Journal of Pedagogical Research
Volume 7, Issue 4, 2023
https://doi.org/10.33902/JPR.202322691

Review Article

Mapping research trends in mathematical creativity in mathematical instructional practices: A bibliometric analysis

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Mathematical creativity is among the most intriguing research fields in the world. This is plausible because research on mathematical creativity, particularly in the field of education, has a positive impact on many dimensions of life. Even though numerous studies have been conducted on this topic, there are still many aspects that have not been examined. Using bibliometric analysis, the authors of this study evaluated scientific articles on mathematical creativity from 2002 to 2022 that were indexed in Scopus using Biblioshiny and VOSviewer. The authors analyzed 162 publications in terms of document distribution patterns and growth trends, contributions and impacts from countries, institutions, authors, and journals, patterns of development and evolution of the theme of mathematical creativity, and future research opportunities. Despite a decrease in the average number of citations per document, the results suggest a significant increase in the number of publications between 2002 and 2022. The United States and the University of Haifa are the nations and institutions with the highest publication output, ZDM-Mathematics Education has the highest impact, and Bicer is a core author who is extremely productive and influential. "Creativity" has been the most popular keyword over the past two decades, but it is not the only one. This study encourages future research on mathematical creativity in mathematics education to not only focus on the theme of discipline-specific instructional practices, but also on the theme of general instructional practices involving more person, process, product, and press/environment creativity.

Keywords: Mathematical creativity; Bibliometric analysis; Scopus database; Trends

Article History: Submitted 21 June 2023; Revised 29 August 2023; Published online 25 September 2023

1. Introduction

Mathematical creativity is one of the world's most intriguing research subjects. This is evidenced by the yearly increase in the number of studies on mathematical creativity (Hernández-Torrano & Ibrayeva, 2020; Hersh & John-Steiner, 2017; Huang et al., 2020; Runco, 2014). This increase was brought about by the abundance of empirical data demonstrating the connection between mathematical creativity and student success in various aspects of life, including academic achievement (Sebastian & Huang, 2016; Stolz et al., 2022), psychological life such as self-confidence

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How to cite: Saefudin, A. A., Wijaya, A., & Dwiningrum, S. I. A. (2023). Mapping research trends in mathematical creativity in mathematical instructional practices: A bibliometric analysis. *Journal of Pedagogical Research, 7*(4), 439-458. https://doi.org/10.33902/JPR.202322691

(Bicer et al., 2020; Gunawan et al., 2022), social life such as equity (Luria et al., 2017), and overall life success (Sternberg, 2006a). In addition, creativity is a skill that must be cultivated as a means of adapting to ambiguous, complex, and ever-changing times (Partnership for 21st Century Skills, 2019; Leikin, 2013). Mathematical creativity is one of the objectives developed in elements of students' thinking abilities (Haylock, 1987; Piirto, 2011; Zhang et al., 2020) in the field of education. Consequently, several nations consider the promotion of mathematical creativity in education, particularly mathematics education, to be one of the objectives of national education policy (Beghetto, 2010; Lin, 2011).

Initially, creativity research focused primarily on the arts and literature (Oatley & Djikic, 2017; Tomas, 1958). Nonetheless, several mathematicians, including Haylock (1987), Ervynck (1991), Silver (1997), Neumann (2007), and Sriraman (2009), emphasize the significance of developing creativity in mathematics education. Consequently, the number of studies on mathematical creativity is swiftly increasing. Aside from this, the study of mathematical creativity is expanding concerning other fields, such as science (Maker, 2020), learning technology (Abramovich & Freiman, 2022; Freiman & Tassell, 2018), engineering (Kynigos & Diamantidis, 2022), and computing (Clements, 1995).

The definition of mathematical creativity has not yet been agreed upon by researchers (Haylock, 1987; Kattou et al., 2013; Nadjafikhah, 2012; Sriraman, 2009). This occurs because researchers examine mathematical creativity from two distinct perspectives. On the one hand, mathematical creativity is viewed as a talent that not everyone possesses, and on the other, it is viewed as a skill that an individual can acquire and develop (Bicer, 2021a). For example, Guilford (1959) proposed a definition of creativity, positing that it encompasses an individual's exceptional ability to generate a wide range of novel ideas across various domains of life. Within the realm of mathematics, several characteristics are observed, including the use of heuristics, the resolution of diverse mathematical problems, the utilization of imagery, and the manifestation of the creative process encompassing the stages of preparation, incubation, illumination, and verification (Kozlowski & Si, 2019; Sriraman, 2009). This characteristic is particularly well-suited for individuals who are mathematicians or actively engaged in the practice of mathematics and demonstrate exceptional aptitude in the discipline. However, current research on mathematical creativity appears to corroborate the notion that it can be acquired rather than innate. According to Silver (1997), mathematical creativity refers to an individual's ability to generate novel, fluent, and flexible concepts within the framework of inquiry-based mathematics instruction, specifically through tasks, problem-solving, and problem posing activities. This point of view suggests that the instruction and fostering of mathematical creativity by teachers to students within the educational setting of mathematics learning is more appropriate.

