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MATHEMATICAL REPRESENTATION: A BIBLIOMETRIC MAPPING OF THE RESEARCH LITERATURE (2013–2022)

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ABSTRACT

Mathematical representation ability is an essential skill for students to understand mathematical concepts. Many studies have been conducted regarding this ability, but it is necessary to map existing research to provide a clearer picture of future research topics. This study aims to provide a bibliometric review of trends using mathematical representation skills in mathematics teaching research. The method in this study is bibliometric analysis, which aims to analyze and classify bibliographic material by presenting representative summaries of the literature in the Scopus database. The search was carried out using the keyword "mathematical representation" and selecting "article title" in the search menu in the Scopus.com database. Perish or Publish (PoP) software analyzes the author's name, number of document citations, document title, year of publication, document source, publisher, and document type. The results showed 99 publications and 357 citations related to mathematical representations, where the number of publications and citations fluctuated. The application of learning models and approaches, computer media, and analysis of mathematical representations is a research trend related to this variable. Therefore, paying attention to mathematical representations in learning mathematics and using effective strategies to improve students' mathematical representation abilities is essential. The findings of this study indicate the need to develop syntax and learning media based on mathematical representations to strengthen students' mathematical abilities.

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1. INTRODUCTION

Mathematical representation is a person's ability or skill to understand mathematical concepts in various ways or forms, such as graphs, tables, diagrams, and symbols (Putra et al., 2018). These skills need to be owned by students to solve complex mathematical problems (Hanifah et al., 2020; Widakdo, 2017). Substantial contributions to the field of mathematics education have been provided by these studies, where it has been elucidated that the ability to accurately represent mathematical concepts not only bolsters students' comprehension (Imama & Caswita, 2023; Mulyono et al., 2020; Taqwa & Rahim, 2022), but also enhances their problem-solving acumen (Isyam & Hidayati, 2022; Loc & Phuong, 2019). Santia et al. (2019) and Safitri et al. (2023) also stated that students who can make mathematical representations tend to more easily understand mathematical concepts and can solve complex mathematical problems. Coesamin et al. (2021) and Noto et al. (2016) also found that mathematical representation mastered by students is a key element in expressing mathematical ideas. On the other hand, Duval (2017) explains that mathematical objects such as ideas, concepts, and relations can be accessed through multiple representations; even the activity of disclosing these mathematical objects will be affected by the use of representations.

Students with good mathematical representation skills will be able to learn independently in constructing knowledge concepts through multiple representations (Chang et al., 2017). As stated by the National Council of Teaching Mathematics (NCTM), this mathematical representation ability will prepare students to solve mathematical problems (National Council of Teachers of Mathematics, 2000). In addition, students can also be skilled in analyzing and stating arguments in the form of visuals, verbal and even symbols to state the truth of a mathematical concept (Widakdo, 2017). Therefore, it can be noted that this mathematical representation ability will assist teachers in engineering learning. Of course, improving students' understanding of mathematical concepts will also be helpful.

Research that examines mathematical representations also leads to the creation of learning technologies such as the creation of interactive media software (Rahayu & Kuswanto, 2021), virtual media manipulatives (Nurlisna et al., 2020; Septian, Suwarman, et al., 2020), and augmented reality media (Shaghaghian et al., 2022). Pedersen and Welch (2018) conducted a literature review on the relationship between mathematical representation ability, the use of digital technology, and the design of learning tasks. On the other hand, research with this theme/topic has also been studied a lot with quantitative research approaches, such as the effect of applying certain cooperative learning models to Mathematical Representation abilities (Putra et al., 2021; Sari & Karyati, 2022; Wijayanti et al., 2020); the relationship between mathematical representation and understanding of concepts (Taqwa & Rahim, 2022) and problem-solving (Isyam & Hidayati, 2022; Loc & Phuong, 2019). Knowing the research developments related to this variable is important to assess the extent to which further research can benefit this field. However, based on the data and information above, it can be stated that research on mathematical representations has not led to bibliometric analysis.

Bibliometric analysis can provide benefits for us to see the development of research on the topic of mathematical representation, such as: knowing the relationship between research, finding potential collaborators, obtaining information about relevant journals, and assessing the impact of research (de Oliveira et al., 2019; Ikeziri et al., 2019). Apart from that, we can also take advantage of published articles to find out trends and patterns in mathematical representation research. In the study of bibliometric analysis in the area of mathematical ability, several studies have been conducted. These studies include bibliometric analysis of mathematical reasoning (Afifah, 2022; Çoban & Tezci, 2022),

mathematical thinking style (Evendi, 2022), mathematical problem solving (Suseelan et al., 2022), mathematical reflective thinking (Muntazhimah et al., 2022), mathematical communication (Batubara et al., 2022; Yani & Soebagyo, 2023), and mathematics concept (Sreylak et al., 2022).

However, no clear research related to bibliometric analysis related to mathematical representation exists. Therefore, this study will examine in depth to provide a bibliometric and bibliographic review of the trend of using mathematical representation abilities in mathematics learning research. In particular, this research formulates four questions as follows: 1) What is the development of publication and citation of mathematical representation studies in the last decade?; 2) Which documents, authors, countries, institutions, and sources contributed most to mathematical representation studies?; 3) What are the social interactions among authors, countries, and institutions related to mathematical representation studies?; 4) What are the main emerging themes of mathematical representation studies in the last decade?

2. METHOD

2.1. Research Design

A systematic review using bibliometric analysis was conducted to present the trend of mathematical representation studies in the last decade and suggest possible future research. Moreover, Donthu et al. (2021) explained that bibliometric analysis is a well-known and harsh method to explore and analyze large volumes of scientific data in which it can get a one-step overview, acquire novel ideas for the next research, and recognize knowledge gaps. To conduct bibliometric analysis, Fuad et al. (2022) stated that there are five steps such as (1) specifying the search keyword, (2) exploring initial search results, (3) refining the documents, (4) compiling the initial statistical data, and (5) analyzing the data. Particularly, every step to perform bibliometric analysis in this study was elucidated in the following subsections.

2.2. Specifying the Search Keyword

The Scopus database was utilized to discover the documents regarding mathematical representation studies because it had many electronically well-qualified documents from numerous scientific fields (Zhu & Liu, 2020). The specific keyword ("mathematical representation") was established to seek the prospective documents suitable to the studies related to mathematical representation. The search process of documents in the Scopus database was performed on Mar 14, 2023, specifically at 10.27 AM in Western Indonesian Time.

