



BIBLIOMETRIC ANALYSIS OF SCIENTIFIC STUDIES ABOUT MATHEMATICAL PROBLEM SOLVING

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Abstract: This research aims to conduct a bibliometric analysis of articles on mathematical problem solving published at various educational levels. The Web of Science database was used to screen primary studies. As of January 13, 2025, the final number of studies passing through the PRISMA flow diagram was reduced to 523. The analysis findings demonstrate a significant surge in the volume of publications and citations related to mathematical problem solving following 2010. The United States is leading in productivity and impact, while China's strong collaboration with the U.S. enhances its impact value. Türkiye ranks third in productivity, and regional collaborations in European and Asian countries contribute to the increasing number of influential publications. Recent research trends have shifted towards digitalization and individual differences. While studies focusing on mathematics education theories and problem solving form one cluster, research on self-regulation and learning strategies constitutes a separate cluster. In future studies, quantitative findings obtained through bibliometric analysis can be supported by integrating qualitative findings from systematic literature reviews and other qualitative methods.

Key words: Mathematics, problem solving, bibliometric analysis, literature review.

1. Introduction

Problem-solving is a vital component of mathematics education (Liljedahl et al., 2016), facilitating the connection between mathematical concepts and real-life scenarios (Verschaffel et al., 2010). In elementary school, students begin engaging with mathematical problem-solving, transforming word problems into mathematical expressions using appropriate arithmetic operations. This process encourages students to question mathematical concepts, as they must determine the appropriateness of concepts for given situations, enhancing their mathematical insight (Lithner, 2008). Various studies have been conducted on the pedagogy of problem-solving, one of the most significant research areas in mathematics education (Liljedahl et al., 2016; Cai et al., 2005). Despite the general agreement in the literature on the effectiveness of mathematical problem-solving, Suseelan et al. (2022) highlighted the importance of bibliometric studies, citing disagreements regarding the effectiveness of different methods. Bibliometric analysis helps identify research gaps and focal points (Chen et al., 2018).

The term "mathematical problem-solving" has been explored in conjunction with metacognition (Jacobse & Harskamp, 2012; Izzati & Mahmudi, 2018; Desoete, Roeyers & De Clercq, 2003), creativity, motivation, technology integration (Symons & Pierce, 2019; Cruz & Martinez, 2012; Gautam, 2023), and individual differences (Mayer, 1993; Threadgill-Sowder, 2013; Tazeyeva, Arsalidou & Konopkina, 2021; Vessonen et al., 2024) (Kıymaz, 2009; Kara, 2013; Kandemir, 2006; Ipekoğlu & Kepceoğlu, 2024; Esendemir, 2011; Saka & Durmuş, 2021; Pohan, Asmin & Menanti, 2020; Irhamna, Amry & Syahputra, 2020; Özcan & Eren Gümüş, 2019; Özcan, 2016; Hutajulu, Wijaya & Hidayat, 2019). Identifying current trends in mathematical problem-solving is crucial for guiding future research and recognizing research gaps.

Throughout history, humans have perceived objects in their surroundings and assigned numerical values to them, initially using this system for counting. Over time, they encountered various challenges and developed and applied mathematical structures such as counting and measurement to solve problems. At this point, situations that later emerged as problems and problem-solving have

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been regarded as central to mathematics (Halmos, 1980; Schoenfeld, 1985; NCTM, 2000; Olkun & TolukUçar, 2004; Liljedahl et al., 2016; Temel, 2018). In the literature, there is a strong consensus that problem-solving constitutes the core of mathematics (Çilingir, 2015; Loğoğlu, 2016; Divrik, 2019; Can, 2021). However, there is no complete agreement on providing adequate instruction to enhance individuals' problem-solving skills (Lester & Cai, 2016).

George Pólya (1887–1985) is widely recognized as a foundational figure in problem-solving. In his 1957 work, he described the problem-solving process as involving stages, from identifying appropriate strategies to resolving encountered challenges. In this context, when faced with a problem situation, an individual: (i) understands the problem, (ii) devises a plan for an appropriate solution, (iii) implements the plan, (iv) verify the result, and (v) evaluates the entire process from start to finish. Additionally, it has been noted that problem-solving is a fundamental activity for those engaged in mathematics (Halmos, 1980; Schoenfeld, 1985). Problem-solving, considered one of the five fundamental domains of school mathematics, is recognized as an essential competency that should be developed at all educational levels (NCTM, 1980, 2000; Zakaria et al., 2010; Liljedahl et al., 2016; MoE, 2018). Throughout their lives, individuals utilize their mathematical knowledge at the highest level during problem-solving processes (Krulik & Rudnick, 1996; Cai & Lester, 2010; Yew & Zamri, 2018). They apply their existing knowledge, develop strategies, and generate new approaches (NCTM, 2000). This internally constructed process highlights the significance of problem-solving. Given its extensive coverage in the literature, problem-solving has also been incorporated into Türkiye's national middle school mathematics curriculum (MoE, 2018, 2024). Furthermore, the NCTM (2000) standards emphasize that problem-solving should not only be considered an objective but also a tool to facilitate different learning experiences.

Extensive research has been conducted on problem-solving and various areas within mathematics education (Cai et al., 2005). Meta-analysis, meta-synthesis, and systematic reviews have been employed to examine prior studies, identify prevailing research patterns, and inform future investigations. In the national literature, problem-solving has been examined about topics such as student achievement and attitudes (Kaya, 2016; Kurt & Yeşilyurt, 2020), elementary school mathematics (Kanbolat & Balta, 2019; Bayar, 2023), and non-routine problems (Yeşil & Kablan, 2019). Additionally, studies on problem-solving, including theses and articles, have been analyzed using appropriate research methods (Baş & Katrancı, 2021; Coşkun & Soylu, 2021; Can & Özdemir, 2022; Ergül et al., 2022; Aksungur & Aydın, 2023). In international research, problem-solving has been explored from various perspectives, including schema-based instruction (e.g., Peltier & Vannest, 2017), challenges related to learning difficulties (e.g., Lambert & Tan, 2017; Cook et al., 2020; Lei et al., 2020), and the integration of problem-solving in mathematics curricula (e.g., Olivares et al., 2021), with appropriate methodological approaches applied throughout these studies.

In addition to these studies, a bibliometric analysis encompasses 159 studies on problem-solving in primary school mathematics education conducted between 1969 and 2021 in international literature (Suseelan et al., 2022). Bibliometric analysis studies enable a comprehensive examination of numerous studies on a specific topic, facilitating the identification of general trends. Such methods also enable the examination and visualization of both the collaborative networks among researchers and the underlying cognitive frameworks that inform the studies. In this context, a bibliometric analysis study on problem-solving, encompassing all years and all educational levels of studies published within the Web of Science (WoS) database, is significant for offering a broad perspective.

