellectual structure and emerging trends within specific research topics or fields (Donthu et al., 2021). Bibliometric also allows the analysis of the most prolific authors, the evolution of research themes, and the identification of author collaborations. Moreover, several bibliometric studies have been conducted to investigate the evolution of CT research in general (Chen et al., 2023; Ilic et al., 2018; Roig-Vila & Moreno-Isac, 2020; Tekdal, 2021). In the meantime, bibliometric studies concerning the integration of CT in mathematics education have yet to be extensively explored. Existing studies on the integration of CT in mathematics education tend to analyze the empirical impact of integration (Broza et al., 2023; Fang et al., 2023; Lewis Presser et al., 2023) and conduct systematic literature reviews (Su & Yang, 2023). In order to address this knowledge gap, a comprehensive bibliometric analysis of this field is required.

Considering the discussion above, this study aims to analyze, present, and visualize the research trends of CT in mathematics learning using a Bibliometric analysis. Based on this aim, six questions are addressed in this study, as follows.

1. What are the trends and developments in CT in mathematics learning according to the publication years?
2. What are the most productive journals publishing literature on CT in mathematics learning?
3. Who are the most prolific authors who have published articles related to CT in mathematics learning, and how is the collaborative network among these authors?
4. What are the most prolific countries that have emphasized studies on CT in mathematics learning?
5. What are the most references cited by others related to CT in mathematics learning?
6. What are the most occurring keywords/topics appearing on CT research in mathematics learning, and how do these keywords/topics form a networking map?
7. How is the thematic evolution of research of CT in mathematics learning from year to year?

Through a comprehensive analysis, this research aims to contribute to the development and implementation of CT in the context of mathematics learning and stimulate further research to advance this field.

THEORETICAL FRAMEWORK

Computational Thinking in Mathematics Learning

CT has become prevalent among researchers as an indispensable ability to acquire in the present day. The term *computational thinking* is first introduced by Papert (1980, 1996), emphasizing its main concept with *the way of thinking* as a computer scientist (Wing, 2017). CT is a cognitive process that breaks down complex problems into simpler ones for ease of resolution (decomposition), employs a set of rules to discover solutions (algorithms), and utilizes abstraction to generalize these solutions to similar problems (Yadav et al., 2017). Nonetheless, CT was taken less attention by academic enthusiasm to be nurtured by students, until an article entitled 'computational thinking' published by Wing (2006) in which CT began to gain significant popularity (Chen et al., 2023; Haseski et al., 2018). As an ability that individuals need to acquire in this modern society, CT has grown into a widely expanding area of educational research that is projected to keep on growing (Palts & Pedaste, 2020).

As a novel idea, CT has undergone development in terms of its definition. CT definitions vary among researchers' perspectives (Cansu & Cansu, 2019). 59 CT-related definitions have been identified in the literature (Haseski et al., 2018). Papert (1980) defined CT as an ability that forms the core practice of software engineering developed by students while working in programming. This definition was refined by Wing (2006), who stated that CT is an ability that encompasses problem-solving, system design, and comprehension of human behavior through fundamental computer science concepts. Later, the definition of CT is broadened to include formulating problems and expressing solutions so that humans or machines can effectively carry them out (Wing, 2017). Hence, the present notion of CT exhibits an ability to solve complex problems systematically and effectively, with or without the assistance of computers.

One practical and widely used categorization of CT components is pattern recognition, abstraction, decomposition, and algorithm (PRADA) (Dong et al., 2019). These four components are key elements employed in the development of CT. Pattern recognition involves observing patterns, trends, and regularities within data, processes, or problems. Abstraction is the process of making artifacts more comprehensible by reducing unnecessary details. Decomposition is a way of thinking about artifacts based on their parts, making them separately understandable, solvable, expandable, and evaluable. The algorithm entails the development of step-by-step instructions to solve a problem (Csizmadia et al., 2015; Dong et al., 2019; Zeng et al., 2023). However, there is no fixed order for utilizing these four components (Dong et al., 2019). Hence, the sequence of employing the four CT components can be tailored to the subject matter's and learners' characteristics.

A number of studies revealed that CT has a strong relationship with mathematics (Aho, 2012; Barcelos et al., 2018; Gadanidis et al., 2017; Weintrop et al., 2015). Shute et al. (2017) state that CT shares similarities with mathematical thinking while retaining its distinct characteristics. The primary similarity between CT and mathematical thinking lies in problem-solving, including modelling, analyzing, and interpreting (Sneider et al., 2014; Wing, 2008). Integrating CT into mathematics education has the potential to mitigate disparities in CT learning (Wang et al., 2022; Weintrop et al., 2015). Moreover, Israel and Lash's (2020) study reported three types of integration between mathematics and CT within classroom learning activities: no integration, partial integration, and full integration. Some studies have been conducted with full integration, namely teaching mathematics through CT activities, while others have been done partially, with a primary emphasis on mathematical content (Nordby et al., 2022). Considering the important of CT and prior studies concerning the implementation of CT in mathematics learning, therefore, there are opportunities to explore more about the integration of CT and mathematics learning in further research.

METHOD

To collect all the publications on CT in mathematics learning, the data was extracted from the Scopus database (https://www.scopus.com) on 16 May 2023, with the central theme 'computational thinking'. According to Phuong et al. (2023), the Scopus database is the most comprehensive and widely used academic database. For this study, the Scopus database was considered for five reasons: it provides relevant and reliable information, has broader coverage, includes all cited authors in the references, permits direct data download, and can be processed by various bibliometric analysis software (Gao et al., 2022).

The query string used for the database search was: (TITLE-ABS-KEY ("computational thinking") AND TITLE-ABS-KEY (mathematics OR mathematical) AND TITLE-ABS-KEY (education OR teaching OR learning OR study OR learn OR didactic OR didactical)) AND PUBYEAR > 2009 AND PUBYEAR < 2023 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")). **Figure 1** depicts the query string and the result of the data collection using the Scopus database.