2.3. Exploring Initial Search Results

The initial search results discovered 372 documents published in 2013 – 2023 and sourced from journals, books, conference proceedings, and book series. The publication stage of documents was in final and press, consisting of the article, book chapter, conference paper, review, editorial, conference review, book, note, and short survey. The documents were written in many languages, such as English, Spanish, French, Portuguese, German, Chinese, Japanese, Turkish, Italian, Russian, and Korean.

2.4. Refining the Documents

Some inclusion criteria were established to gain the documents related to mathematical representation studies. Firstly, the document's title had to contain the keyword "mathematical representation." Secondly, the document was only written in English, and the publication stage of the document had been final. Thirdly, the document was only sourced from journal and conference proceedings, and the type of document was an article, review, and conference paper. Fourthly, the document was published from 2013 to 2022. The document which did not meet the inclusion criteria were removed from the selection process. Some literature stated that there were five steps to select the document systematically that were: (1) identification, (2) screening, (3) eligibility, and (4) inclusion (Fuadi et al., 2022; Helsa et al., 2023; Jaya & Suparman, 2022; Juandi et al., 2022; Sulistiawati et al., 2022; Suparman & Juandi, 2022a, 2022b; Suparman et al., 2022). The process of document selection using the PRISMA protocol is presented systematically in Figure 1.

2.5. Compiling the Initially Statistical Data

The eligible documents were downloaded from the Scopus database in two formats that were Comma Separated Values (CSV) and Research Information System (RIS); whereby the formats contained some information such as bibliometric information, abstract and keyword, and bibliographic information (Muhammad et al., 2022). Additionally, the RIS format presented in the software of Perish or Publish (PoP) provided the data such as author names, number of document citations, document titles, publication years, document sources, publishers, and document types (Fuad et al., 2022). Moreover, the appearance of PoP software presented the descriptive analysis summary, such as the total of publications (TP), the total of citations (TC), the number of citations per year (NCY), the number of citations per publication (NCP), the number of authors per publication (NAP), h-index, g-index, and the period of publication and citation years (Muhammad et al., 2022). On the other hand, the CSV format presented in the software of VOSviewer displayed the most numerous publication and citations viewed from the unit of document, author, country, source, and institution, and also keyword occurrence, a total of strength link, some visualizations, and clustering (Fuad et al., 2022).

2.6. Analyzing Data

Some analyses, such as performance analysis, citation analysis, co-authorship analysis, and co-word analysis, were performed to analyze the data. In particular, performance analysis was applied to present the development of publication and citation of mathematical representation studies in the last decade. In addition, citation analysis provided information regarding the productive and influential documents, authors, and countries contributing most to mathematical representation studies. Moreover, co-authorship analysis was performed to show the social interactions among authors and countries related to mathematical representation studies. Then, co-word analysis was employed to present the most frequently emerging keywords and the distribution of appearing keywords regarding mathematical representation studies in the current period, which at least could provide the possibilities of future research in mathematical representation. Some additional analyses include visualization and clustering, enriched co-authorship, and co-word analysis. According to Fuad et al. (2022) and Kornia et al. (2022), performance analysis could be supported by the software of PoP, while the software of VOSviewer supported other analyses such as citation analysis, co-authorship analysis, and co-word analysis.