Studies on mathematical problem-solving predominantly focus on the middle school level. Given that fundamental skills are acquired at the elementary level and considering international assessments such as PISA and TIMSS, as well as high school entrance exams, the emphasis on middle school-level studies is understandable (Ipekoğlu & Kepceoğlu, 2024). Previous studies have examined mathematical problem-solving at the elementary level in Google Scholar between 2020 and 2023 (Zahrah et al., 2024) and between 1969 and 2021 (Suseelan, Chew & Chin, 2022). Suseelan, Chew, and Chin (2022) analyzed trends, citation analyses, country-wise distribution of studies, and global collaborations. Additionally, they identified key research focus in elementary-level mathematical problem-solving: (i) Arithmetic and mathematical forms of representation, (ii) Word problems in mathematics teaching and learning, (iii) Cognitive and affective elements in elementary problem-

solving, (iv) Algebra-related problem-solving and the teacher's role in guiding problem-solving instruction. However, their study was limited to the Scopus database and research up to 2021, highlighting the need to consider recent studies using multiple databases. The fact that Zahrah et al. (2024) and Suseelan, Chew, and Chin (2022) conducted their studies at the elementary level and the absence of other bibliometric analyses on mathematical problem-solving indicate a research gap encompassing all educational levels. In this context, the present study aims to investigate scientific publications in the field of Research, indexed in the SSCI, ESCI, and SSCI-expanded indices of the Web of Science database, using bibliometric approaches. The research questions that shape this study are as follows:

- (1) How have the number of publications and citations on mathematical problem-solving changed over the years?
- (2) Which countries are the most productive regarding publication count and have the highest impact on citations received on mathematical problem-solving studies?
- (3) Which institutions contribute the most publications and have the highest citation impact in the area of mathematical problem-solving research?
- (4) According to co-citation analysis, what scientific connections and relationships exist among the most frequently cited keywords in mathematical problem-solving research?
- (5) What are the relationships and scientific interactions in mathematical problem-solving studies based on author co-citation analysis?
- (6) What are the relationships and scientific interactions in mathematical problem-solving studies based on journal co-citation analysis?

2. Method

This study conducted a bibliometric analysis of articles related to mathematical problem-solving, sourced from the Web of Science database. Bibliometric analysis serves as a valuable tool in academic research evaluation, providing a quantitative approach to analyze, assess, and review large volumes of data (Donthu et al., 2021; Zupic & Cater, 2015; Dede & Özdemir, 2022). Bibliometric analysis also offers the opportunity to visualize and analyze trends, themes, and research gaps in studies within a specific field, as well as the collaboration structure of researchers, the intellectual structure guiding the studies, and the cognitive structure (Börner et al., 2003; Donthu et al., 2021; Van Eck & Waltman, 2014; Zupic & Cater, 2015). Bibliometric metrics such as total number of publications, total number of citations, average number of citations, normalized citation count, and average normalized citation count are used in performance analysis to identify the publications, authors, keywords, institutions, journals, and countries in a particular field (Waltman, 2017; Zupic & Cater, 2015). In this context, this study aims to evaluate research on mathematical problem solving using bibliometric analysis techniques such as citation analysis (by countries and universities), co-occurrence analysis, and co-citation analysis (by authors and scientific journals). The general procedure of the study is presented in Figure 1.



Figure 1. *Searching procedure*

2. 1. Data collection

To conduct a bibliometric analysis of scientific studies related to mathematical problem solving, bibliometric data was obtained from the widely used and accepted Web of Science (WoS) database on January 13, 2025. WoS was chosen for this study over other scientific databases due to its widespread

use, acceptance by large academic audiences, and its comprehensive inclusion of the most prestigious and high-quality publications (Birkle et al., 2020; Zhang et al., 2016). Zupic and Cater (2015) have outlined two methods for collecting bibliometric data. The first method involves conducting research using keywords. In contrast, the second consists of examining all publications from a scientific journal or a small group of high-quality scientific journals in the field. In the present study, keyword research was employed since the goal was to access all publications related to mathematical problem-solving in mathematics education. Therefore, the first step involved searching for the WoS database using the keyword "mathematical problem solving" through the topic (title, abstract, keywords) field. As a result of this search, 1253 studies related to mathematical problem solving were identified (see Table 1 and Figure 2).

Table 1. *Criteria used for article selection*

Criteria	Value
Data Source	Wos (Web Of Science)
Searching for words	"Mathematical Problem Solving"
Publication period	Until January, 2025
Searching fields	Education research
Publication type	Article
Citation index	SSCI, ESCI and SSCI-Expanded
Number of articles	523

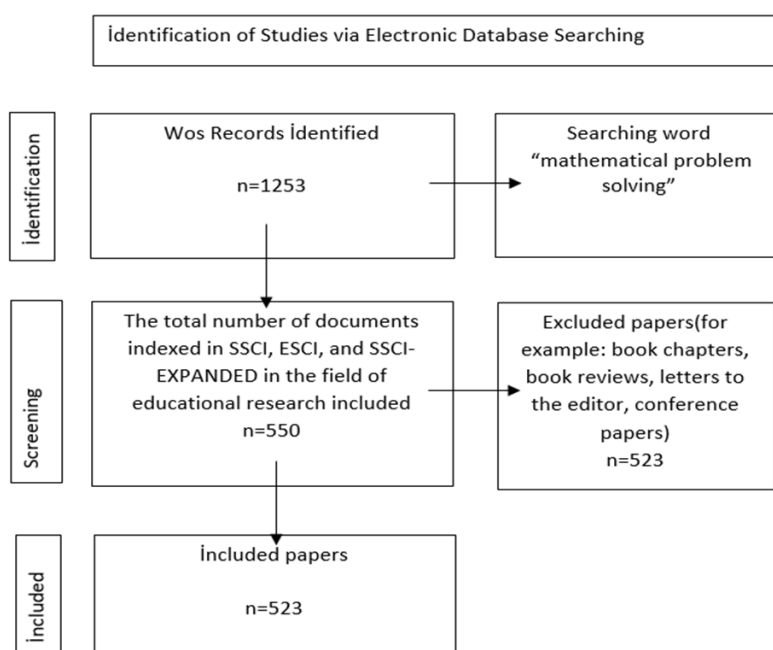


Figure 2. *PRISMA flow diagram*

The research area filter was applied, selecting "Education & Educational Research" from the WoS research areas. This focused the study on 833 scientific works in the field of education. The publication type filter also excluded book reviews, book chapters, editorials, and conference papers, leaving 557 articles for analysis. Finally, only articles indexed in the SSCI, ESCI, and SCI-expanded indices of Web of Science were included, resulting in 523 articles being part of this study. In addition to the above restrictions, only articles published by January 13, 2025, were included in this study.

2. 2. Data screening and cleaning

Since bibliometric data may contain duplicate, erroneous, or incomplete records, cleaning and organizing the data before starting the bibliometric analysis is crucial. This step ensures that the

analyses yield more accurate and reliable results (Donthu et al., 2021; Van Eck & Waltman, 2014; Zupic & Cater, 2015). Therefore, after obtaining all bibliometric data for the 523 articles from the WoS database, this study proceeded with examining, organizing, and correcting errors in the data. No erroneous, incomplete, or duplicated data were found in the reviewed articles.

2. 3. Data Analysis

In this study, the bibliometric data of 523 articles were analyzed using version 1.6.17 of the VOS viewer software. VOS viewer, a distance-based visualization tool, displays frequently co-occurring items within the same color-coded cluster, representing the strength of the relationship between items through links (Van Eck & Waltman, 2010; Van Eck & Waltman, 2014). Each item is represented as a node, and the node's size indicates that the item occurs more frequently, is more influential, or is more essential in the examined characteristic. Additionally, related items are shown in proximity to each other, and the thickness of the links represents the strength of the relationship between two items—the stronger the relationship, the thicker the link (Dede & Özdemir, 2022). VOS viewer was chosen for this study due to its free availability and ability to generate bibliometric maps to represent relationships within large datasets easily.

Bibliometric analysis is generally classified into two main categories: performance analysis and scientific mapping (Cobo et al., 2011; Donthu et al., 2021; Zupic & Cater, 2015). Performance analysis is a bibliometric method that measures the contributions of authors, publications, or institutions within a specific research area to assess their productivity and impact. At the same time, scientific mapping is a bibliometric analysis method that visualizes knowledge networks in a research area and examines the relationships and interactions between research entities (authors, publications, countries, institutions) (Cobo et al., 2011; Donthu et al., 2021). In this study, performance analysis and scientific mapping were employed to explore and interpret the cognitive and intellectual landscape of mathematical problem-solving research within the WoS database.