In **Figure 1**, the application of the query string (TITLE-ABS-KEY) helps the search engine obtain publications relevant to the proposed theme by defining

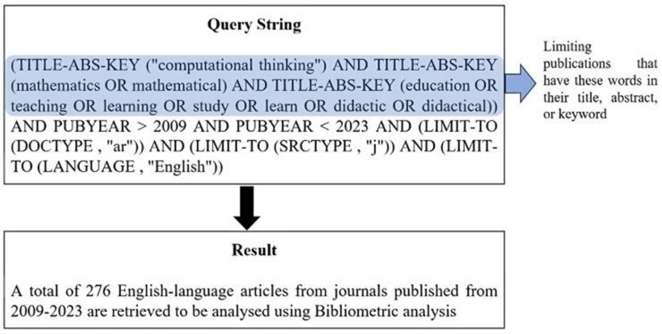

Figure 1. Diagram of querying string & result of collected data from the Scopus database (Source: Authors' own elaboration)

the tittle (TITLE), abstract (ABS), or keywords (KEY). The search string was also limited to the year 2009-2023. Only journal articles were included in the data among the document and script types available because we intend to see the impact of top journals. We also excluded articles written other than English. After filtering all publications according to the aim of this study, there were 276 articles retrieved from the database.

In this study, bibliometric analysis and bibliometric visualization techniques were employed. Bibliometric analysis provides an approach to understanding the sheer volume of research and its capacity to reveal the intellectual structure and emerging trends in a specific topic or research field (Donthu et al., 2021; Tekdal, 2021). Technically, this study follows the four steps of bibliometric analysis outlined by Donthu et al. (2021), which include determining the objectives and scope of the bibliometric study, selecting bibliometric analysis techniques, collecting data for bibliometric analysis, executing bibliometric analysis, and presenting the results. In this study, bibliometric analysis was used to manage, analyze, and visualize the development of research trends concerning CT in mathematics learning.

The data analysis was conducted using Bibliometrix software version 4.1.2 and VOSviewer version 1.6.18. Bibliometrix is a comprehensive R package for bibliometric analysis (Aria & Cuccurullo, 2017). Bibliometrix was used to obtain information about the development of related literature, productive authors, relevant journals, most frequently cited references, highly cited articles, author productivity by country, author collaboration networks between countries, thematic maps, and research theme evolution. On the other hand, VOSviewer is a software developed for bibliometric analysis that provides excellent visualization of networks, overlays, and data density (van Eck & Waltman, 2010). This study used VOSviewer to create collaboration networks among researchers, author citation networks, and keyword networks based on author associations.

Table 1. Main information of data collected

Description	Results
Timespan	2009-2023
Sources	136
Documents	276
Annual growth rate	28.09%
Document average age	2.73
Average citations per document	19.88
Author's keywords	819
Authors	804
Authors of single-authored documents	36
International co-authorships	15.22%
Co-authors per document	3.24
Corresponding author's countries	41
References	14,145

RESULTS

As mentioned, using the bibliometric analysis approach, the study sought to manage, analyze, and visualize the research trend developments of CT in mathematics learning. This aim is addressed into seven categories: publication trends and development, the most productive journals, the most prolific authors and networking among authors, the most prolific countries, the most cited references, the most occurring keywords and co-occurrences of keywords, and thematic evolution. Specifically, networking authors and keywords co-occurrence were analyzed and visualized with VOSviewer, whereas the rest of the categories were processed using Bibliometrix. The following sections will present the findings of this study.

Publication Trends & Development

The search results in the Scopus database yielded 276 journal articles on CT in mathematics learning. Through the data analysis using Bibliometrix software, comprehensive information on the article publication distribution was obtained, including published articles timespan, documents, sources, document average age, annual growth rate, average citations per document, authors, author's keywords, international co-authorships, co-authors per document, authors of single-authored documents, and references, as presented in **Table 1**.

Table 1 indicates that, from 2009 to 2023, documents pertaining to CT in mathematics learning have increased annually by 28.09%, with a total of 276 published articles from 136 different journals. Each article is cited about 19.88 on average. A cumulative count of 804 authors from 41 different countries have made contributions to the advancement of this field of study, distributing 819 keywords and 14,145 references used by the authors. **Figure 2** presents a bar chart to illustrate the progression of the number of publications of CT in mathematics learning from 2009 to 2013 at 15-year intervals. The bar

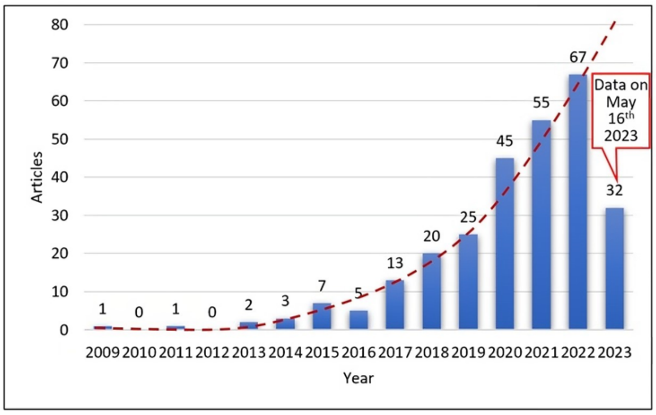

Figure 2. Progression of number of publications on CT in mathematics learning from 2009 to 2023 (Source: Authors' own elaboration)

shows the publication's annual rise, and the dashed line deals with the total number of the publication.

As depicted in **Figure 2**, the publication output for the first four years of the selected period (2009-2012) is relatively low, with less than two articles published annually. A significant increase in the number of publications began in 2013, reflecting the growth of research interest on CT in mathematics learning. This finding supports Tekdal's (2021) study, which stated that the research trend on CT has experienced exponential growth since 2013. The peak publication, the most productive year on this topic, occurred in 2022, with 67 published articles. As for 2023, up until 16 May, there were already 32 published articles. Considering the growth trend, we predicted that the number of publications will increase for the rest of the year 2023, and the number of annual publications is expected to increase further.

Most Productive Journals

A total of 136 journals have contributed to the publication of 276 articles on CT in mathematics learning. Using the Bibliometrix, we managed the data of top-10 productive journals based on their total publication (TP) and total citation (TC), as described in **Table 2**.