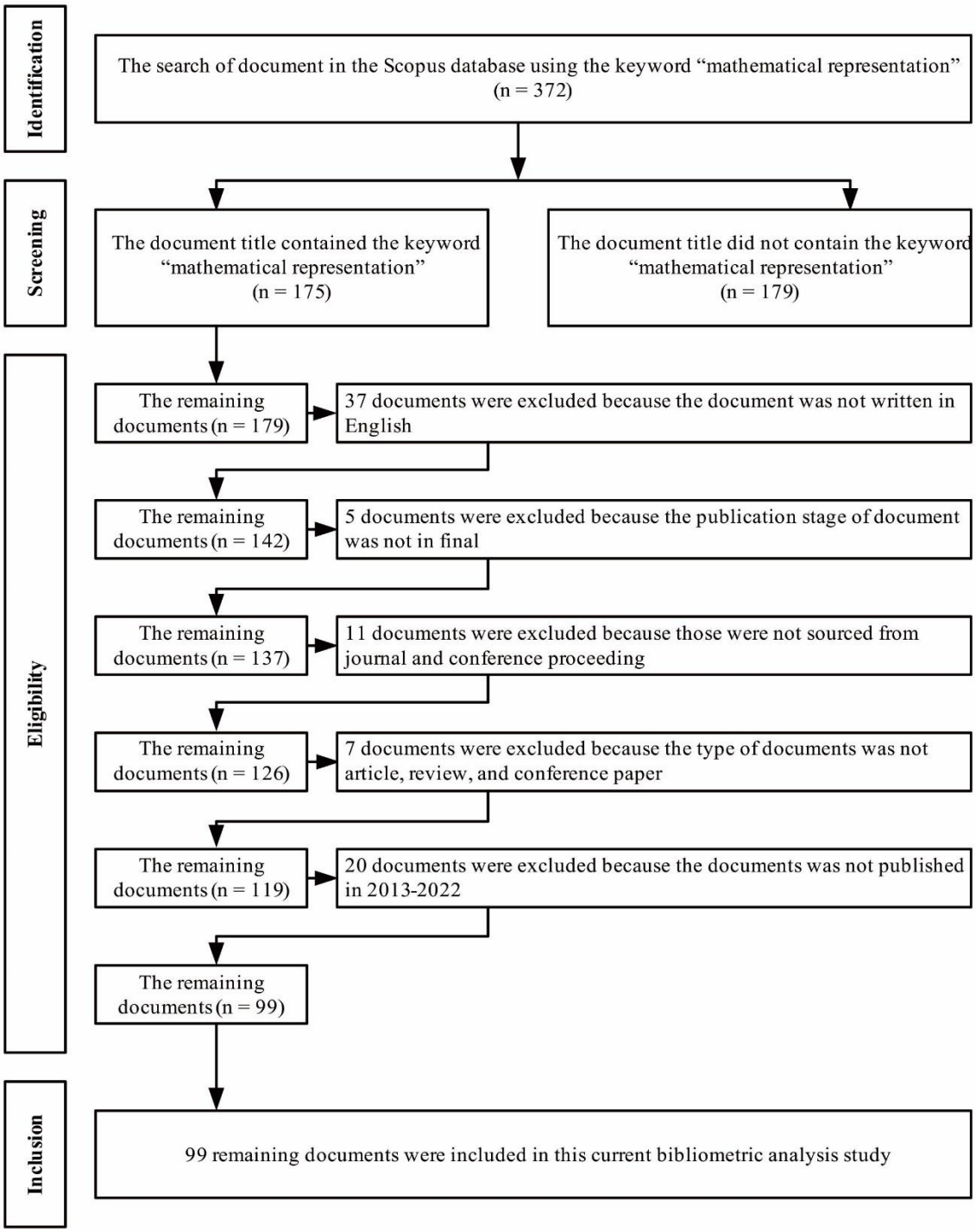

Figure 1. The process of document selection

3. RESULT AND DISCUSSION

3.1. Performance Analysis

3.1.1. Publication-and-citation-related metric

After the selection process, 99 documents were obtained according to predetermined criteria. Metrics related to the publication and citation of these documents are then shown in Table 1 with the help of PoP software.

Table 1. Publication and citation metrics

Description	Results
Publication years	2013-2022
Citation years	10
Total Publication	99
Total Citation	357
Author	248
Cites/year	35,70
Cites/paper	3,61
Authors/paper	3,05
h-Index	11
g-Index	16
m-index	0,69

Table 1 shows that between 2013 and 2022, there were 99 documents related to mathematical representation skills, and overall these documents have been cited 375 times, with an average citation per year of 35.70. In addition, the documents collected had an average citation per paper of 3.61, indicating that each document was cited at least three times or more. The number of authors per paper is 3.05, while the number of authors involved in the overall publication of documents is 248 people. Furthermore, the document's h-index is 11, meaning there are 11 documents with a minimum of 11 citations. The g-index is 16, which indicates that there are 16 documents with the highest citation of at least 256. This shows that the m-index of the document collection is declared at 0.69, which indicates the ratio between the h-index and g-index is 11:16. Based on this data, the h-index is always lower than the g-index (Donthu et al., 2020).

3.1.2. Publication and citation trend analysis

This analysis of publications and citations is used to map the development of the number of publications and citations related to mathematical representation in 2013-2022. Trends in publications and document citations are presented in Figure 2.

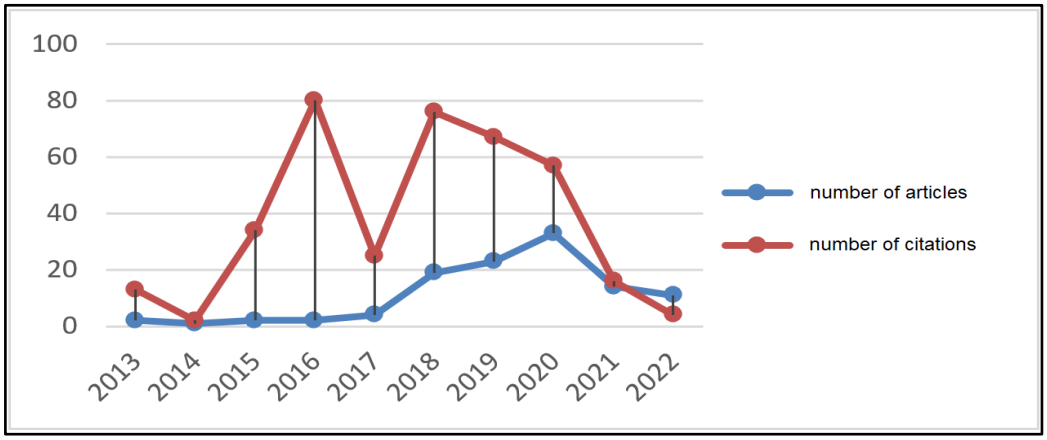

Figure 2. Publication and citation trend of the documents from 2013 until 2022

Figure 2 shows the development of "mathematical representation" publications from 2013 to 2022. The largest increase in publications occurred in 2020, with 33 documents. However, the number of publications in 2021 and 2022 has decreased to 16 and 11 published documents, respectively. These findings indicate that the development of the publication of documents regarding "mathematical representation" is relatively fluctuating. It is estimated that the publication trend in the Scopus database will decline by the end of 2023, considering the trend that occurred in the previous two years.

Meanwhile, the development of citations is also relatively fluctuating. Most of the citations occurred in 2016, with 80 of which 62 were obtained from the article by Jitendra et al. (2016) and 18 from Hebert and Powell (2016). Then, the year with the second highest number of citations was 2018, with 76 citations, of which 34% were contributed by articles written by Yuanita et al. (2018) with 26 citations. However, from 2018 to 2022, there has been a significant decline in the citation of related articles. Therefore, it is necessary to conduct further research to identify the factors that influence the development of publications and citations related to "mathematical representation.

From the 99 articles selected, 31 articles came from journals, and 68 were from conferences. This shows the dominance of documents from conferences compared to journals. Although several bibliometric analyses show that many authors prefer to publish journal articles (Fuad et al., 2022; Juandi et al., 2022; Saregar et al., 2022), this is not in accordance with our findings. This may be due to the difficulty of publishing Scopus-indexed articles in related journals. The divergence observed in our study's outcomes may be feasibly linked to the unique forces shaping mathematical representation as a research topic in Scopus-indexed publications. These journals, characterized by their exceptional rigor and competitive landscape, may exhibit a decreased propensity to accept articles focusing on mathematical representation, influenced by a number of variables. This could possibly stem from perceptions of insufficient originality or lack of meaningful additions to the established body of knowledge, since the stewards and evaluators of these publications typically accord higher priority to research endeavors that break new ground and introduce innovation.

3.2. Science Mapping and Network Analysis

3.2.1. Citation analysis

Citation analysis analyzes the relationship between publications by identifying publications cited by other researchers in related fields (Donthu et al., 2021; Fuad et al., 2022). This study will use citation analysis to display documents, authors, countries, affiliations, journals, and publishers related to mathematical representation abilities in the 2013-2022 period. Each component of the research is specifically and comprehensively explained. The contribution of documents most related to mathematical representation ability is measured using the h-index, which will be used as a benchmark in research (Donthu et al., 2020). Table 2 shows that the h-index of the collection of documents that have been obtained is 10, meaning that eleven documents contribute related to mathematical representation ability.