To more accurately compare the effectiveness of countries based on current publications, the average normalized citation count metric is used, which balances the changes in citation counts of publications across different years and allows for a more accurate measurement of the relative impact of these publications (Waltman, Van Eck, & Van Raan, 2011). Citation analysis was conducted to identify the most influential and valuable countries and universities in the field of mathematical problem solving. Additionally, co-citation analysis was performed to visualize the relationships between authors and journals, as well as the scientific interaction networks, with a focus on pioneering and foundational publications in mathematical problem-solving research. On the other hand, co-occurrence analysis aimed to reveal trends, research themes, and notable keywords that will be significant in the field in the future.

3. Findings

This section presents the data obtained from the WoS database and the findings generated using the VOS viewer program.

3. 1. Change in the number of publications and citations of scientific papers on mathematical problem solving over the years

A descriptive analysis was conducted to examine trends in the number of publications and citations over the years. Figure 3 illustrates the evolution of publications on mathematical problem solving and the corresponding citations received over time.

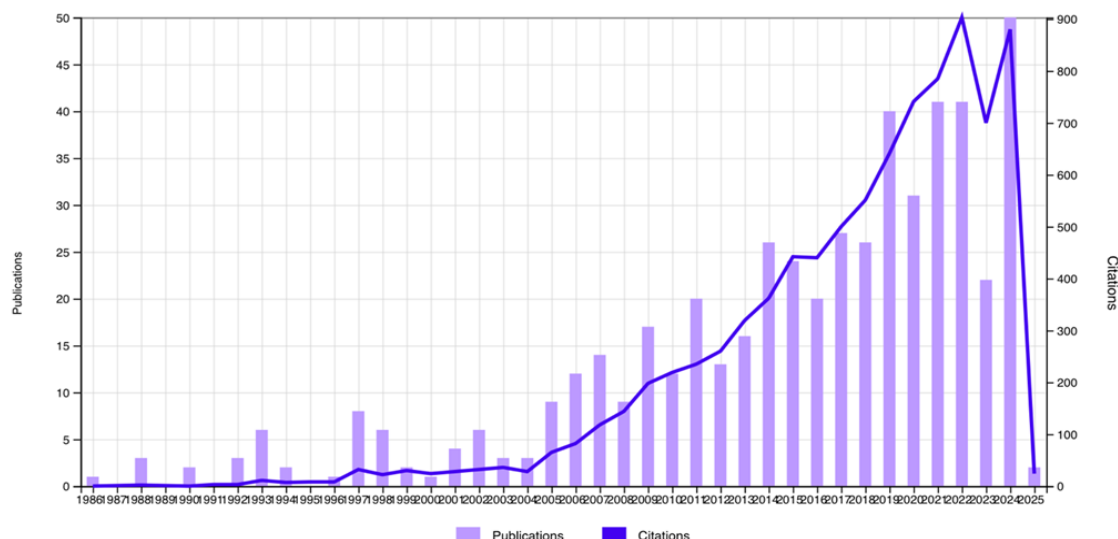


Figure 3. Changes in the total number of publications and citations over the years

Figure 3 provides a comprehensive overview of the temporal distribution of publications and citations related to mathematical problem-solving between 1986 and 2025. The data indicate that annual publication counts remained relatively low until the early 2000s, followed by a notable upward trend that began in the mid-2000s and accelerated significantly after 2010. This increase culminated in 2024, which recorded the highest number of publications (50 articles, 9.5%), with 2021 and 2022 maintaining a consistent output (41 articles, 7.839% each). Despite a marked decrease in 2023, the overall trend suggests sustained academic growth in the field. Citation counts followed a similar trajectory, remaining limited in the early years and rising considerably after 2010, reflecting the increasing impact and recognition of the research. Although a recent decline in citations is observed, this is likely due to the recency of publications, which have not yet had sufficient time to accrue citations. The parallel rise in both publication and citation metrics between 2010 and 2020 underscores a period of significant scholarly momentum, highlighting the field's growing academic relevance.

3. 2. Citation analysis of scientific publications on mathematical problem-solving by country

A citation analysis was conducted to identify the most influential and productive countries in mathematical problem-solving research. In the citation analysis, the criteria were set in VOS viewer to include countries with at least two publications and five citations. Among the 59 countries analyzed, 36 met these criteria and were included in further analysis. To narrow the focus of the study and provide meaningful and reliable research findings based on solid foundations, the 20 most influential and productive countries were selected and presented in Table 2. An examination of Table 2 reveals that, regarding both productivity and impact in the relevant literature, the United States holds the leading position with 168 publications and 3,845 citations. In terms of productivity, the United States is followed by Spain and Türkiye, while in terms of impact, Singapore and Israel follow. Another noteworthy finding in Table 2 is that although Türkiye ranks as the third most productive country in the field, it ranks eleventh in terms of the number of citations received.

Table 2. The most influential and productive countries in mathematical problem-solving research

Order	Country	Number of Articles	Total Citations	Avg. Citations	Norm. Citations	Avg. Norm. Citations
1	ABD	168	3845	22.89	167.98	0.14
2	Türkiye	26	198	7.62	25.98	0.29
3	Canada	18	173	9.61	18.00	0.53
4	Netherlands	11	137	12.45	11.00	1.13
5	Spain	39	205	5.25	39.04	0.13
6	Germany	20	291	14.55	20.00	0.73

7	Israel	19	477	25.11	18.99	1.32
8	England	21	308	14.67	21.00	0.70
9	China	19	250	13.16	19.00	0.69
10	Taiwan	14	396	28.29	14.00	2.02
11	Singapore	12	674	56.17	12.00	4.68
12	Sweden	15	163	10.87	14.00	0.78
13	Belgium	8	215	26.88	8.00	3.36
14	Finland	10	241	24.1	10.00	2.41
15	Indonesia	20	49	2.45	20.00	0.12
16	South Africa	17	99	5.82	17.01	0.34
17	Cyprus	4	116	29.00	4.00	7.25
18	Australia	18	222	12.33	18.00	0.69
19	Norway	7	43	6.14	7.00	0.88
20	France	2	5	2.5	2.00	1.25

Figure 4 visualizes the citation analysis by country. The findings indicate that the United States holds a central position in the international literature and is the most cited country. The U.S. has strong citation linkages with countries like the United Kingdom, Germany, Canada, and China (see Figure 5).