According to the number of published articles about CT in mathematics learning, **Table 2** shows that Education and Information Technologies journal stands out as the most prolific journal, contributing to 19 publications, accounting for 6.88% of the total articles found, followed by Journal of Science Education and Technology (11 publications, 3.99%), Education Sciences Journal (10 publications, 3.62%), and other journals (eight or less publications). On the other hand, based on the number of cited articles, Computer and Education Journal appears to be the most cited journal with a total of 1,071 citations, followed by the Journal of Science Education and Technology (841 citations), Education and Information Technologies (481 citations), and others (28-135 citations). From these top-10 journals, Springer Nature produces the most productive journals (three journals), followed by Elsevier, MDPI, and Wiley-Blackwell (two journals each), and ACM (one journal). Considering the data presented in **Table 2**, we conclude that the Education and Information Technologies journal and Journal of Science Education and Technology are the journals with the most contribution to the development of CT in mathematics learning research based on their TP and TC.

Most Prolific Authors

As mentioned in **Table 1**, there are a total of 804 authors who have published articles related to CT in mathematics learning. 10 most prolific authors are listed in the following **Table 3**. Their TP and TC determine the ranked list of authors.

According to the number of published articles, **Table 3** showcases that K. M. Rich, A. Yadav, Z. Cui, and V. Dagienė are the most prominent authors since each of them has published four articles about CT in mathematics learning. Another contribution is also made by the other six authors, namely U. J. Wilensky, G. Biswas, P. Sengupta, T.-C. Hsu, M. Román-González, and O. L. Ng, with three published articles for each of them. Moreover, in terms of the total number of citations, U. J. Wilensky is the author with the most cited references, with a total of 695 citations. Biswas and Sengupta position the second with 416 citations each. There are 296 citations in articles written by T.-C. Hsu

Table 2. Top-10 most relevant sources

Journal	TP (%)	TC	Publisher
Education and Information Technologies	19 (6.88%)	481	Springer Nature
Journal of Science Education and Technology	11 (3.99%)	841	Springer Nature
Education Sciences	10 (3.62%)	69	MDPI
Computer Applications in Engineering Education	8 (2.90%)	116	Wiley-Blackwell
Computers and Education	7 (2.54%)	1,071	Elsevier
British Journal of Educational Technology	6 (2.17%)	109	Wiley-Blackwell
International Journal of Child-Computer Interaction	6 (2.17%)	116	Elsevier
Mathematics	6 (2.17%)	28	MDPI
ACM Transactions on Computing Education	5 (1.81%)	135	ACM
Educational Technology Research and Development	5 (1.81%)	71	Springer Nature

Table 3. 10 most prolific authors

Author	Scopus ID	TP	TC	Affiliation
K. M. Rich	57191205854	4	45	American Institutes for Research
A. Yadav	23096666800	4	43	Michigan State University
Z. Cui	57219744088	4	41	Chinese University of Hong Kong
V. Dagienė	9638194400	4	34	Vilniaus Universitetas
U. J. Wilensky	6507819920	3	695	Northwestern University
G. Biswas	57211726890	3	416	Vanderbilt University
P. Sengupta	9743355400	3	416	University of Calgary
T.-C. Hsu	35173046500	3	296	National Taiwan Normal University
M. Román-González	57188680243	3	102	Universidad Nacional de Educacion a Distancia
O. L. Ng	56581733600	3	41	Chinese University of Hong Kong

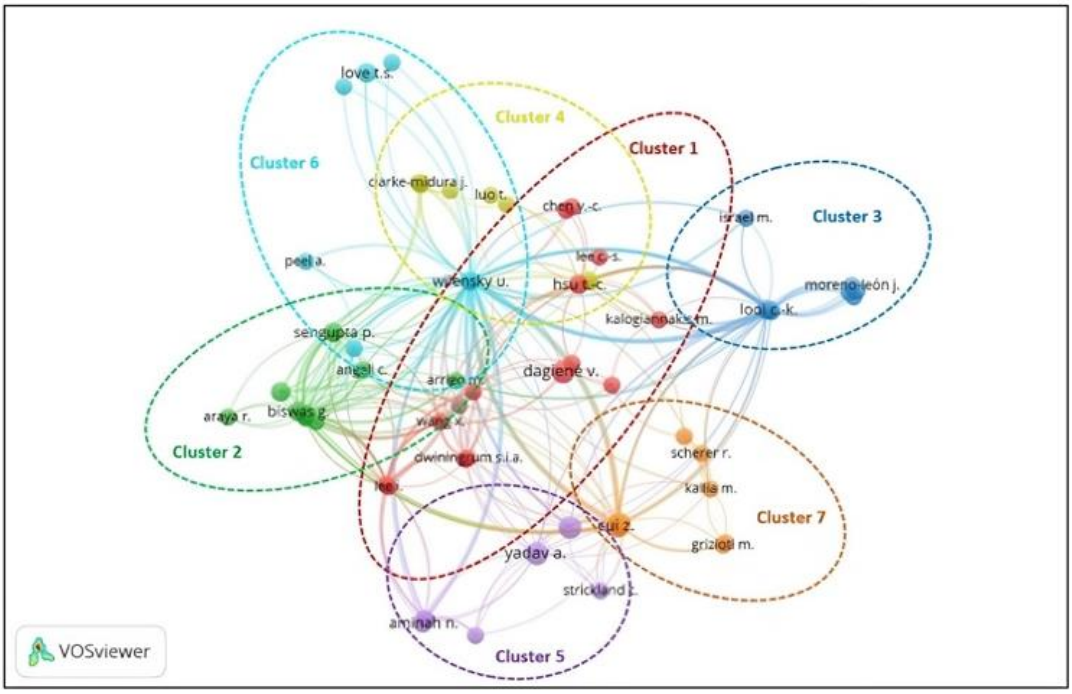

Figure 3. Collaborative network between authors on CT in mathematics learning (Source: Authors' own elaboration, using VOXviewer)

and 102 by M. Román-González, ranking them in the third and fourth position, respectively. Meanwhile, the rest of the authors have around 34-45 citations in their published articles. Notice that the Chinese University of Hongkong contributes two prolific authors in this research topic, namely O. L. Ng and Z. Cui. This finding indicates that the university conducts productive research on CT in mathematics learning.

Furthermore, this study also intended to see the networking collaboration among authors in this research specialty. The collaborative network analysis between authors was processed and visualized using VOSviewer software. The result of the analysis is presented in **Figure 3**.