Table 2 shows that the research conducted by Jitendra et al. (2016) entitled "Is mathematical representation of problems an evidence-based strategy for students with mathematics difficulties?" is a highly contributed article and has been cited 62 times by other articles. This shows that the document has an average of six citations per year from 2013-2022. In addition, the document's authors are affiliated with various countries, including Indonesia, which have made a high contribution regarding mathematical representation

ability. It is important to note that all documents with the highest number of citations are journal articles, indicating that they have a very important role in the eleven with the highest number of citations.

Table 2. Ten documents with the highest citation

Author(s)	Title	Journal	Year	Citation
Jitendra, A. K., Nelson, G., Pulles, S. M., Kiss, A. J., & Houseworth, J.	Is the mathematical representation of problems an evidence-based strategy for students with mathematics difficulties?	Exceptional Children	(2016)	62
Yuanita, P., Zulnaidi. H., & Zakaria, E.	The effectiveness of realistic mathematics education approach: The role of mathematical representation as a mediator between mathematical belief and problem-solving	Plos One	(2018)	26
Bolden, D., Barmby, P., Raine, S., & Gardner, M.	How young children view mathematical representations: A study using eye-tracking technology	Educational Research	(2015)	19
Hebert, M. A., & Powell, S. R.	Examining fourth-grade mathematics writing: Features of organization, mathematics vocabulary, and mathematical representations	Reading and Writing	(2016)	18
Zhang, J., Xu, P.-D., & Wang, F.-Y.	Parallel systems and digital twins: A data-driven mathematical representation and computational framework.	Acta Automatica Sinica,	(2020)	15
Earnest, D.	From number lines to graphs in the coordinate plane: Investigating problem-solving across mathematical representations	Cognition and Instruction,	(2015)	15
Nie, B.-D., & Cao, B.-Y.	Three mathematical representations and an improved ADI method for hyperbolic heat conduction.	International Journal of Heat and Mass Transfer,	(2019)	14
Park, E.-J., & Choi, K.	Analysis of student understanding of science concepts, including mathematical representations: pH values and the relative differences of pH values.	International Journal of Science and Mathematics Education	(2013)	13

Author(s)	Title	Journal	Year	Citation
Supandi, S., Waluya, S. B., Rochmad, R., Suyitno, H., & Dewi, K.	Think-Talk-Write model for improving students' abilities in the mathematical representation	International Journal of Instruction	(2018)	12
Widakdo, W. A.	Mathematical representation ability by using project-based learning on the topic of statistics	International Conference on Mathematics and Science Education	(2017)	12

Furthermore, of the ten documents published, it shows that in one year, two documents were published at most, namely in 2015, 2016, and 2018. This shows that these documents strongly influence studies related to mathematical representation. Of the ten documents, there is one document from British authors (Bolden et al., 2015), one document from South Korean authors (Park & Choi, 2013), two documents from Chinese authors (Nie & Cao, 2019; Zhang et al., 2020), three documents from United States authors (Earnest, 2015; Hebert & Powell, 2016; Jitendra et al., 2016), and three documents from Indonesian authors (Supandi et al., 2018; Widakdo, 2017; Yuanita et al., 2018). This shows that most of the documents are dominated by Asian researchers.

The author's contribution to mathematical representation ability is measured based on the total number of publications and citations received. Table 3 shows the five authors with the most publications and the largest citation scores.

Table 3. Five authors with the highest number of publications and citations

Author	Total Publications	Total Citations	Affiliation
Kuswanto, H.	5	18	Universitas Negeri Yogyakarta
Septian, A.	3	5	Universitas Suryakancana
Retnawati, H.	3	4	Universitas Negeri Yogyakarta
Jupri, A.	3	4	Universitas Pendidikan Indonesia
Wilujeng, I.	3	2	Universitas Negeri Yogyakarta

Table 3 shows that Kuswanto is a very prolific writer, having published five documents that were cited 18 times. The five documents, the most cited document is entitled "Android physics comics to train the mathematical representation of abilities on momentum and impulse of senior high school students," published in 2020 (Priyadi et al., 2020). Furthermore, Septian became the author with the second most documents by publishing three documents, which were cited five times. Of the three documents, the most cited document is "Mathematical representation ability through geogebra-assisted project-based learning models," published in 2020 (Septian, Darhim, et al., 2020). After that, Retnawati and Jupri became the authors with the third most documents by publishing three documents each, and these documents were cited four times. Of the three documents, the one most cited by Retnawati's author is "Mathematical representation: The roles, challenges, and implications on instruction," published in 2019 (Samsuddin & Retnawati, 2018). The most cited

document by Jupri's author is "Students' ability of mathematical representation on statistics topic in elementary school," published in 2016 (Farokhah et al., 2019).

Total publications and citations measure countries contributing greatly to mathematical representation ability. There are seven authors with the highest publication and citation scores in Table 4.

Table 4. Six countries with the highest publications and citation scores

Country	Total Publication	Total Citation
Indonesia	78	155
United States	8	104
China	3	29
South Korea	1	13
Malaysia	1	2
United Kingdom	1	1

Table 4 shows that Indonesia is a country that contributes a lot and has published 78 documents related to mathematical representation abilities, where these documents are cited 155 times. Of the six countries, four are in Asia: Indonesia, China, South Korea, and Malaysia. One country is in America, namely, the United States, and one is in Europe, namely the United Kingdom. This shows that countries located in Asia made the biggest contribution regarding mathematical representation abilities in the 2013-2022 period. Fifteen countries contributed to this study, distributed to several continents, such as Asia, America, Europe, and Africa. The data are presented in Figure 3.