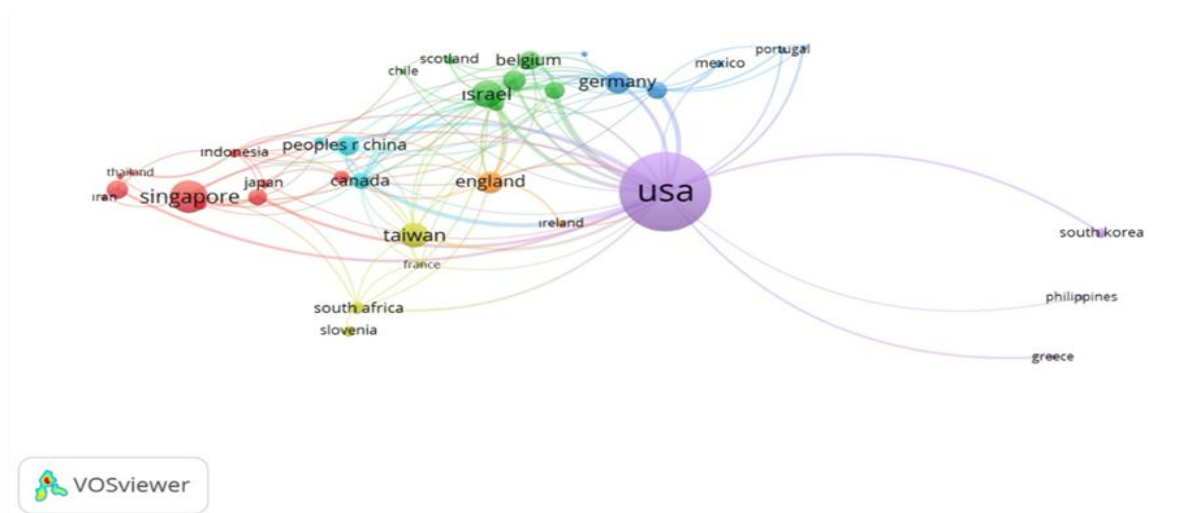


Figure 4. Visualization of countries based on citation count

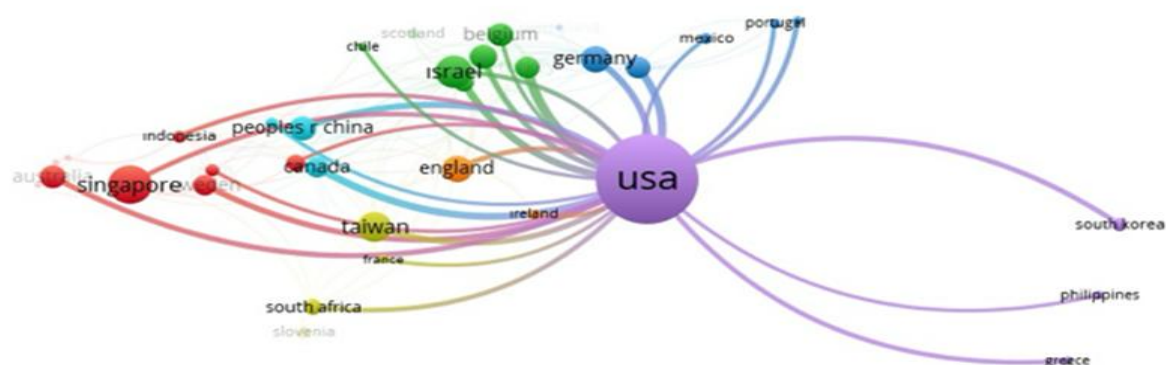


Figure 5. Visualization of the citation network of the United States with other countries

In Figure 5, the clusters reflect regional and thematic collaborations, with Asian countries grouped in the red cluster and European countries in the green cluster. The size of the nodes is related to the total number of citations for the countries. The United States has the largest node, with significant contributions from Singapore and China. Thick lines represent intense citation traffic, while thin lines

denote limited connections. Overall, the leadership of the United States and the regional collaborations between Asian and European countries are prominent, with smaller countries positioned at the periphery of the network. This analysis provides important insights into understanding international academic collaborations.

The research intensity and recency over the years in the citation network between countries are presented in Figure 6. The color scale represents the distribution of studies by year, with blue shades corresponding to older studies and yellow shades representing more recent ones. Accordingly, the countries that have conducted the most recent studies are Indonesia, Thailand, Chile, South Korea, the Philippines, and Switzerland.

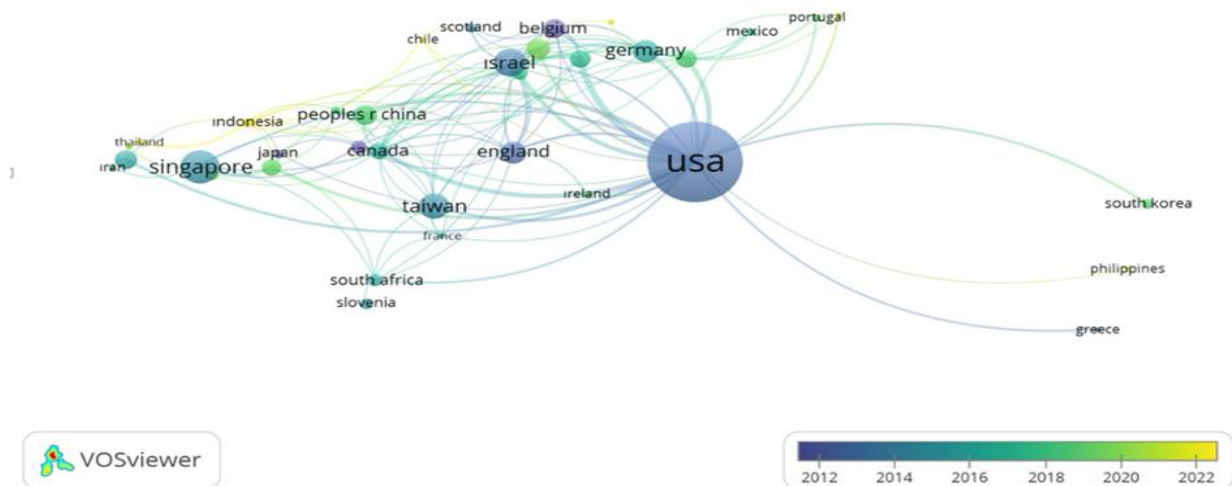


Figure 6. Visualization of citation counts for countries with the most recent publications

Recent publications in mathematical problem-solving tend to receive fewer citations than older articles. This creates challenges in comparing the impact of recently published papers with those published earlier in the field. The average normalized citation score metric more accurately compares countries' impact with recent publications. Countries' publications in mathematical problem-solving are visualized according to their average normalized citation count in Figure 7.

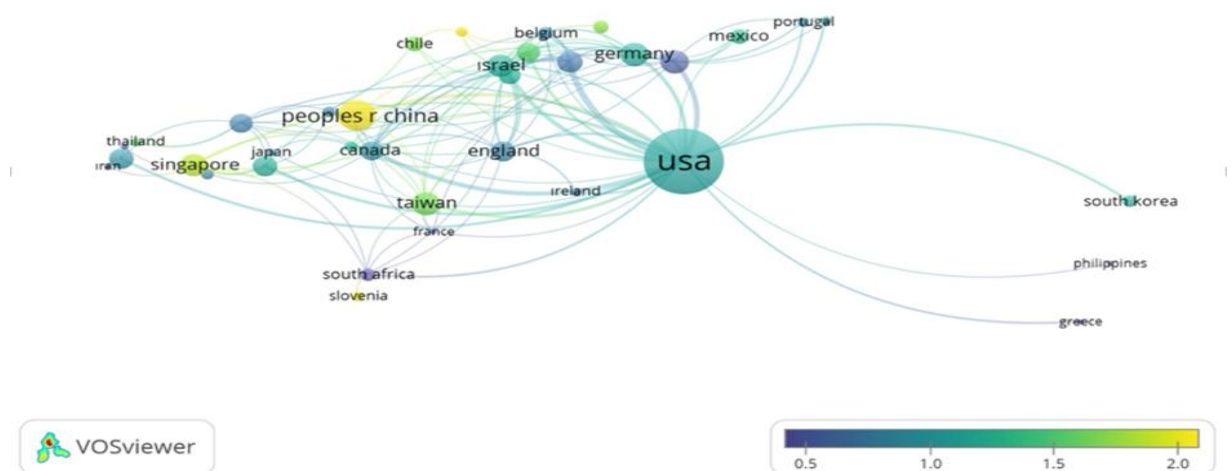


Figure 7. Visualization of countries based on average normalized citation count

The color scale in Figure 7 represents the average normalized citation count for each country. Blue shades (0.5-1.0) indicate countries with low average normalized citation counts, reflecting countries

with less impactful work in the literature, such as South Africa, the Philippines, and Greece. Green shades (1.0 - 1.5) represent countries with moderately effective research. These countries have more impactful work but are not in a leading position: Singapore, Portugal, and South Korea. Yellow shades (1.5 - 2.0) indicate countries with high average normalized citation counts, signifying countries with highly influential work in the literature, internationally recognized: the United States, the People's Republic of China, and Israel. The United States is the leader in both publication count and impact. China, with its strong collaborations with the U.S., has a high impact in the field, while Israel, despite fewer publications, has generated a significant normalized citation impact. With its high normalized citation count, Israel is a small but highly impactful player in the literature.