VOSviewer author collaboration network citation analysis results, as depicted in **Figure 3**, form seven research collaboration clusters. Clusters indicate a group of authors who frequently have collaborations in publishing articles. For instance, in cluster 1 (bounded by the red labels and dash lines), twelve authors commonly published articles together (paired with one or more authors), and V. Dagienė is the center of cluster 1 (she has collaborated with the other eleven authors).

Therefore, cluster 2 (colored green) and cluster 3 (colored dark blue) are centered by G. Biswas and M. Román-González, respectively. The center of cluster 4 (represented by yellow), cluster 5 (represented by purple), and cluster 6 (portrayed by light blue) are J. Clark-Midura, A. Yadav, and U. J. Wilensky, respectively. Lastly, cluster 7 is centered around Z. Cui, as indicated by the orange. Also, notice that different sizes of circles labelling each author's name indicate frequent number of collaborations done by each author.

Authors with big circles have done many collaborations in their articles, while authors with small circles are the other way. Hence, it can be seen from **Figure 3** that the center of each cluster (V. Dagienė, G. Biswas, M. Román-González, U. J. Wilensky, and Z. Cui) have the most collaborated papers with other authors inside or outside the cluster. Additionally, all of these

Table 4. 10 most prolific countries

Country	TPC (%)	TCC	The Most Prolific Institution	TPI (%)
United States	87 (31.52%)	3,121	Michigan State University	7 (8.05%)
Spain	22 (7.97%)	330	Universidad Nacional de Educacion a Distancia	5 (22.73%)
Turkey	17 (6.16%)	134	Ondokuz Mayis Üniversitesi	2 (11.76%)
Canada	13 (4.71%)	280	Western University	3 (23.08%)
China	12 (4.35%)	89	South China Normal University	2 (16.67%)
Greece	12 (4.35%)	199	University of Crete	2 (16.67%)
Indonesia	12 (4.35%)	9	Universitas Negeri Yogyakarta	3 (25.00%)
Malaysia	11 (3.99%)	41	Universiti Kebangsaan Malaysia	5 (45.45%)
Norway	10 (3.62%)	97	Universitetet i Oslo	4 (40.00%)
Taiwan	8 (2.90%)	346	National Taiwan Normal University	4 (50.00%)

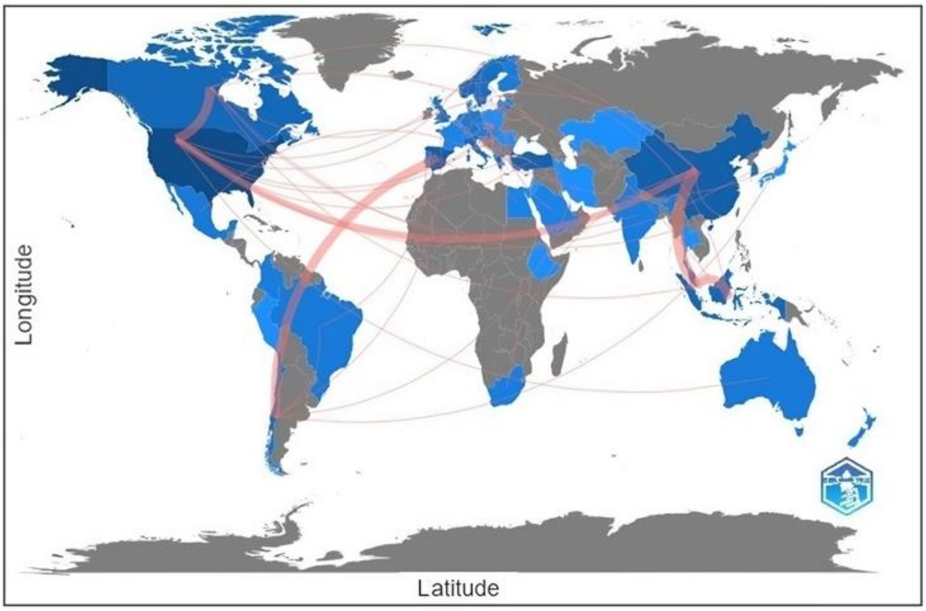

Figure 4. World map of collaboration of authors between countries (Source: Authors' own elaboration, using Bibliometrix)

authors appear among the top prolific authors in research of CT in mathematics learning (**Table 3**).

Most Prolific Countries

Based on **Table 1**, it is evident that publications related to CT in mathematics learning are distributed across 41 countries. Using the Bibliometrix software, we can analyze top-10 dominant countries presenting research on CT in mathematics learning. **Table 4** describes more detailed information about 10 countries with the highest publication count, the accumulated citations of articles from each country, and the institutions with the highest publication count in each country. The ranking of countries is based on the total publications of a country (TPC) and the total citations of a country (TCC).

Referring to **Table 4**, the United States is reported to have the highest number of publications (87 articles), leading to approximately 31.54% of TPC among 10 countries. Spain is the second most productive country with 22 (7.97%) TPC, followed by Turkey (17, 6.16%), Canada (13, 4.71%), Cina, Greece, Indonesia (12, 4.35% each), Malaysia (11, 3.99%), Norway (10, 3.62%), and Taiwan (8, 2.90%). The cumulative publications from the abovementioned top-10 countries amount to 204 articles, accounting for 73.91% of all 276 articles retrieved in this study. The remaining 72 articles (26.09%) are distributed around the other countries. Research on TCC showed that the United States also leads the total cited references among the other countries, with 3,121 citations. Although Taiwan places the tenth in the number of published papers, the country takes the second in terms of total citation (346 TCC), followed by Spain (330 TCC), Canada (280), Greece (199 TCC), Turkey (134 TCC), Norway (97 TCC), China (89 TCC), Malaysia (41 TCC), and Indonesia (nine TCC).