Using data from the Scopus database, the authors of this bibliometric study will identify the countries, institutions, authors, and journals that have had the greatest impact on mathematical creativity research over the past two decades, from 2002 to 2022. In addition, trends in research topics will be presented. The dominant and evolvable patterns of topics of interest to researchers, as well as potential future directions of mathematical creativity research. Therefore, it is essential to do this research as it presents an initial study and mitigates the issue of topic redundancy in the field of mathematical creativity research. Furthermore, this study serves as a valuable resource for academics seeking to establish a strategic plan for future research in the field of mathematical creativity. It is important to do the assignment in order to foster the development and growth of research on the topic of mathematical creativity within the field of mathematics education, hence facilitating a deeper and meaningful understanding of this topic area. Consequently, the following research topics will be covered to ascertain the characteristics and information contained in the prior literature on mathematical creativity using bibliometric indicators:

RQ1) Which countries and universities have made major contributions to research on mathematical creativity?

RQ2) Which authors and sources have made major contributions to research on mathematical creativity?

RQ3) What are the main research topics and patterns of evolution of topics of interest to researchers about mathematical creativity over the past two decades?

RQ4) What are the possible future research directions on the topic of mathematical creativity?

2. Research Method

This study employs the bibliometric method to determine the global trend of research patterns in the study of mathematical creativity. A systematic analysis of this research was carried out to ascertain the number of articles, citations, and the impact of the articles on the research trends (Maditati et al., 2018). The quantitative systematic analysis was carried out on the periodic distribution of publications, journals, countries, author performance, issues of utmost concern, and changes in emphasis on these topics.

2.1. Research Design

In this study, bibliometric data analysis was used to examine scientific publications about "mathematical creativity." To identify research groups and apprehend research themes associated with mathematical creativity, two analyses are conducted: (1) bibliometric mapping to examine trends in the study of mathematical creativity and (2) analysis of keywords indexed in papers (Djeki et al., 2022). In addition, this research design identified appropriate bibliographic databases, developed search criteria, and selected suitable software tools for analysis (Gao et al., 2021).

In this study, bibliometric analysis was conducted using the Scopus database. At least four factors contribute to this: 1) Through peer review, the Scopus database provides comprehensive and reliable information on transdisciplinary academic research and stringent policies (Durán Dominguez, 2017). 2) The Scopus database has a 20% longer temporal range than the Web of Science (WoS), which is advantageous for evolution and citation analysis (del Rama et al., 2020). (3) According to Zupic and Cater (2015), the Scopus database includes all pertinent bibliographical information for a piece of writing, including the author, title, abstract, publication year, citation, etc. 4) The majority of bibliometric analysis software can support a variety of Scopus-exported data formats (Gao et al., 2021).

Researchers investigated comprehensive data in the Scopus database (http://www.scopus.com). One technique to perform a data search is to enter search phrases and operators that follow the search engine's syntax. Both "mathematical creativity" AND "mathematical creative thinking" were entered as search phrases. To locate these keywords, the search document searches the article title, abstract, and document keywords.