3.3. Citation analysis of scientific publications on mathematical problem-solving by institutions

To identify the most influential and productive universities in mathematical problem-solving, citation analysis established criteria within the VOS viewer program. A university was required to have at least one publication and a minimum of 50 citations. Out of 535 universities, 58 met these criteria. Further analysis was conducted with the 44 universities that had the highest connection strength and the strongest associations among these 58. The 20 most influential universities, ranked by citation count, are listed in Table 3. An examination of Table 3 reveals that the three most productive institutions in the field are, in order: Florida State University (USA), Vanderbilt University (USA), and the University of Minnesota (USA). Among the universities publishing scientific papers on mathematical problem-solving in the WoS database, Vanderbilt University (USA) emerged as the most influential institution, with 674 citations. While Florida State University (USA) ranks first in productivity, it ranks second in influence. Additionally, Nanyang Technological University, the most influential institution in the field, ranks third in productivity.

Table 3. *The most influential and productive universities in mathematical problem-solving research*

Order	University	Number of Articles	Total Citations
1	Florida State University	18	330
2	Miami University	8	331
3	University of North Caroline Charlotte	4	128
4	University of Minnesota	9	259
5	Vanderbilt University	14	674
6	University of Carolina	4	95
7	Harvard University	4	118
8	Missouri State University	2	125
9	University of Oviedo	4	71
10	University of Houston	2	148
11	Arizona State University	1	71
12	Bar Ilan University	9	348
13	Bronfman Jewish Education Centre	1	62
14	Lehigh University	2	125
15	University of Ghent	3	186
16	University of Missouri	3	142
17	Bahçeşehir University	3	68
18	Nanyang Technology University	11	665
19	Prince George's County Public Schools	1	118
20	University of Florida	1	60

The network map created using the VOS viewer to examine collaboration and citation relationships among universities is analyzed in Figure 8.

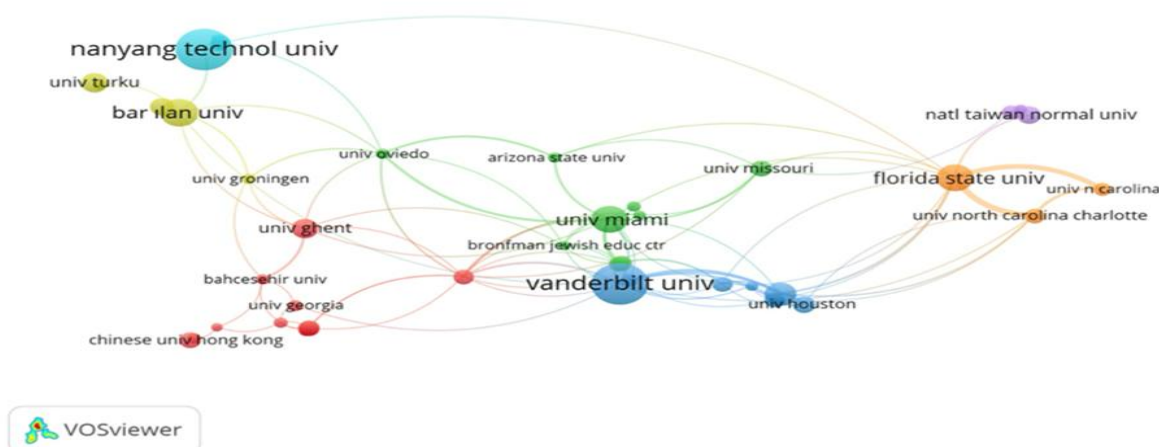


Figure 8. Visualization of institutions based on citation count

Citation analysis by universities helps visualize the intensity of connections between institutions and the central actors within the network, thereby revealing the structure of international academic collaboration. The clusters, represented by different colors on the map, illustrate the universities' strong collaborative relationships, with institutions such as Vanderbilt University, Nanyang Technological University, and Florida State University occupying central positions as key actors in the network. With high citation density, these institutions establish strong ties with other universities through their academic influence. Additionally, the connections between Nanyang Technological University (Singapore) and Bar-Ilan University (Israel), reflecting international collaboration, are noteworthy. Universities located at the map's periphery, with fewer connections, have a more limited impact. These findings provide valuable insights for enhancing academic collaboration and establishing strategic partnerships in mathematical problem-solving research.

3. 4. Co-word analysis of scientific publications related to mathematical problem solving

Co-occurrence word analysis has been applied to identify the most frequently discussed topics, concepts, and keywords in research on mathematical problem-solving. Additionally, the current trends and tendencies in the field over recent years have been explored by visualizing the conceptual framework of mathematical problem-solving studies. The co-occurrence word analysis was conducted using the VOS viewer program, and out of 1196 keywords examined, 99 met the criterion of being used at least three times. Further analysis was conducted with these 99 keywords. The results of the co-occurrence word analysis revealed the top 10 most frequently occurring keywords among the 99 identified, as shown in Table 4. Upon reviewing Table 4 and Figure 9, the three most frequently used keywords among the 99 are, in order: "problem solving" (109 occurrences), "mathematical problem solving" (73 occurrences), and "mathematics" (67 occurrences).

Table 4. The most commonly used keywords in mathematical problem-solving research

Order	Keyword	Occurrences
1	Problem solving	109
2	Mathematical problem solving	73
3	Mathematics	67
4	Mathematical problem-solving	34
5	Mathematics education	32
6	Problem-solving	28
7	Metacognition	20
8	Collaboration	9
9	Computational thinking	8
10	Assessment	8

Figure 9 visualizes the conceptual structure of studies on mathematical problem-solving and the relationships between the most frequently used keywords in these papers.

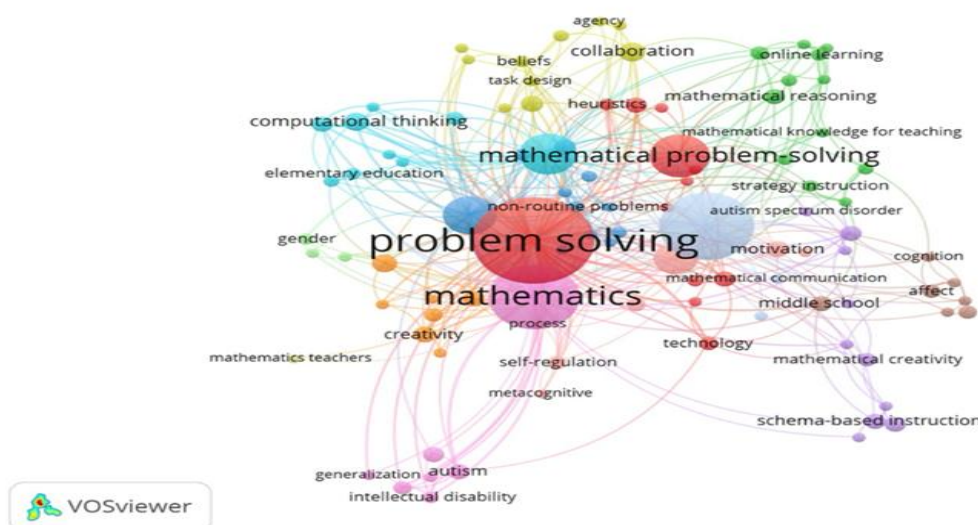


Figure 9. Visualization of the conceptual structure and keyword relationships in studies on mathematical problem-solving.