Furthermore, **Figure 4** illustrates the bibliometric map of international collaboration between the selected 41 countries using Bibliometrix world map network visualization mode, clustered per country. Countries colored blue in **Figure 4** indicates that they contribute the most publication related to CT in mathematics learning. Different blue saturations in each country show the rates of articles published by the authors affiliated with a given country. The darker the blue, the greater the number of publications produced by the country. The Red lines correspond to the inter-collaboration between

Table 5. Top-10 most cited references

Title	Reference	TC
Computational thinking	Wing (2006)	222
Mindstorms: Children, computers, and powerful ideas	Papert (1980)	176
CT in K-12: A review of the state of the field	Grover and Pea (2013)	157
Defining CT for mathematics and science classrooms	Weintrop et. al. (2015)	108
CT in elementary and secondary teacher education	Yadav et al. (2014)	107
CT and tinkering: Exploration of an early childhood robotics curriculum	Bers et al. (2014)	97
Bringing CT to K-12: What is involved and what is the role of the computer science education community?	Barr and Stephenson (2011)	73
New frameworks for studying and assessing the development of computational thinking	Brennan and Resnick (2012)	72
Which cognitive abilities underlie computational thinking? Criterion validity of the CT test	Román-González and Pérez-González (2017)	66
A K-6 CT curriculum framework: Implications for teacher knowledge	Angeli et al. (2016)	49

countries, where the thicker the line, the stronger the research collaboration between countries.

Figure 4 offers valuable insights into two significant aspects: the distribution of publications across countries and the intricate international collaboration network among authors. Firstly, **Figure 4** highlights nine countries prominently colored in dark blue. These countries, namely the United States, Spain, Turkey, Canada, China, Greece, Indonesia, Malaysia, and Norway, stand out as the most productive, with the number of publications quantified in **Table 4**. Conversely, countries shaded in light blue are characterized by a lower frequency of publications, encompassing diverse nations. Secondly, the red lines interconnecting countries on the map represent collaborative endeavors among authors. Notably, several countries have strong collaborations, including China and Singapore, Indonesia and Malaysia, Malaysia and Singapore, Spain and Chile, and the United States and Canada. Moderate collaboration exists between Slovakia and the Czech Republic, as well as between the United States and China. However, it is noteworthy that collaboration with other countries remains relatively limited, signifying potential areas for future international research partnerships.

Most Cited References

Referring to **Table 1**, it is informed that there are 14,145 references used in the 276 articles. Top-10 most cited reference sources, their authors, publication years, and citation counts are presented in **Table 5**. The ranking is based on each reference source's TC.

Table 5 showcases that 'computational thinking' by Wing (2006) is reported to have the highest number of cited references, leading with 222 TC, followed by Papert's (1980) study titled 'Mindstorms: Children, computers, and powerful ideas' as the second highest cited reference (176 TC). While Papert's (1980) study is credited as the reference for the initial concept of CT, Wing's (2006) study becomes the reference that brings CT gaining popularity in educational research. 'CT in K-12: A review of the state of the field' by Grover and Pea (2013) and 'Defining CT for mathematics and science classrooms' by Weintrop et al. (2015) is positioned as the third and the fourth most cited references, 157 and 108 TC, respectively. Grover and Pea's (2013) study has contributed to CT research in school education, particularly in primary and secondary education, whereas Weintrop et al.'s (2015) study has provided a solid framework for researchers seeking to incorporate CT into mathematics and science education. The fifth top-cited reference is taken by 'CT in elementary and secondary teacher education' written by Yadav et al. (2014), which contributes to research integrating CT into pre-service teacher education (107 TC). Similarly, the article' CT and tinkering: Exploration of an early childhood robotics curriculum' by Bers et al. (2014) has sparked research on CT in early childhood educational settings, bringing it to the sixth position (97 TC). The remaining four studies have also served as invaluable references for research on CT in mathematics learning.

Figure 5 displays the network of the most co-cited authors using the VOSviewer bibliometric networking visualization mode, clustered into six colors (red, green, yellow, purple, dark blue, and light blue). The number or circles in a cluster indicates the number of authors involved ana collaborated. The greater the number of circles in a cluster, the greater the number of authors contributing and the closer the collaboration relationship.

Figure 5 shows cluster 1 (red) consists of 149 authors, including A. Yadav and O. Korkmaz. Cluster 2 (green) comprises 89 authors, including D. Weintrop and M. Horn. There are 79 authors grouped in cluster 3, including U. Wilensky and M. Resnick. Cluster 4 includes 62 authors, including A. Repenning and K. Brennan. Cluster 5 encompasses 58 authors, including J. M. Wing and M. U. Bers. Lastly, cluster 6 comprises 15 authors, including D. Athanasios. Notice that some authors are included in more than one cluster, indicating strong collaboration with authors inside and outside the cluster. From this analysis, J. M. Wing has played a

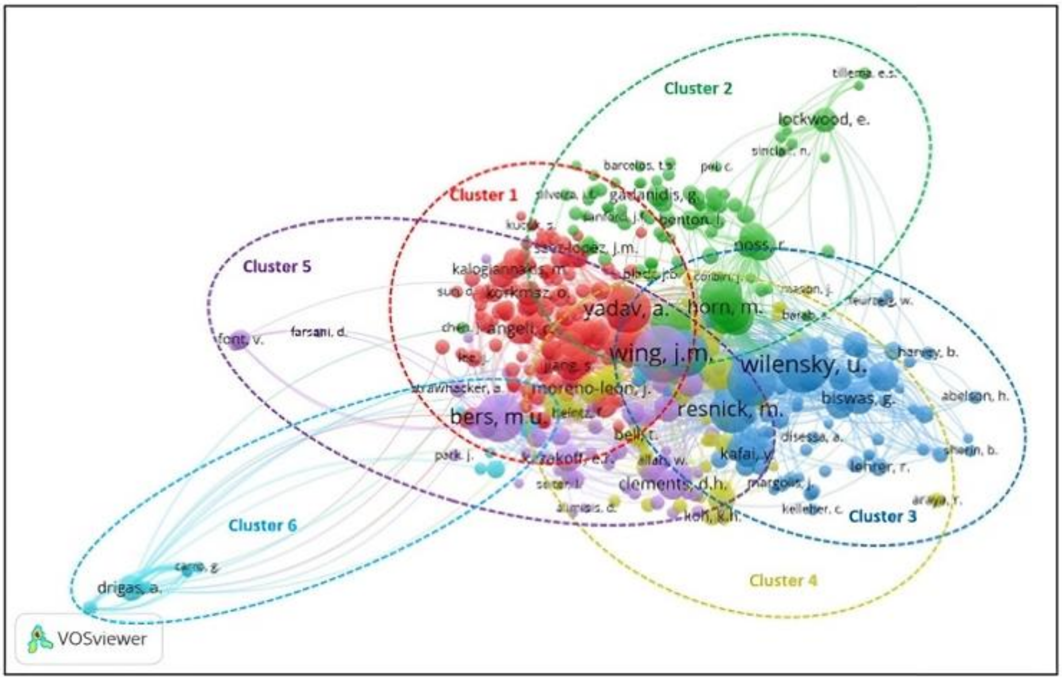

Figure 5. Network map of the most co-cited authors (Source: Authors' own elaboration, using VOSviewer)

Figure 6. Top-50 author keywords, frequency, & proportion (Source: Authors' own elaboration, using Bibliometrix)

significant role in stimulating research endeavors about CT, where she involves in five different clusters.