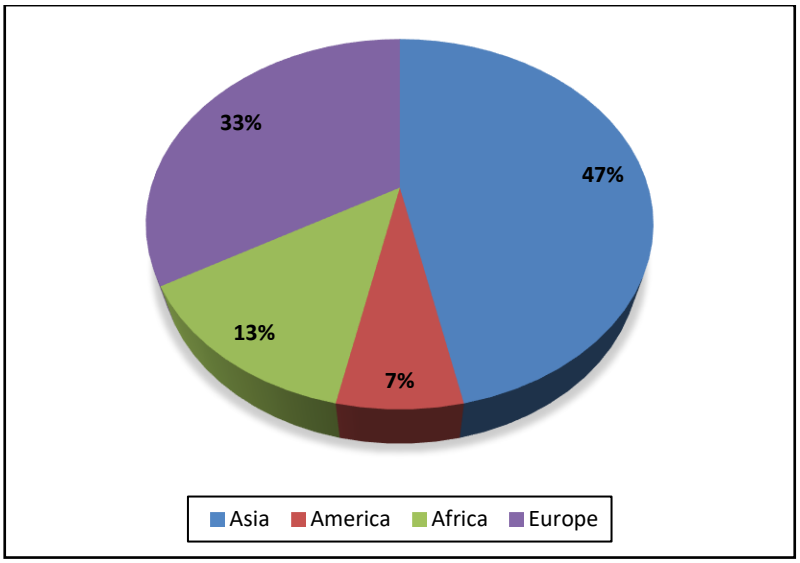

Figure 3. Distribution of countries on each continent

Figure 3 shows four continents contributing to the study of mathematical representation abilities, of which seven countries are in Asia, followed by five countries in Europe, two countries in Africa, and one in America. This shows that most countries that contributed were those located in Asia in the 2013-2020 period. Ahyan et al. (2021) also revealed that in terms of bibliometric analysis studies that have been carried out, the publications that have contributed the most from several countries are located in Asia.

After that, total publications and citations measured the affiliation that contributed the most to mathematical representation ability. Five affiliates contribute to the publication, and the highest citation scores are presented in Table 5.

Table 5. Five publication affiliation and highest citations

Affiliation	Total Publication	Total Citation
Universitas Pendidikan Indonesia	3	14
Universitas Suryakencana	3	5
Universitas Lambung Mangkurat	2	14
Universitas Bengkulu	2	7
Universitas Negeri Yogyakarta	2	5

Table 5 shows that all affiliates related to the study of mathematical representation abilities are from Indonesia. The Indonesian University of Education is the affiliate with the most publications and citations, publishing three documents cited 14 times. Suryakencana University is the affiliate with the second-highest number of publications and citations by publishing three documents that have been cited five times. Lambung Mangkurat University is the third-highest affiliate, publishing two documents cited 14 times. Furthermore, Bengkulu University and Yogyakarta State University became the fourth and fifth-highest affiliates by publishing two documents cited 7 and 5 times, respectively. Overall, the five affiliates with the highest total publications and citations related to the study of mathematical representation abilities are located in Asia, specifically in Indonesia. According to research by Çoban and Tezci (2022), a bibliometric analysis study of mathematical ability shows that many affiliates who contributed to the publication are in Asia.

Furthermore, journals that greatly contribute to the study of mathematical representation ability are measured by the number of publications and citations. Seven journals contribute with the highest publications and citations presented in Table 6.

Table 6. Seven journals and publishers with the highest publications and citations

Journal/Conference	Publisher	Total Publication	Total Citation
Journal of Physics: Conference Series	IOP Publishing	56	78
Exceptional Children	SAGE Publication Ltd	2	62
International Journal of Instruction	Gate Association for Teaching and Education	2	23
Journal on Mathematics Education	Universitas Sriwijaya, in collaboration with the Indonesian Mathematical Society (IndoMS)	3	21
Educational Research	Taylor & Francis Group	1	19
Reading & Writing	Springer	1	18
AIP Conference Proceedings	AIP Publishing	6	12

Table 6 shows that the Journal of Physics: Conference Series is a journal that greatly contributes to the study of mathematical representation ability. The journal has published fifty-six documents from 2013-2022 with 78 citations. Journal of Physics: Conference Series is supported by IOP Publishing as a publisher that assists in publishing documents and provides open access. IOP Publishing is also the publisher with the highest contribution regarding the number of documents and citations in the study. In addition, research by Supriyadi (2022) also shows that journals with conference series make the highest contribution to the publication.

3.2.2. Co-word analysis

Co-word analysis is a way to reveal and explore hidden structures in text, seeking relationships between concepts in the research field. It can identify topics currently developing in a particular domain (Abbas et al., 2014; Callon, 1984; Sternitzke et al., 2008). This study utilizes co-word analysis to present the most frequently occurring keywords related to the study of mathematical representation. Furthermore, co-word analysis is employed to identify the distribution of keywords that appear most frequently in the current period. Initially, the author's keyword analysis is conducted to present the most frequently appearing keywords by selecting a minimum number of words from a set of 40 interconnected three-word keywords organized into five clusters: red, green, blue, yellow, and purple (see Figure 4).

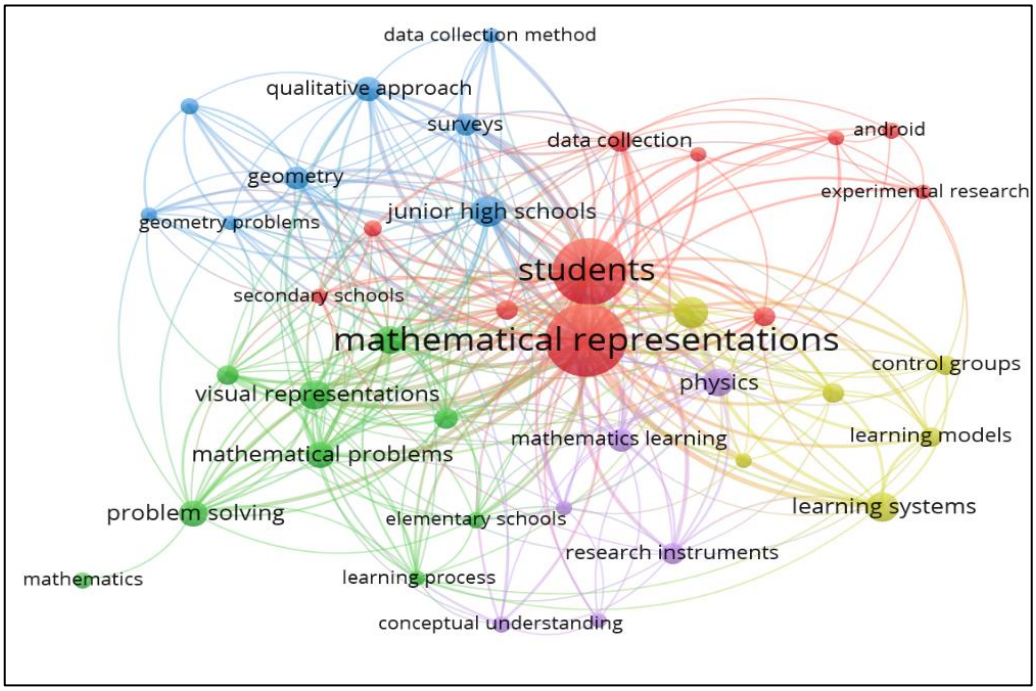

Figure 4. Network visualization of co-word analysis

Table 7 reveals that the red cluster consists of eleven keywords, the green cluster has nine keywords, the blue cluster has eight keywords, the yellow cluster has six keywords, and the purple cluster has six. Furthermore, the keyword "Mathematical Representations" appears most frequently in the red cluster, with 83 occurrences, followed by "Students" in the same cluster, which appears 57 times. The keywords "Education Computing" in the yellow cluster and "Junior High Schools" in the blue cluster occur 13 times. "Mathematical Representations" is the most prevalent keyword among the five clusters.