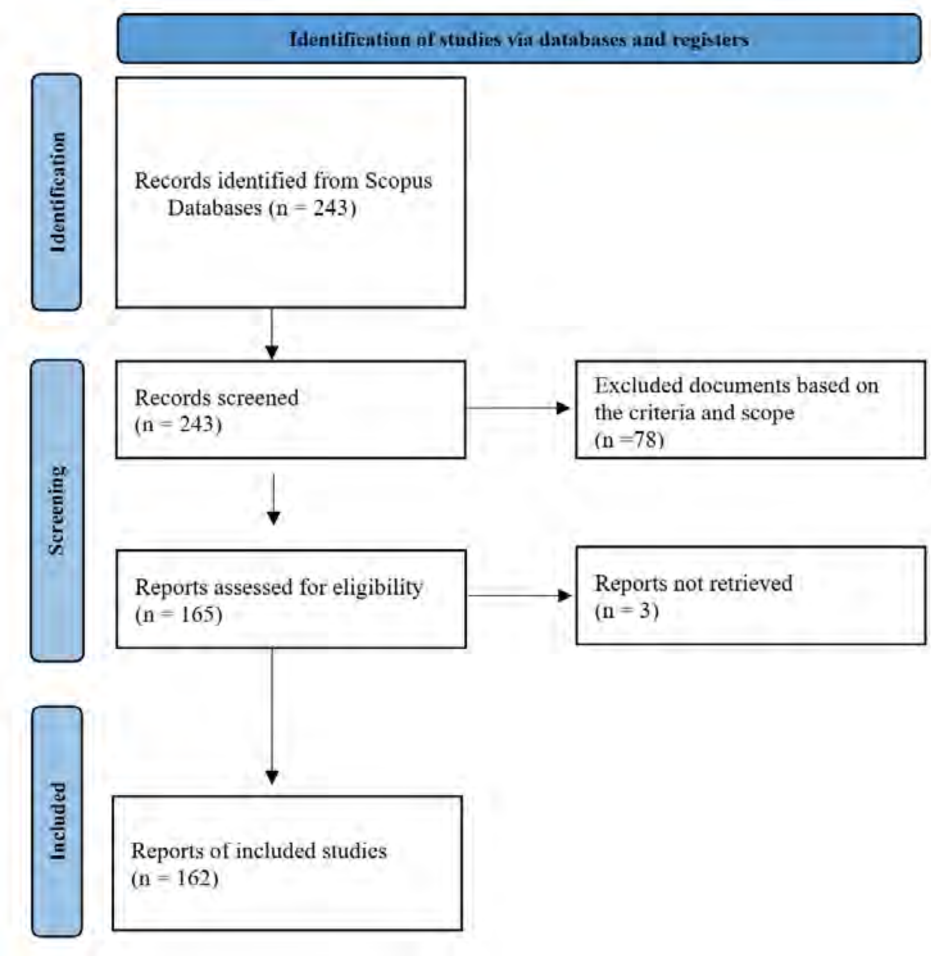
To analyze bibliometric data swiftly and efficiently, the researchers used two software tools: Biblioshiny and VOSviewer. Moral-Muoz et al. (2020) claim that biblioshiny is used to characterize bibliographic data and do analytical and graphical assessments of the contributions of the authors as well as their social networks. To map and display the data network architectures in this study, subjects and themes are arranged and mapped using VOSviewer (Gao et al., 2022).

2.2. Data Collection

Only articles, conference papers, books or book chapters, and reviews can be retrieved from Scopus. The author may also restrict searches in English documents. In addition, the inquiry is limited to works published between 2002 and 2022 by the author. Similarly, there are few documents in the social sciences section. On December 30, 2022, query data for 243 items were generated from the Scopus database using TITLE-ABS-KEY ("mathematical creativity'" OR "mathematical creative thinking"). 165 papers were exported in "CSV" (comma-separated value) format after being screened for titles, abstracts, and keywords extraneous to the study question. The data can then be retrieved from up to 162 documents after the researcher has selected the data that can be studied, specifically deleting the data that is missing information, such as the author's identity or place of employment. Preferred Reporting Items for Systematic Review and Meta-

Analysis (PRISMA) (Liberati et al., 2009) (See Figure 1) was used to conduct the search and data collection for this investigation.

Figure 1
Identifying the documents using the PRISMA approach



In this bibliometric study, essential characteristics of the collected data set were identified through data analysis. Biblioshiny and VOSviewer were utilized to perform a quantitative evaluation of the data. Biblioshiny identifies the most prolific and well-known authors, books, journals, and countries in the field of mathematical creativity research. The program VOSviewer is used to examine significant network characteristics, such as co-occurrence, cluster, and thematic evolution evaluations. The outcomes of the visualization will provide a comprehensive picture of the mathematical creativity research in the field as well as a systematic understanding of the key relationships among those trends.

3. Results

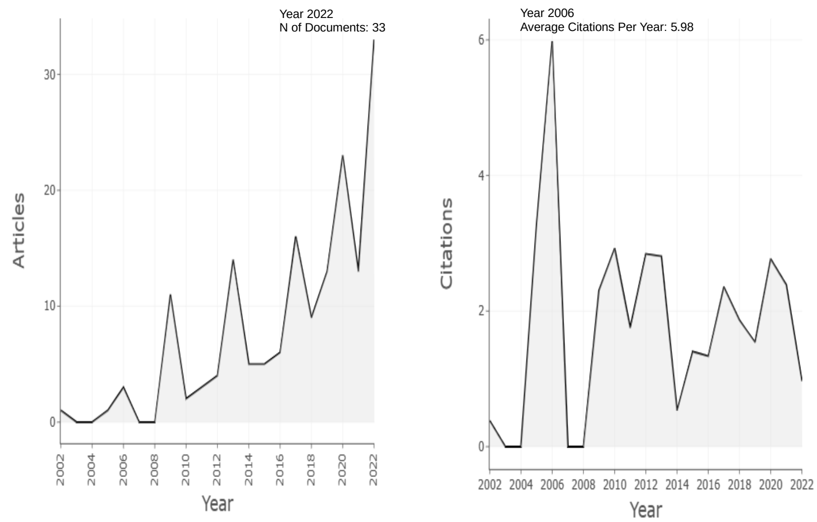
In addition to producing several key terms that pertain to mathematical creativity in mathematics education, a search for references about mathematical creativity may also yield several less pertinent terms. Therefore, this procedure of locating references must be refined to obtain literature that is pertinent to the topic being researched. Moreover, based on the results of the analysis of themes and keywords, our findings provide additional information on how to characterize the evolution of themes and research trends in mathematical creativity in mathematics education over the past two decades. In conclusion, it can be stated that these results provide a representative picture of the field of mathematical creativity in mathematics education and provide valuable research insights for academics and practitioners to explore and investigate the subject of mathematical creativity in mathematics education for the future benefit of the larger community.