Most Occurring Keywords

Within this section, we draw attention to the study of the occurrences of keywords to define the focus on CT in mathematics learning. Of the 819 author keywords reported from 276 articles obtained, 50 keywords meet the threshold of three minimum number of keyword occurrences. In **Figure 6**, the keyword frequencies, proportions, and percentages are elaborated using Bibliometrix keywords visualization mode to illustrate the occurrence. The bigger area of the keyword indicates that the keyword is likely to be the top topic of interest within research related to CT in mathematics learning.

Figure 6 shows that 'curriculum' and 'engineering education' are the most frequently occurring keywords, appearing 21 times, leading to approximately 7.00% of the total keywords. Following them, we have 'STEM' (17 times, 6.00%), 'mathematical programming' (13 times, 5.00%), 'computer programming' (12 times, 4.00%), 'problem-solving' (10 times, 3.00%), 'educational computing' (nine times, 3.00%), 'thinking' (nine times, 3.00%), 'computation theory' (eight times, 3.00%), and 'robotics' (eight times, 3.00%). Other keywords appear three to 7 times.

Furthermore, we intend to explore the networking map between keywords mentioned before, as displayed using VOSviewer overlay visualization mode to illustrate the network in **Figure 7**. Each keyword is

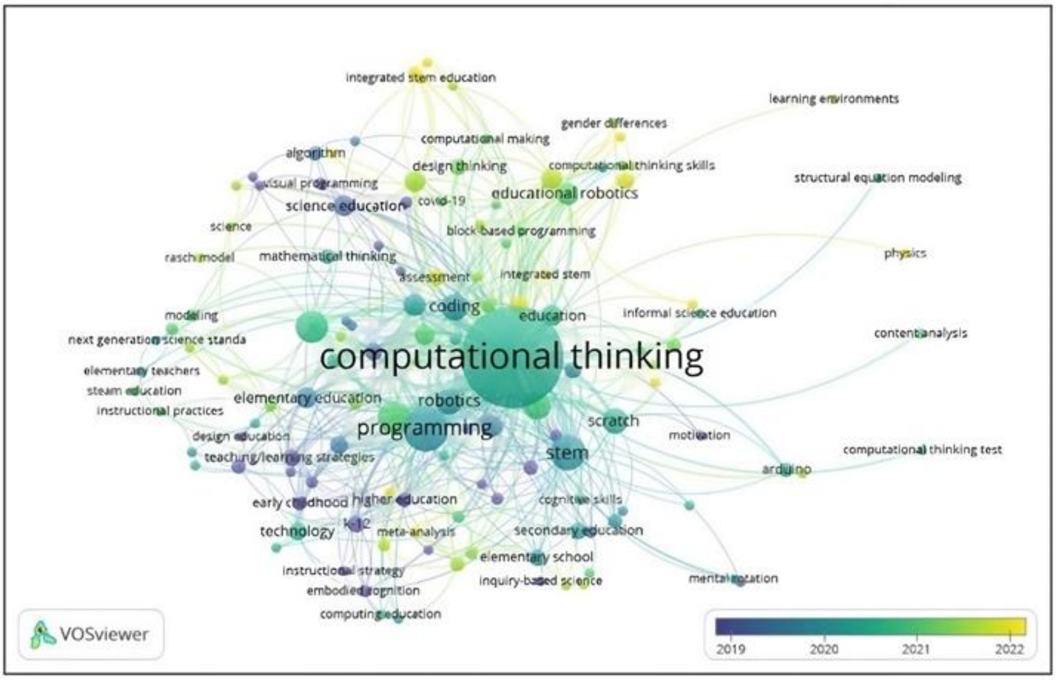

Figure 7. Network map of author keywords by year (Source: Authors' own elaboration, using VOSviewer)

represented by a circle from blue-ish to yellow-ish color. The keyword color informs the publication year, where the keyword appeared.

Thus, we can see in **Figure 7** that keywords used in late years (from 2019) are displayed with dark blue and slowly change to a brighter color to yellow, displaying keywords applied in recent years (until 2022). The size of circles informs the co-occurrences of a given keyword. The bigger the circle sizes, the more often the keyword is used in publications about CT in mathematics learning.

In general, 'computational thinking' appears as the frequent keyword used, followed by other related keywords such as 'programming', 'STEM', 'robotics', 'coding', and 'education'. This finding shows that numerous research studies have been carried out on CT linked with topics around STEM education. As reflected in **Figure 7**, CT in STEM education, including mathematics learning, constantly developed around 2020-2021. While contributions of research in CT emphasize the mathematical thinking, assessment, and teaching/learning strategies already began in 2019, integrated STEM education and CT have become one of the most recent topics (approximately started in 2022), signifying its emerging development for future study. Likewise, keywords that have not been connected with lines, for example, CT with integrated STEM education and gender differences, provide a novelty to be investigated in further research. Note that every category included in this analysis was determined solely by the author's keywords. Consequently, other information could be overlooked if the articles did not include the subjects as keywords.

Thematic Evolution

Furthermore, based on the thematic mapping using Bibliometrix, a thematic evolution map is presented in **Figure 8**. Thematic evolution analysis aims to categorize the themes used in previous literature on CT in mathematics learning: motor, niche, declining, and basic themes. According to Cobo et al. (2018), organizing these themes into quadrants within the thematic map is based on the centrality and density of each theme. Centrality measures the intensity of connections between specific clusters and others, while density characterizes the strength of links that bind the words forming a cluster together (Cobo et al., 2018).