Among the 40 keywords organized into five clusters, several keywords exhibit a high occurrence in conjunction with "mathematical representation," namely "Student," "Junior High Schools," "Education Computing," and "Visual Representation." This indicates a close relationship between "mathematical representation" and these four keywords, suggesting mutual influence. To begin with, the keyword "Student" signifies that the utilization of "mathematical representation" can aid students in learning mathematics (Darmayanti et al., 2022; Hegarty & Kozhevnikov, 1999; Mainali, 2021). Additionally, the keyword "Junior High Schools" indicates that research about the use of "mathematical representation" primarily focuses on the junior high school level of education (Fauzan & Diana, 2020; Yuanita et al., 2018).

Furthermore, the keyword "Educational Computing" highlights that computing or technology plays a significant role in the implementation of "mathematical representation" (Umbara et al., 2020). Finally, the keyword "Visual Representation" underscores the importance of visualization as a key element in employing "mathematical representation" to enhance comprehension of mathematical concepts (Abdullah et al., 2012). Therefore, research related to "mathematical representation" should consider these factors: students, junior high school education, technology, and visualization. By considering these aspects, research can optimize the utilization of "mathematical representation" to enhance understanding of mathematical concepts and facilitate learning at the junior high school level."

Table 7. Hierarchical clustering of keywords

Cluster	Keyword	Number of Occurrences	Total Link Strength
Cluster 1 (Red)	Mathematical Representations	83	277
	Students	57	254
	Data Collection	6	33
	High School Students	5	21
	Mathematical Problem Solving	5	23
	Education	4	16
	Android	4	9
	Android (Operating System)	3	13
	E-Learning	3	11
	Experimental Research	3	14
	Secondary Schools	3	17
Cluster 2 (Green)	Visual Representation	11	64
	Mathematical Expressions	10	59
	Mathematical Problems	9	58
	Problem-Solving	9	44
	Qualitative Research	6	35
	Symbolic Representation	5	37
	Elementary School	4	22
	Mathematics	4	1
	Learning Process	3	22
Cluster 3 (Blue)	Junior High Schools	13	67
	Qualitative Approach	8	39
	Geometry	7	33
	Surveys	6	31
	Research Subjects	4	20

Cluster	Keyword	Number of Occurrences	Total Link Strength
	Data Collection Method	3	15
	Geometry Problems	3	21
	Qualitative Method	3	19
Cluster 4 (Yellow)	Education Computing	13	66
	Learning Systems	11	46
	Control Groups	5	20
	Learning Models	5	25
	Mathematical Education	5	27
	Calculations	3	12
Cluster 5 (Purple)	Physics	10	41
	Mathematical Learning	7	33
	Research Instruments	6	28
	Conceptual Understanding	4	15
	Multiple Representation	3	15
	Teaching	3	7

Moreover, several keywords describe the technology utilized in the learning process concerning mathematical representation, such as "E-learning," "Android," and "Android (Operating System)." In general, digital technology has become extensively employed in education. Cooper (2019) argues that digital technology is widely utilized in education and has become an integral part of the modern education system. Various digital technologies are employed in multi-representational learning, including Zoom meetings, Google Meet, Google Classroom, Edmodo, and Moodle (Diaz-Nunez et al., 2021; Fitriani et al., 2021; Ngo & Ngadiman, 2019). Overall, digital technology serves as a valuable tool to support learning activities related to mathematical representation

Secondly, visualization overlay analysis is employed to identify the keywords with the highest occurrence in the current period. The author uses a keyword analysis approach to present the keywords by selecting a minimum number of words from each, with at least one word appearing in 356 related keywords. Figure 5 showcases several noteworthy keywords, including "design and evaluation," "interactive learning environment," "comparative research," "artificial intelligence," and "augmented reality," which are the most recent keywords appearing in 2022.

Based on these findings, it can be concluded that there exists a connection between the two concepts of learning and the representation of mathematics through the application of interactive technology and computer media. This demonstrates that using interactive technology and computer media can effectively support learning processes and the development of mathematical skills. The study also highlights the significant relationship between learning and mathematical representation and how interactive technologies can be harnessed to enhance this relationship.