3.1. General Statistical Information and Research Trends

Figure 2 displays general information regarding the data acquired and analyzed in this study regarding the annual increase in the number of articles and citations.

Figure 2
General statistical information on data (left), the trend in the number of articles (middle), and the number of citations (right)

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2002:2022
Sources (Journals, Books, etc)	75
Documents	162
Annual Growth Rate %	19.1
Document Average Age	5.79
Average citations per doc	13.55
References	1
DOCUMENT CONTENTS	
Keywords Plus (ID)	113
Author's Keywords (DE)	388
AUTHORS	
Authors	333
Authors of single-authored docs	31
AUTHORS COLLABORATION	
Single-authored docs	44
Co-Authors per Doc	2.65
International co-authorships %	11.73
DOCUMENT TYPES	
article	128
book chapter	19
conference paper	9
review	6

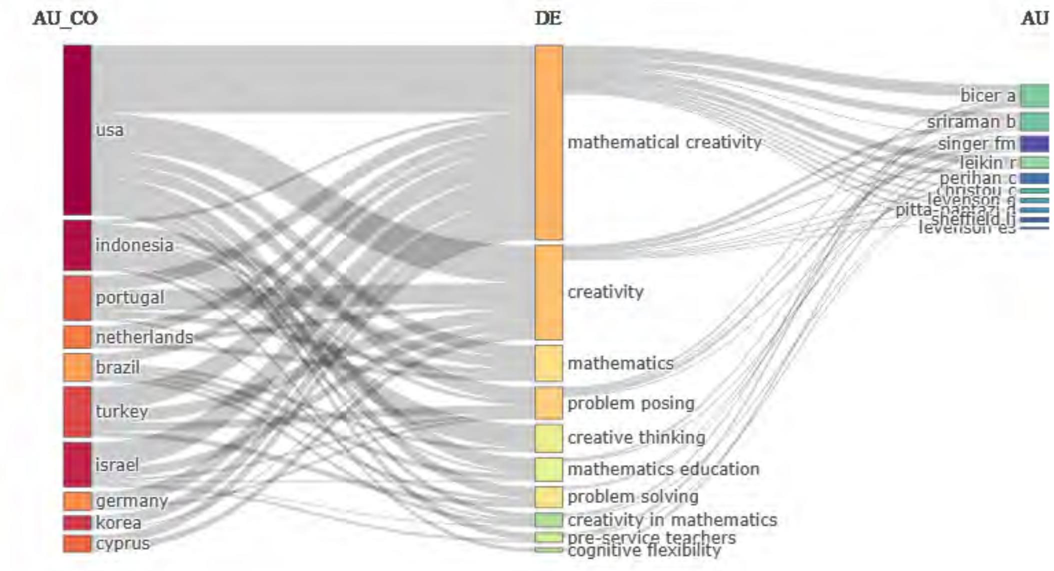


Bibliometric analysis is used to provide information regarding the data summary of research document abstracts. From 2002 to 2022, 162 documents will be produced in the scientific field. Most were journal articles (128), followed by book chapters (19), conference papers (9), and review articles (6). Regularly, 75 periodicals and books are cited in the article's sources. While the annual growth rate of articles is 19.1%, 333 authors contributed to these publications during this period. The Keyword Data reveals that the Author Keywords (DE) are 388 words, while the Keyword Plus (ID) indicator is 113 words. The percentage of international co-authors is 11.73 percent, with an average of 2.65 co-authors per publication. The relationship between article publication and year is depicted in the middle line of Figure 2's graph, which demonstrates an upward trend with a peak of 33 in 2022. Despite 2006 having the highest average citation of 5.98, the number of annual citations has decreased, as depicted by the line graph on the right. Two software programs, Biblioshiny and VOSviewer, were utilized by the researchers to analyze bibliometric data rapidly and effectively. Moral-Muoz et al. (2020) assert that Biblioshiny is utilized to characterize bibliographic data and conduct analytical and graphical evaluations of the contributions of authors and their social networks. To map and display the data network architectures in this study, subjects and themes are organized and mapped using VOSviewer (Gao et al., 2022).

3.2. Productivity and Impact of Countries and Institutions

The output and influence of a country or institution's publications can be determined using bibliometric analysis indicators. Figure 3 depicts a three-field depiction in the form of a Sankey diagram that examines the relationship between the document's author, its abstract keywords, and its country of origin.