Themes with strong centrality and high density are formed in quadrant 1, located in the upper right, and are referred to as motor themes. Motor themes represent important and well-developed research areas. Moreover, themes with strong centrality but low density are placed in quadrant 2, located in the lower right, and are labelled as basic themes. Basic themes represent fundamental and general areas of significance for research but are not necessary to be extensively developed. On the other hand, themes with weak centrality but high density are situated in quadrant 3, found in the upper left, and are known as niche themes. Niche themes may have previously been central but are currently becoming marginalized or experiencing a decline in interest among researchers. Finally, themes with weak centrality and low density occupy quadrant 4 in the lower left and are referred to as newly emerging or declining themes

According to **Figure 8**, it becomes evident that distinct thematic clusters have emerged, shedding light

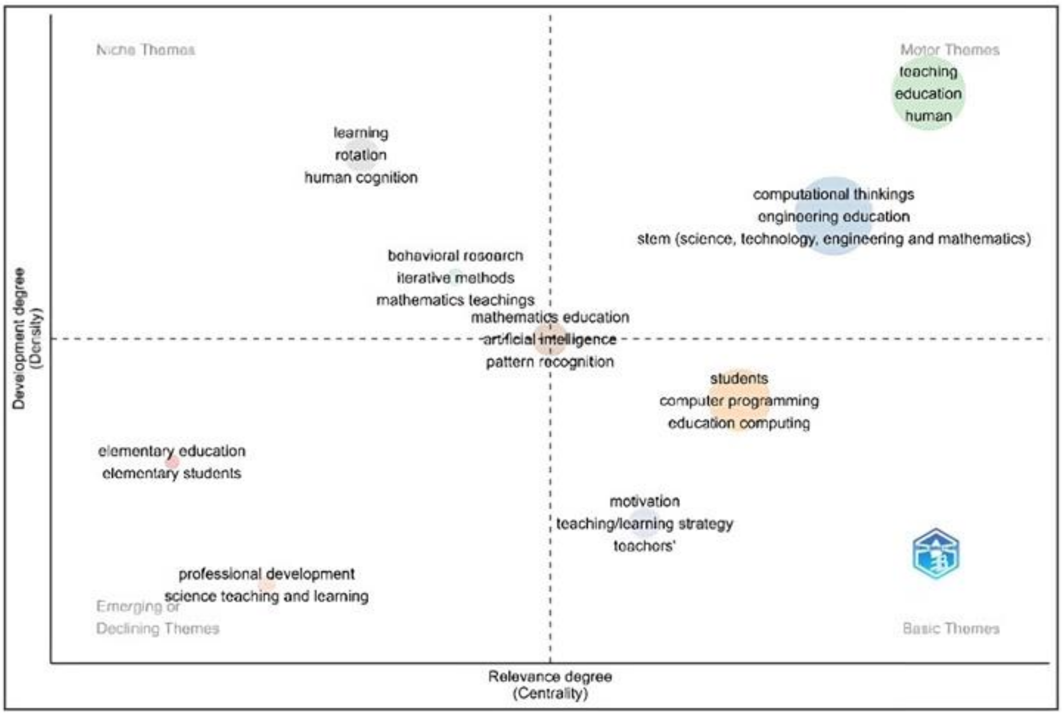

Figure 8. Thematic evolution map of CT in mathematics learning research (Source: Authors' own elaboration, using Bibliometrix)

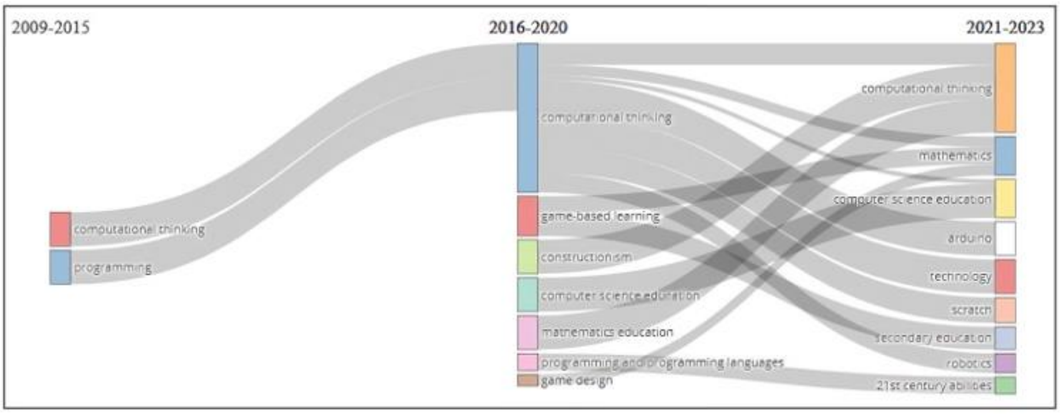

Figure 9. Thematic evolution 2009-2023 (Source: Authors' own elaboration, using Bibliometrix)

on the current state and trajectory of research themes of CT in mathematics learning. In motor themes, we find two clusters involving 'computational thinking', 'STEM', 'teaching', and others, which stand as robust and extensively explored themes in integrating CT in mathematics. Moving to basic themes, we encounter two distinct clusters with 'students', 'computer programming', 'education computing', and other fundamental themes that deserve further exploration. The niche themes unveil two clusters, marked by 'learning', 'human cognition', 'iterative methods', and other themes indicating a similar trend of declining interest among researchers. Finally, the emerging and declining themes. Themes like 'professional development' and 'science teaching and learning' signify newly emerging areas of research, while themes like 'elementary education' and 'elementary students', which, once prominent, have now entered a phase of decline in research interest. This comprehensive thematic analysis provides the dynamic nature of research trends in this domain and highlights potential areas for future exploration.

The thematic evolution of CT-related research from 2009 to 2023 is presented in **Figure 9**. Over the years, from 2009 to 2023, a division was made into three periods: 2009-2016, 2016-2020, and 2021-2023. In each period, emerging themes for that year are listed below. Themes are listed sequentially, with the most frequently occurring themes mentioned at the top. Gray lines depict the shift in themes across periods.