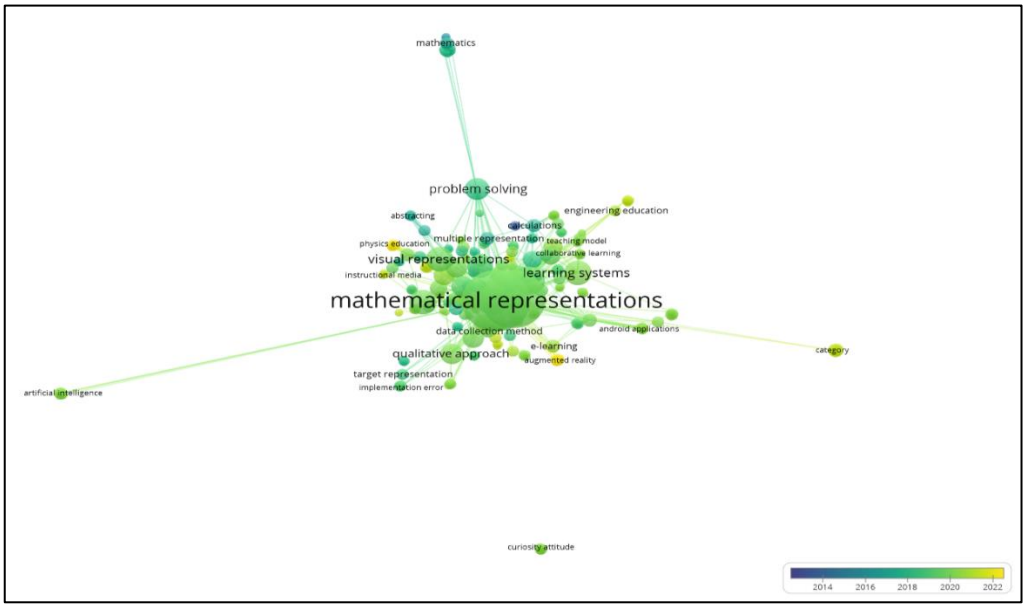

Figure 5. Overlay visualization of co-word analysis

3.2.3. Co-author analysis

Co-author analysis is used to see social interactions or relationships between authors and affiliations and countries in the development of the research field being studied. It is also used to represent the social relations between the writer and the country of origin related to mathematical representation ability. In addition, this analysis is also used to see authors who made major contributions in the 2013-2022 period.

First, the author's unit of analysis is used to present social interactions between authors by selecting a minimum number of author documents of two documents. There are six authors in five groups, red, blue, green, purple, and yellow, presented in Figure 6.

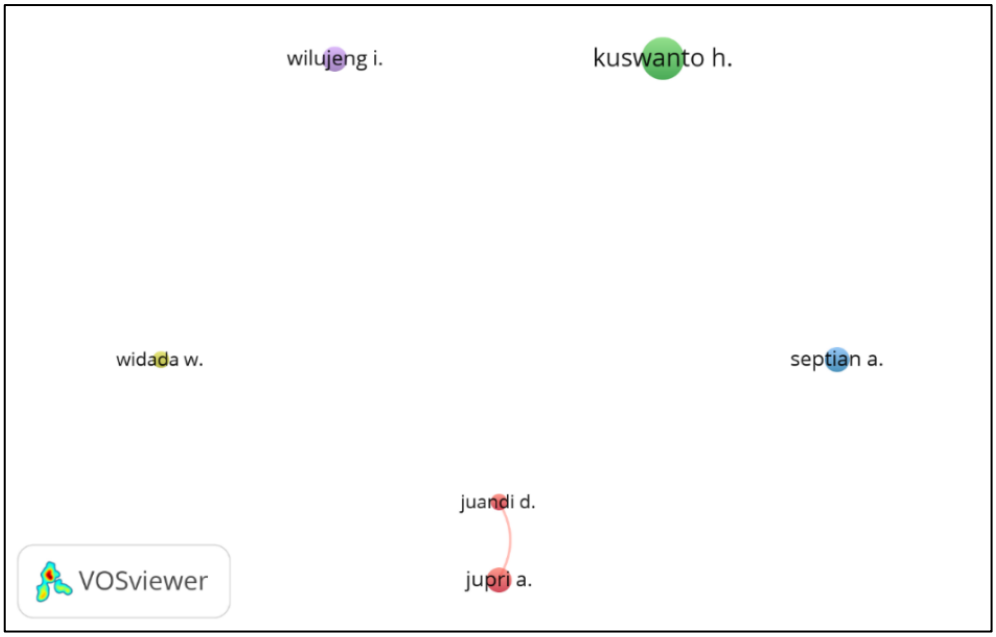

Figure 6. Network visualization of co-word analysis

Figure 6 shows that Juandi and Jupri are in the red group, followed by Septian in the blue group, Kuswanto in the green group, Wilujeng in the purple group, and Widada in the yellow group. Juandi and Jupri are two writers who have social relations. They conducted the same research titled "Didactical design for distance concept in solid geometry to develop mathematical representation ability in vocational high school" (Rahayu et al., 2021). Still, they also conducted a separate study related to mathematical representation abilities. Juandi conducted a study on geometric transformation material (Nirawati et al., 2020), and Jupri on basic statistics material (Farokhah et al., 2019). Meanwhile, the other authors, namely Septian, Kuswanto, Wilujeng, and Widada, had no relationship with each other, nor did they interact socially with Juandi and Jupri. Kuswanto has published five documents related to mathematical representation ability on the effectiveness of the use of carom comic game learning media (Rahayu & Kuswanto, 2021), multimedia learning modules (Setiyadi et al., 2019), Android-based Google Classroom (Wulandari et al., 2019), as well as physics comics (Sari et al., 2020) and CAKA (Kurniawan & Kuswanto, 2021) based on local wisdom. Meanwhile, Septian examines learning related to increasing mathematical representation abilities assisted by GeoGebra by applying somatic, auditory, visualization, intellectual, and project-based learning models (Septian, Suwarman, et al., 2020) and GeoGebra in the integral field (Septian, Darhim, et al., 2020). Wilujeng examines learning related to increasing mathematical representation abilities with the help of e-books (Haryanti et al., 2020) and web modules with image representations (Ahmad & Wilujeng, 2018), while Widada examines ethnomathematics-based mathematical representation abilities through realistic mathematics learning (Widada, Nugroho, et al., 2019) and inquiry learning (Widada, Herawaty, et al., 2019).

Secondly, overlay visualization analysis is used to see authors who contributed a lot to writing articles for 2013-2022. The author analysis unit presents new authors by selecting a minimum number of one author's document appearing in the 278 authors in Figure 7.