Figure 3
Three-field plot for countries of publications, keywords in abstracts, and authors



The diagram illustrates the relationship between the top countries and the keywords extracted from the collected data. The scientific publication output of the top ten countries is displayed on the left. These countries include the United States, Indonesia, Portugal, the Netherlands, Brazil, Turkey, Israel, South Korea, and Germany. In the middle column, the top 10 keywords, including "mathematical creativity," "creativity," "mathematics," "problem-posing," "creative thinking," "mathematics education," "problem-solving," "creative in mathematics," "pre-service teachers," and "cognitive flexibility," are listed. The list of the most prolific authors is displayed on the far right, in ascending order of article output.

The scatter plot reveals that articles from the United States contain eight of ten keyword sets, excluding "creativity" and "cognitive flexibility"; articles from Indonesia contain six of ten keyword sets, excluding "creativity", "problem-solving", "creativity in mathematics", and "pre-service teachers"; and articles from Korea and Cyprus contain "mathematical creativity" and "creativity" as keywords. Bicer, Sriraman, Singer, Leikin, Perihan, Christou, Levenson E., Pitta-Pantazi, Sheffield, and Levenson E.S. are among the prominent authors featured in the narrative.

Figure 4
Patterns of distribution of country publications seen from multi-country (MCPs) and single-country (SCPs) publications (left) and country collaboration in publications (right)

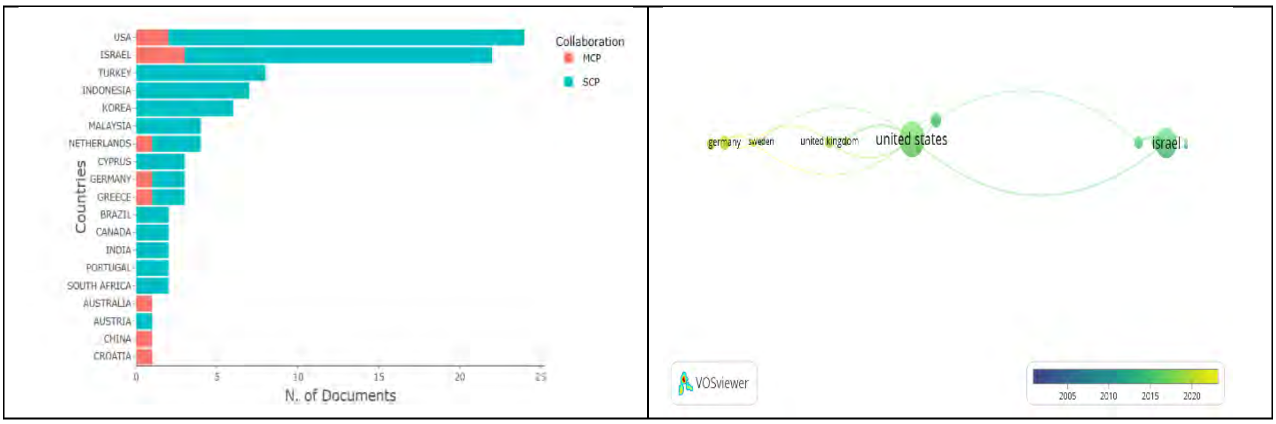


Figure 4 depicts the distribution of publications in a data set by single-country publishing (SCP) and multi-country publishing (MCP). Publications that qualify as MCP have at least one co-author from a different country than the corresponding author. According to a bar chart and collaboration visualization of the articles, the top two countries represented in the MCP are Israel and the United States, while the top four nations represented in the SCP are the United States, Israel, Turkey, and Indonesia.

Figure 5
Top productive institutions in the world

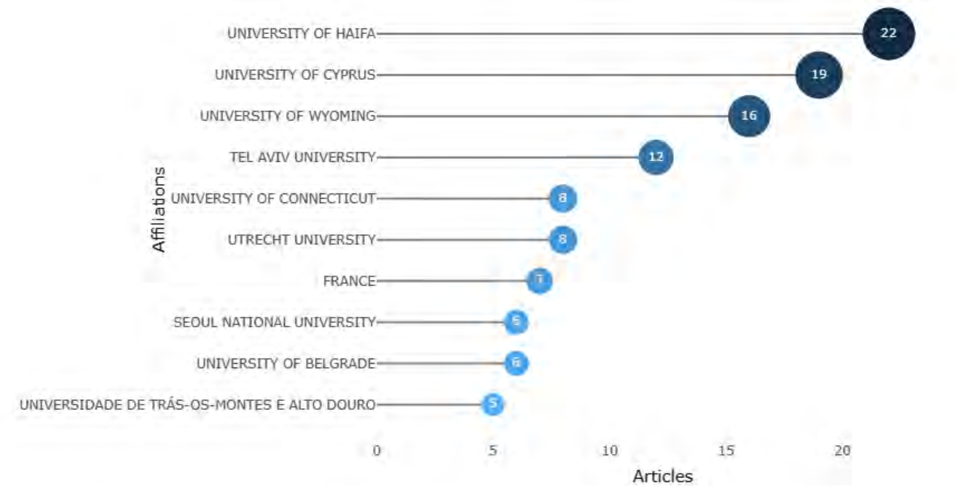
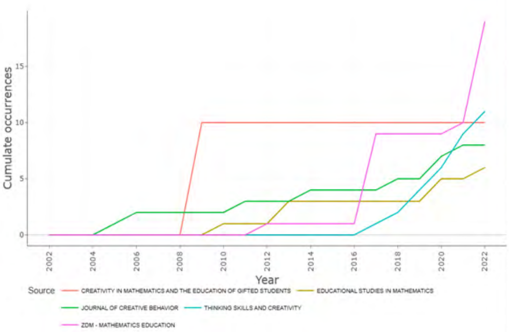