Figure 9 presents a keyword co-occurrence analysis in mathematical problem-solving research, emphasizing the centrality of problem-solving and mathematics as core concepts. Thematically clustered keywords form distinct research domains, with node sizes indicating frequency and scholarly interest. Prominent concepts, such as mathematical problem-solving, metacognition, and motivation, reflect the field's focus on the cognitive and affective dimensions of mathematical thinking. Furthermore, emerging areas like technology-enhanced learning, special education, and STEM education signal a diversification of research interests. The strong linkage between mathematics and mathematics education further underscores the depth of literature surrounding instructional approaches in the discipline.

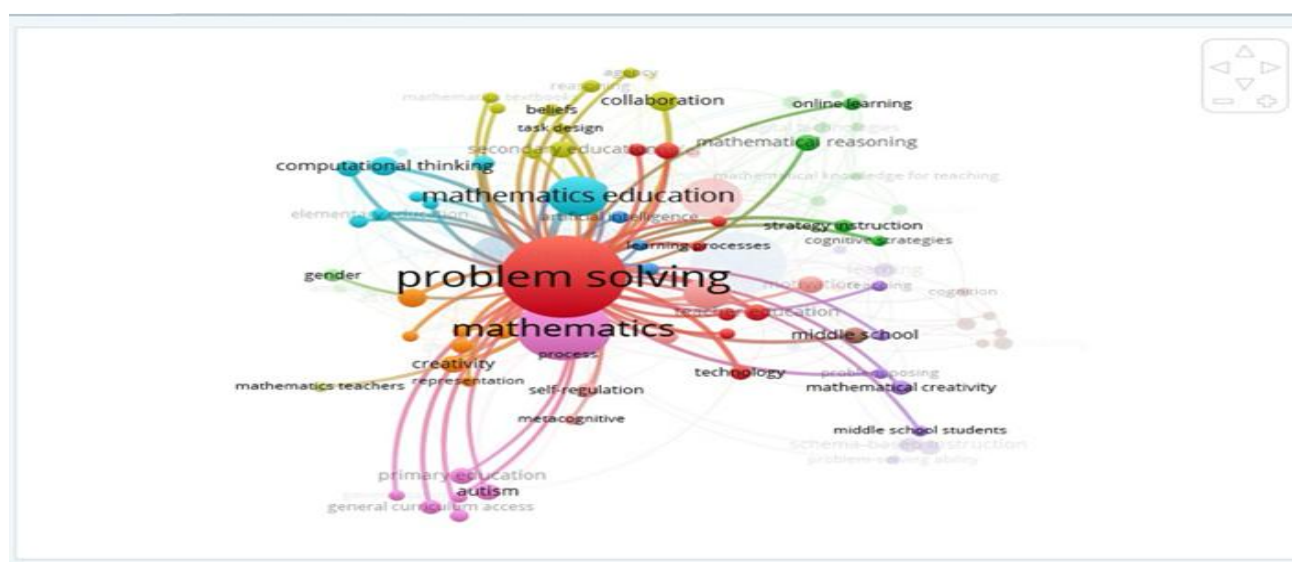


Figure 10. Visualization of the relationship between the keyword problem-solving and other keywords

Figure 10 clearly illustrates the central role of problem solving in mathematics education research and its multidimensional relationships with other critical concepts. Problem solving has been associated with key topics in literature, including mathematical learning, reasoning, teaching strategies,

creativity, cognitive processes, and technology. The bibliometric map highlights strong connections with nodes such as mathematics and mathematics education, emphasizing that problem-solving is a fundamental component of these fields. Furthermore, the associations of problem-solving with computational thinking, artificial intelligence, and autism reveal its interdisciplinary nature and adaptability to individual differences.

Although the most frequently used keywords in mathematical problem-solving articles have been discussed above, the emergence timeline of these keywords is also considered to provide more detailed insights into the research trends in mathematical problem-solving studies. Therefore, the visualization of the temporal evolution of keywords appearing in problem-solving articles is presented in Figure 11. In addition to the network map illustrating the co-word analysis over time, a timeline depicting the changes in keyword usage across different years is provided in Figure 12. In Figure 11, the temporal evolution of keywords is represented through color gradients. Blue tones indicate earlier years (around 2014), green tones represent intermediate years (2016–2020), and yellow-green to yellow tones correspond to the most recent studies (post-2020). The bibliometric map in Figure 11 and the timeline in Figure 12 illustrate the evolution of research on mathematical problem-solving over the years and highlight emerging research trends in recent years.

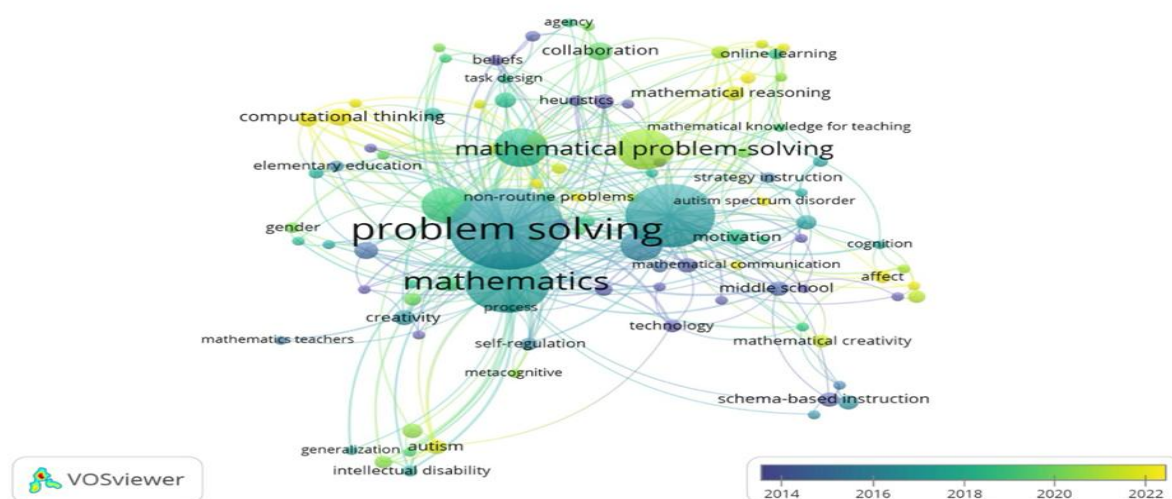


Figure 11. Visualization of the temporal evolution of keywords in studies on mathematical problem-solving

Figure 11 illustrates the temporal evolution of research themes in mathematical problem-solving, revealing a shift from foundational education and instructional practices to more complex domains such as cognitive and emotional processes, creative thinking, and technology integration. Recent studies conceptualize problem-solving not only as a technical skill but also as a multifaceted process involving cognitive, emotional, and social dimensions. Emphasis has grown on digital learning tools, inclusivity, and individual differences. Key themes include the integration of technology, promotion of metacognitive skills and motivation, and the use of collaborative and strategy-based instructional approaches, all of which contribute to the design of more personalized, inclusive, and innovative learning environments.