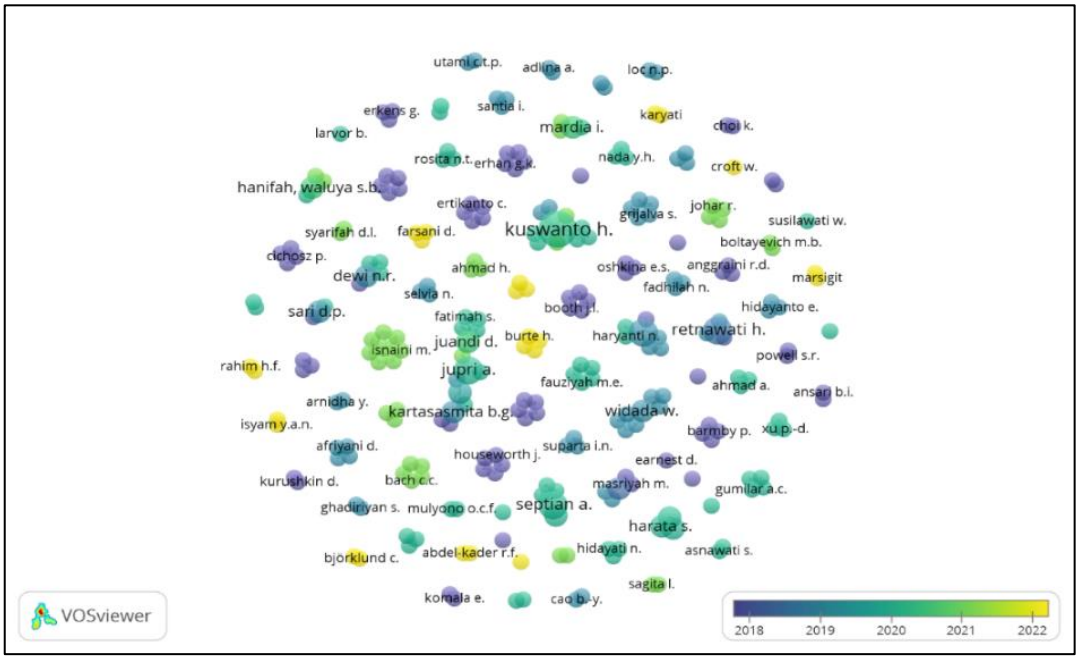

Figure 7. Overlay visualization of co-author analysis

Figure 7 shows that many writers in the 2022 period related to mathematical representation abilities. Karyati, Isyam, Hidayati, Risnawati, Mumpuni, Za'ba, Nufus,

Taqwa, and Rahin are affiliated in Indonesia. Croft, Shaghaghian, Burthe, and Song are affiliated in the United States. Ippolti is affiliated with Italy. Bjorklund and Palmer are affiliated in Sweden. Abulenin and Abdelkader are affiliated in Egypt. Khatin-Zadeh is affiliated with China, and most recently, Farsani is affiliated with Canada. This shows that learning related to mathematical representation ability in the current period, namely 2022, is carried out by researchers in most countries, who come from 7 countries and three different continents, such as Asia, America, and Europe. Several bibliometric analysis studies also show that many researchers in most countries have conducted research related to representation ability

Thirdly, network visualization analysis presents social relations among the author's countries regarding mathematical representation abilities. The country's analysis unit will present social interaction between the author's countries by selecting a document from a country. Three writing countries have social relations from the 24 writing countries, presented in Figure 8.

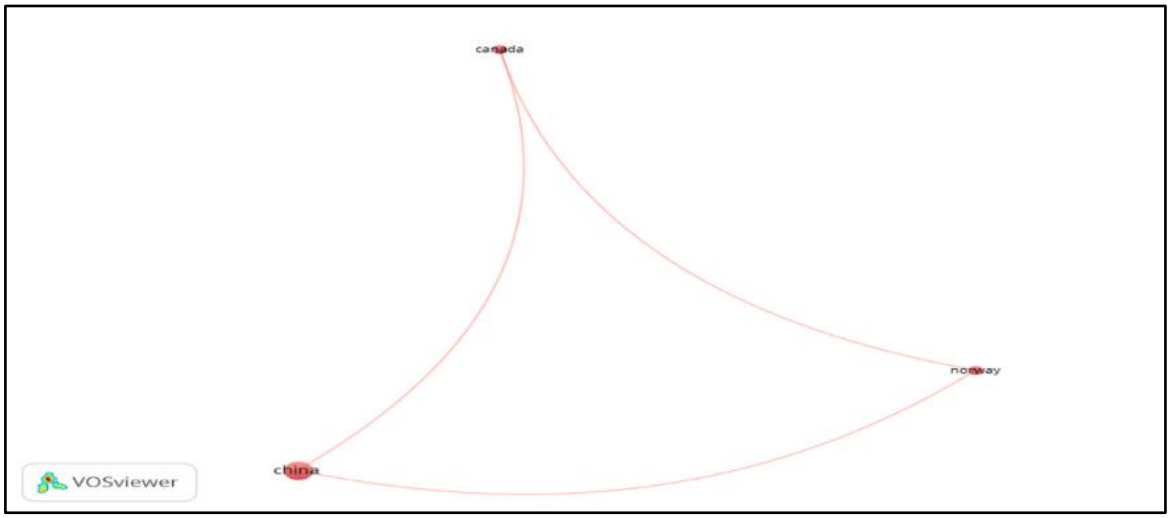

Figure 8. Network visualization of co-author analysis in country unit

Figure 8 shows that of the 24 countries that contribute regarding mathematical representation abilities, three countries have social relations between the authors' countries consisting of Canada, China, and Norway. This means that every continent, namely Asia, America, and Europe, has social relations that connect the author's countries. (Chen et al., 2023) also revealed that America has research networks or social relations with writers in Asia, Europe, and other continents such as Australia and Africa.

4. CONCLUSION

This bibliometric analysis study provides information related to trends and developments in research on mathematical representation over the past century. During this period, 99 publications and 374 citations related to mathematical representation were identified, with the number of publications and citations showing relative fluctuations. The most influential document, with 62 citations, was written by Jitendra and his colleagues and is titled "Is the mathematical representation of problems an evidence-based strategy for students with mathematics difficulties?" Furthermore, Indonesia was the most productive and contributing country, publishing 78 documents cited 155 times, while Yogyakarta State University was the most productive and influential affiliate, publishing five documents cited

18 times. The Journal of Physics Conference Series was identified as the most productive and influential journal/conference, publishing 56 documents cited 78 times.

In the last decade, mathematical representations have become closely related to students, secondary schools, and technological media in learning. These elements are useful for increasing students' ability to understand mathematical concepts. Several digital technologies have been used in multi-representational learning, such as Zoom meetings, Google Meet, Google Classroom, Edmodo, Geogebra, Kahoot, and Moodle. Studies on technology-based learning show that interactive technology and computer media can effectively support learning and improve math skills. This study emphasizes the importance of the relationship between learning and mathematical representation and how interactive technologies can support the relationship.

This research has special implications for learning mathematics, where teachers or lecturers can apply various learning approaches to improve students' mathematical representation abilities. In addition, electronic media such as Kahoot, Zoom, Geogebra, and Moodle are digital technologies that can help improve students' mathematical representation abilities. Thus, learning and media developed based on mathematical representations are very important in the learning process because they can help students better understand mathematical concepts.

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