Figure 5 depicts the top 10 institutions that published the most articles on mathematical creativity research between 2002 and 2022, including two universities each from the United States and Israel, as well as one institution each from Cyprus, France, Korea South, Serbia, Portugal, and the Netherlands. The top three producing institutions are the University of Haifa, the University of Cyprus, and the University of Wyoming.

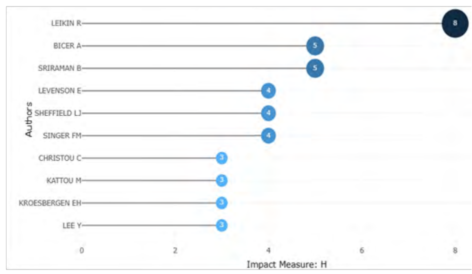
3.3. Productivity and Impact of Sources and Authors

There have been identified 162 documents in this study. Figure 6 depicts the relationship between authors, publication sources, and the h-index for mathematical creativity.

Figure 6
The connections between authors, publication sources, and h-index



Element	h_index
ZDM - MATHEMATICS EDUCATION	8
CREATIVITY IN MATHEMATICS AND THE EDUCATION OF GIFTED STUDENTS	7
JOURNAL OF CREATIVE BEHAVIOR	7
THINKING SKILLS AND CREATIVITY	6
EDUCATIONAL STUDIES IN MATHEMATICS	5
INTERNATIONAL JOURNAL OF MATHEMATICAL EDUCATION IN SCIENCE AND TECHNOLOGY	3
EURASIA JOURNAL OF MATHEMATICS, SCIENCE AND TECHNOLOGY EDUCATION	2
INTERNATIONAL JOURNAL OF INSTRUCTION	2
INTERNATIONAL JOURNAL OF SCIENCE AND MATHEMATICS EDUCATION	2



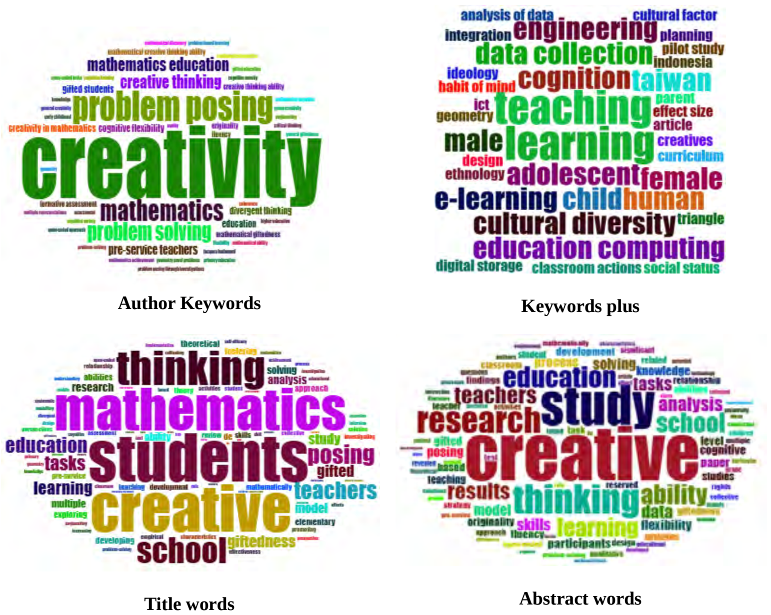
The left side of Figure 6 displays a depiction of the cumulative occurrence frequency of the top five sources of publications on mathematical creativity. Between 2002 and 2022, there has been a fluctuating increase, with varying levels of fluctuation based on the source. The most influential publication source is ZDM-Mathematics Education, followed by four other journals: Thinking Skills and Creativity, Creativity in Mathematics and The Education of Gifted Students, Journal of Creative Behavior, and Educational Studies in Mathematics. This frequency diagram can serve as an indicator of the influence of publication sources, as evidenced by the influence's increase, stagnation, and decline over time. For instance, Creativity in Mathematics and The Education of Gifted Students (2009-2022) and Educational Studies in Mathematics (2013-2019) experienced stagnant document productivity with 10 and 3 scientific publication documents, respectively. During this period, the number of documents produced by other publication sources increased.