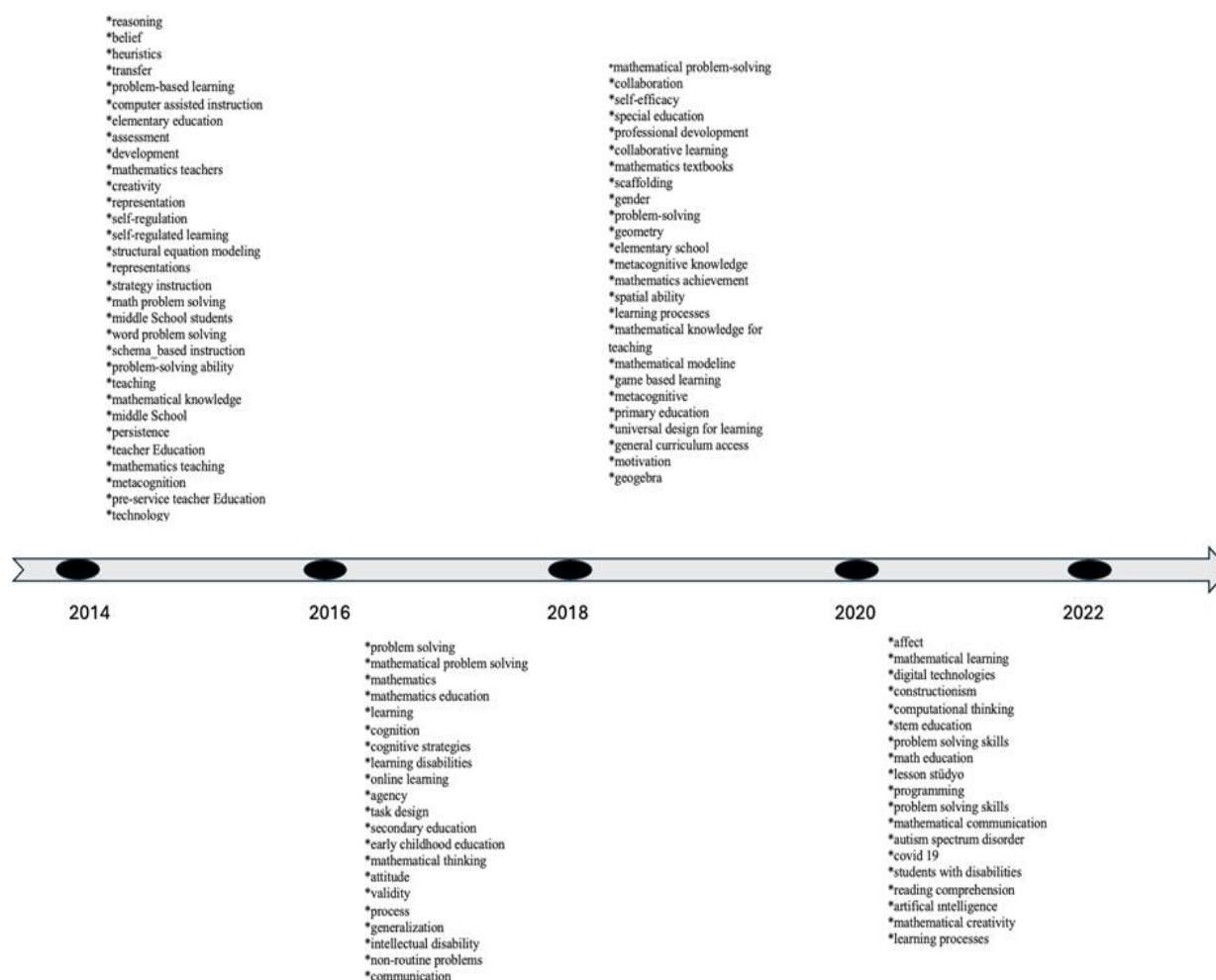


Figure 12. Timeline of frequently used keywords in articles on mathematical problem-solving

3. 5. Co-Citation analysis of scientific publications on mathematical problem-solving by authors

A co-citation analysis of authors was conducted to determine the intellectual structure of research on mathematical problem-solving, identify key influential researchers in the literature, and understand the academic relationships and interactions among authors. For the 523 articles included in the co-citation analysis, a minimum co-citation threshold of 20 was established for an author to be considered. Out of 10,684 authors, 86 met this threshold and were included in the co-citation network. The network visualization map in Figure 13 illustrates authors' distribution based on their publications' co-citations, reflecting the strength of collaboration. The thickness of the lines represents the extent of collaboration, while the size of the circles indicates the number of publications by each author. Different colors represent distinct collaboration clusters.

Figure 13 presents the results of the co-citation analysis of authors in the field of mathematical problem solving. The visualization illustrates co-citation relationships among authors and the clusters formed based on these relationships. The node sizes represent the number of co-citations each author receives, with large nodes such as "Polya, G" indicating key references in the field. The distances between nodes reflect the intensity of co-citation relationships; closely positioned nodes share more frequent co-citations or common research themes. The colors indicate different research focuses, for example, the red cluster centers on theories of mathematics education and problem solving, the green cluster is associated with learning difficulties and educational psychology. In contrast, the blue cluster focuses on self-regulation and learning strategies. The thickness of the connecting lines represents the frequency of co-citation among authors. Overall, this visualization helps identify prominent

researchers in mathematics education, reveals the intellectual structure of the field, and highlights distinct research subthemes.

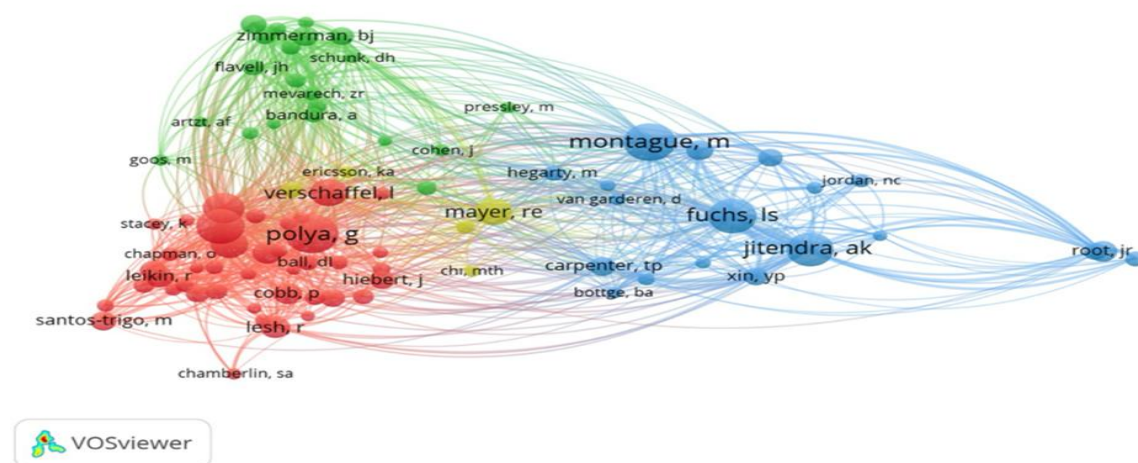


Figure 13. Visualization of co-cited authors in mathematical problem-solving publications

3. 6. Co-Citation analysis of scientific journals on mathematical problem solving

Co-citation analysis is crucial for examining citation relationships among scientific journals, providing insights into how journals interact and how knowledge flows within a research domain. This analysis applied a minimum citation threshold of 20 to each source. Among a total of 8,729 scientific journals, only 143 met this criterion. The 20-citation threshold indicates a publication's academic recognition, ensuring that only journals with a certain level of influence and academic significance are included in the analysis. This approach allows for a more meaningful and robust network visualization, facilitating a more accurate interpretation of co-citation relationships and collaborations among scientific journals. Figure 14 presents a co-citation network map of the most representative 143 journals in the Web of Science (WoS) literature on mathematical problem solving, each having received more than 20 citations. Additionally, the color of the journal nodes on the map indicates the clusters they belong to.