As Depicted in **Figure 9**, during the first period (2009 to 2015), 'computational thinking' emerged as the dominant theme, alongside 'programming'. In the following period, from 2016 to 2020, 'computational thinking' continued to maintain its prominence. However, the research landscape diversified with the emergence of themes like ‘game-based learning’, ‘constructionism’, ‘computer science education’, and others. Notably, this period witnessed a shift among researchers who had initially focused on ‘programming’, redirecting their attention toward ‘computational thinking’. In the most recent period, from 2021 to 2023, ‘computational thinking’ remained the center of research. This phase witnessed an expansion of CT theme, incorporating new dimensions such as ‘mathematics’, ‘computer science education’, ‘21st century abilities’, and others. A noteworthy trend emerged as researchers, particularly in mathematics education and constructivism during the 2016-2020 period, transitioned their focus towards ‘computational thinking’. Simultaneously, scholars initially engaged in ‘computational thinking’ during the 2016-2020 period expanded their research area by interconnecting it with diverse themes.

DISCUSSION

Publications related to CT in mathematics learning first appeared in the Scopus database in 2009 but have only seen significant growth since 2013. The trend in developing publications related to CT in mathematics learning has an annual growth rate of 28.09%. This finding aligns with research conducted by Chen et al. (2023), and Irawan and Herman (2023), Roig-Vila and Moreno-Isac (2020), and Tekdal (2021), which concluded that research related to CT has significantly increased in recent years. This development is closely linked to CT, claimed by Wing (2006, 2008, 2017, 2011) as one of the 21st century skills, alongside reading, writing, and arithmetic. It is inseparable from CT as a working paradigm to prepare the younger generation for success in the digitally driven world (García-Peñalvo, 2018). The increased publications in recent years serve as evidence of the awareness of the importance of this field, which has been on the rise (Ilic et al., 2018). The broad scope of CT, including its connection to mathematics learning, is expected to continue to foster growth and maturity in this field.

Out of 267 articles found, they were published in 136 different journals. This result suggests that the development of CT research has attracted various publishers and journal managers for publication. ‘Education and Information Technologies’, published by Springer Nature, is the journal that has published the most articles related to CT in mathematics learning. Other journals include ‘The Journal of Science Education and Technology’, ‘Education Sciences’, ‘Computer Applications in Engineering Education,’ ‘Computers and Education,’, and other prolific journals. The abundance of journals that accommodate articles related to CT in mathematics learning presents an excellent opportunity for publishing in this field (Roig-Vila & Moreno-Isac, 2020). This finding aligns with the research by Tekdal (2021), which states that journals publishing CT-related articles are predominantly in the fields of technology, educational technology, computing, and social science.

Publications related to CT in mathematics education involve 804 authors from 41 countries. K. M. Rich, A. Yadav, Z. Cui, and V. Dagienė are the most prolific authors producing CT-related publications in mathematics learning. The United States has the highest number of publications, followed by Spain, Turkey, Canada, China, Greece, Indonesia, Malaysia, Norway, and Taiwan. These findings resonate with the conclusion made by Chen et al. (2023) that many research institutions and researchers have contributed to the field of CT research.

While S. Papert is credited with first introducing the term ‘computational thinking’, J. M. Wing is the author most frequently cited by researchers in the field of CT in mathematics learning. Wing’s (2006) article titled ‘computational thinking’ successfully inspired and sparked further research on CT (Ilic et al., 2018). Furthermore, she followed up with additional articles on CT. These four articles by J. M. Wing have made her the most referenced author among researchers. Following her, in consecutive order, are Papert (1980), Grover and Pea (2013), Weintrop et al. (2015), Yadav et al. (2014), Bers et al. (2014), and other authors.

The themes of ‘computational thinking,’ ‘engineering education,’ ‘STEM,’ ‘teaching,’ ‘education,’ and ‘human’ are crucial topics in this field and have seen substantial growth. The evolution of CT-related themes in mathematics education from 2009 to 2023 indicates that CT has become the dominant theme. During the 2021-2023 period, there has been an increase in CT research interest from mathematics education researchers. On the other hand, researchers involved in CT during the 2009-2015 and 2016-2020 periods have expanded their focus by linking CT to themes such as ‘mathematics’, ‘computer science education’, and others. These findings reinforce Tekdal’s (2021), which mentioned the growing integration of CT through STEM. Many researchers in mathematics education are expanding their investigations into CT, indicating that much research will explore the integration of CT in mathematics learning. Thus, the integration of CT through mathematics learning is predicted to grow and mature.

CONCLUSIONS

This study aims to analyze, present, and visualize the research trends of CT in mathematics learning using a Bibliometric analysis. Using Bibliometrix and VOSviewer, seven main conclusions have been drawn from the analysis of 276 academic papers retrieved from Scopus databases. *First*, CT in mathematics learning has emerged as a research focus since 2009 but has experienced significant development since 2013 until the present. *Second*, the journal Education and Information Technologies, published by Springer Nature, is the most productive journal publishing CT-mathematics learning-related articles. *Third*, K. M. Rich, A. Yadav, Z. Cui, and V. Dagienė are the most prolific authors studying CT in mathematics learning. *Fourth*, researchers worldwide have a growing interest in studying CT in mathematics learning, with researchers from the United States leading the field, followed by Spain, Turkey, Canada, China, Greece, Indonesia, Malaysia, Norway, and Taiwan. *Fifth*, the article 'computational thinking' by J. M. Wing is the most referenced source by authors in the field of CT in the context of mathematics learning. *Sixth*, integrating CT through mathematics learning is a relatively new and developing research theme, predicted to continue growing. *Seventh*, many researchers in mathematics education are evolving to investigate CT, indicating that many studies will explore the integration of CT in mathematics learning.

Limitation

Despite relying on credible data sources and utilizing reliable software for analysis, this research has certain limitations. *Firstly*, the data under analysis is restricted to publications indexed within the Scopus database. At the same time, many studies on CT in mathematics learning are published in other scientific journals not indexed in the Scopus database. *Secondly*, the analyzed data is restricted to literature published in English, excluding discussions in articles written in languages other than English. *Thirdly*, the search encompassed titles, abstracts, and keywords, which means there is a possibility of missing some articles that may not explicitly focus on CT in mathematics learning. Therefore, in the future, it is essential to conduct bibliometric research involving a more comprehensive range of data sources, such as Web of Science, Dimensions, and Google Scholar. Additionally, more in-depth systematic literature reviews are needed to explore the use of CT in the context of mathematics learning.

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