The h-index (Hirsch index), which is an index that counts the number of articles published (h) by an author or journal that have been cited (h times), can be used to determine the extent of the influence of publication sources in addition to being evident from the frequency plot (Aria & Cuccurullo, 2017). As shown in the middle of Figure 6, the journal with the greatest impact is ZDM-Mathematics Education, with an h-index of 8. These two publications, Journal of Creative Behavior and Creativity in Mathematics and The Education of Gifted Students had an equal impact on each h-index 7 score. On the right side of Figure 6, the three authors with the highest h-index impact are Leikin (6), Bicer (5), and Sriraman (5).

3.4. Distribution Keywords, Popular Topics, and Theme Development Trends

The analysis of "keywords" is one of the most intriguing bibliometric analysis units. The purpose of keyword analysis is to identify patterns and representations of particular topics concerning trends and the evolution of themes over time in a particular study. In addition, keywords can assist readers in locating and identifying key themes, allowing them to obtain a great deal of information as a guide to data discovery (Xu et al., 2022). The abstract can provide a summary of the article's content and serve as a guide for conveying the essence of the article. To attract readers, the article's title could also include information about the primary subject of the study and a summary of the research results (Chen et al., 2018). Therefore, it is essential to identify the author's keywords, related phrases, and key terms in the title and abstract to comprehend the article's content.

Figure 7
Word clouds showing the author's keywords, "keywords plus" phrases, words in abstracts, and words in titles



In bibliometrics analysis, word clouds can be used to describe a set of terms with large-sized words, indicating that these terms occur frequently in all research articles. The top terms in the "Author's keywords" word clouds are "creativity", "problem-posing", "mathematics", and "problem-solving". In the "Keywords Plus" word clouds section, the words "teaching", "learning", "cognition", and "e-learning" appear frequently. In the meantime, the words "creative", "education", "task", and "thinking" are prominent in word clouds found in titles and abstracts. As shown in Figure 3, each of these terms may have a thematic relationship that represents a latent trend in mathematical creativity research. However, word clouds are insufficient to comprehend the relationship between these significant terms and the subject under inquiry, although they are effective for visualizing keywords (Xu et al., 2022).

Figure 8
The conceptual structure of factor analysis

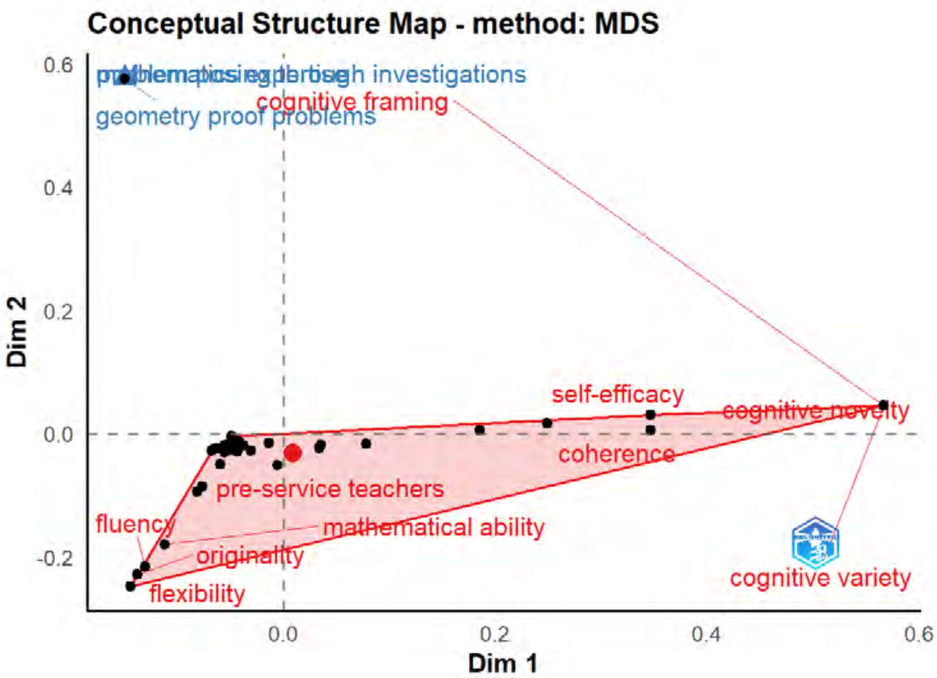
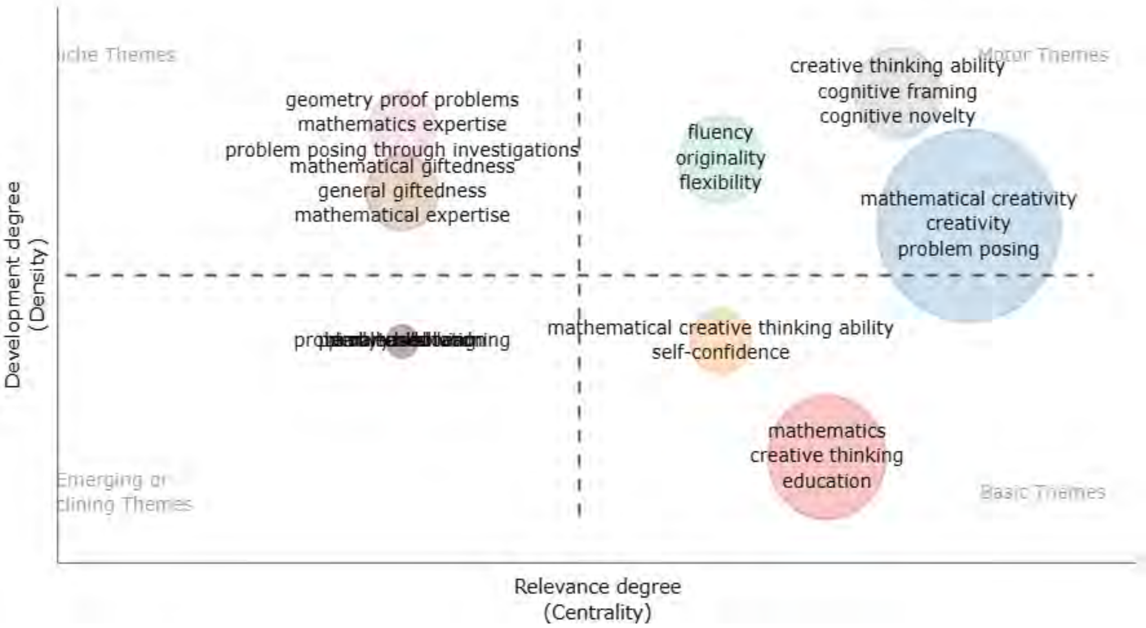