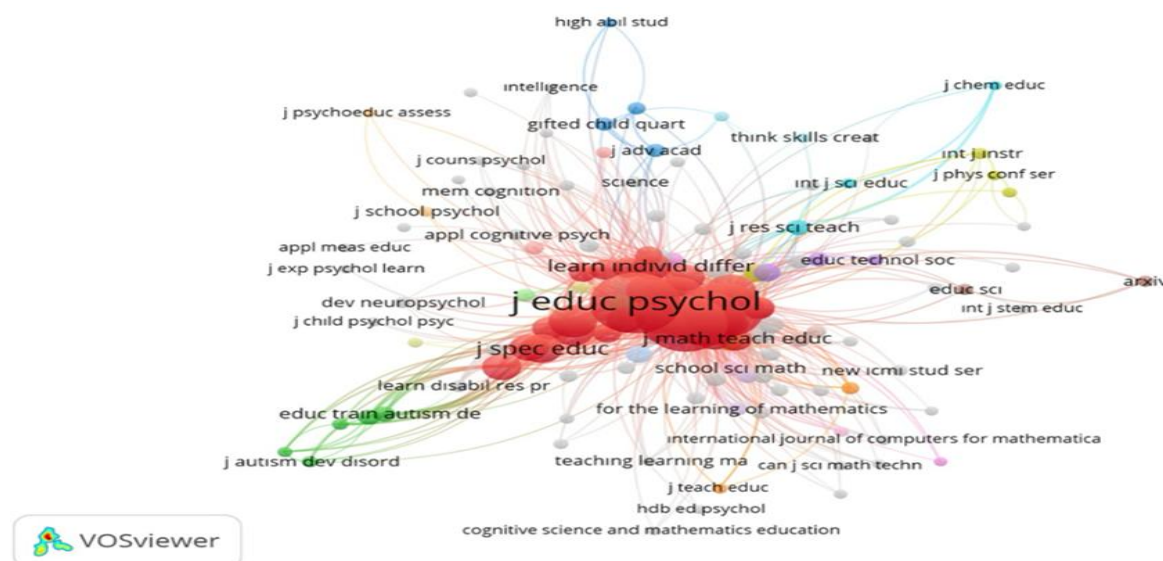


Figure 14. Visualization of co-cited scientific journals in articles on mathematical problem solving

According to Figure 14, the journals with the highest co-citation counts are the *Journal of Educational Psychology* (481 citations), the *Journal for Research in Mathematics Education* (410 citations), and *ZDM – Mathematics Education* (398 citations). Co-citation analysis of scientific journals is a crucial method for understanding the relationships between studies and the flow of knowledge. Such analyses are valuable in identifying literature gaps, tracing research field development, and predicting emerging topics of interest. By leveraging these insights, scientific communities can develop more efficient and effective research strategies.

4. Discussion

This study uses bibliometric analysis to examine the growth of publications and citations in mathematical problem solving, particularly after 2010. While research was limited in the 1980s and 1990s, publications began to rise in the early 2000s, with significant acceleration post-2010. Factors such as STEM education, technology use, and research on problem-solving skills have contributed to this trend. However, a decline in primary education research between 2020 and 2023 suggests the need for more studies on students' emotional well-being during problem-solving.

The citation analysis by country reveals that the United States leads in both productivity and impact, followed by Spain and Turkey in terms of productivity. Israel, despite fewer publications, has a high citation impact. China also benefits from strong collaborations with the U.S., contributing to its influence. However, Turkey, despite ranking third in productivity, lags in citation impact, suggesting a need for stronger international collaborations to enhance global influence.

Institutional analysis reveals that Florida State University, Vanderbilt University, and the University of Minnesota are highly productive, with Vanderbilt University standing out for its significant impact. Nanyang Technological University is also noteworthy for its international collaborations. The findings highlight the importance of strategic partnerships and academic leadership in advancing research in mathematical problem-solving. Universities should focus on international collaborations to not only increase productivity but also enhance the effectiveness of their research.

Keyword analysis of studies in the field of mathematical problem-solving reveals that terms such as problem solving, mathematical problem solving, and mathematics are frequently used, highlighting the central role of problem-solving in mathematics education (Schoenfeld, 1985). Over time, research has shifted from a focus on instructional strategies and basic skills to more complex themes such as metacognition, creativity, motivation, and technology integration (Leikin, 2009). In recent years, a growing emphasis on digitalization and individual differences has highlighted that problem-solving is not merely a technical skill, but a multifaceted process involving both cognitive and emotional dimensions (Drijvers et al., 2010). Current studies recommend enhancing technology integration, developing inclusive approaches that address individual differences, and promoting creative thinking skills. Specifically, AI-supported platforms, online collaborative environments, strategies tailored for individuals with special educational needs, and professional development programs for teachers are recommended to enhance the effectiveness of problem-solving practices (Zimmerman & Schunk, 2011; Leikin, 2009; Schoenfeld, 2016).

The co-citation analysis of authors in research on mathematical problem solving provides significant insights into the intellectual structure and scientific interactions within this field. According to the analysis results, foundational references, such as Polya (1945), have significantly shaped the theoretical framework of the field, as they are among the most effective and frequently cited works in mathematical problem solving. The collaboration and co-citation relationships among authors reveal the existence of distinct thematic clusters in this area. For instance, research focused on theories of mathematics education and problem-solving forms one cluster, while studies concentrating on self-regulation and learning strategies occupy a different cluster. The co-citation network map among authors illustrates thematic diversity, academic collaboration, and scientific interactions among researchers. The strong co-citation relationships among authors indicate a high level of international collaboration in this field, enriching research on problem-solving through diverse perspectives.

The co-citation analysis of scientific journals in mathematical problem-solving research provides essential data for understanding the flow of information in the literature and the scientific interactions

among journals. The analyses reveal that journals such as the Journal of Educational Psychology (481 citations), Journal for Research in Mathematics Education (410 citations), and ZDM-Mathematics Education (398 citations) are among the most cited and central publications in knowledge production within the field. As Zhang et al. (2016) highlighted, such analyses help visualize the thematic areas of research focus and the direction of information flow by identifying the key actors within academic networks. Moreover, the interaction networks of journals, represented through colors and clusters, reflect thematic proximities and interdisciplinary collaborations. These types of analyses contribute to identifying gaps in the literature and developing insights into how research areas may evolve in the future (Van Eck & Waltman, 2014). The findings in the field of mathematical problem solving serve as a guide for scientific communities to develop effective research strategies and to facilitate more inclusive knowledge production in literature.

In conclusion, the bibliometric analysis of the field of mathematical problem solving provides an overview of the research within this domain. The findings help in understanding the trends, concentrations, themes, and key actors in the literature on mathematical problem-solving. It is a significant topic in mathematics education, and this analysis provides essential insights that can guide future researchers in understanding the overall trends in literature and identifying potential opportunities for further development in mathematical problem-solving. However, this study is limited to publications in the WoS database, and future research could yield more comprehensive results by utilizing alternative databases, such as Scopus, Microsoft Academic, and Dimensions, to better understand the dynamics in this area. Additionally, future studies could combine bibliometric analysis with qualitative methods, such as systematic literature reviews, to facilitate a more in-depth investigation by supporting quantitative findings with qualitative insights.

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