Figure 8 depicts a conceptual structure that employs the multidimensional scale (MDS) to illustrate the relationships between concepts and ideas. This conceptual structure clusters together keywords that are analogous in both dimensions (Aria & Cuccurullo, 2017). The distribution of keywords in the structure clustered into two fascinating main subjects: psychology and mathematics. The pink polygons are classified according to keyword clusters associated with psychological aspects, while the blue polygons are classified according to the mathematics cluster. The size of the polygons and the number of keyword points indicate the diversity of the topics discussed. Fifty keywords have been analyzed. "Self-efficacy," "cognitive novelty," "cognitive variety," "cognitive framing," "mathematical ability," "fluency," "originality," and "flexibility" are cluster keywords in psychology. In contrast, the blue triangle that represents the mathematics cluster contains only three keywords: "mathematics expertise", "geometry proof problems", and "problem-posing through investigations".

The thematic map method can be used to elucidate mapping to enhance the understanding of trend themes discussed based on current research topics and keywords. On a thematic map, the horizontal (x-axis) line represents centrality and the vertical (y-axis) line represents the density of themes (Bashir, 2022). The intersection of the two lines creates four quadrants with distinct meanings (Cobo et al., 2011). The size of the circle reflects the number of keywords within a theme. Low centrality and high density characterize the motor theme in quadrant 1 (upper right). In thematic research, the motoric theme is highly developed and significant. The theme in quadrant 2 (upper left) is well-developed but isolated, with low density, low centrality, and well-developed but isolated in the field. The emerging themes in Quadrant 3 (bottom left) indicate that themes in this quadrant will either decrease or arise. Figure 9 demonstrates that quadrant 4 (lower right) has fundamental and transverse themes, high centrality but low density, thereby providing opportunities for future research.

Figure 9
Thematic mapping from keywords



Four quadrants of thematic maps are depicted in Figure 9. Quadrant 1 contains three themes with high density and centrality; it is the propelling force behind the fundamental themes (Bashir, 2022). Considering the location and size of the circles, one of the most examined themes in this cluster is the group theme with light blue circles, which includes "mathematical creativity," "creativity," and "problem-posing." In Quadrant 2, meanwhile, are numerous themes that have been developed but isolated, such as "geometry proof problems," "mathematical expertise," and "mathematical talent." Primary education and problem-solving are the themes of the third quadrant. (Cobo et al., 2011) The themes in quadrants 2 and 3 do not affect themes outside the quadrant. Meanwhile, in Quadrant 4, there are two fundamental themes with varying circle diameters and a very high research contribution significance. Recent studies have linked mathematical creativity to self-confidence (Gunawan et al., 2022), self-efficacy (Rahayuningsih et al., 2022), and perspective (Irakleous et al., 2022). However, there are no thematic circles that intersect with the third and fourth quadrants, indicating that there are few research topics that link mathematical creativity to the field of elementary school education.

Figure 10
Co-coccurence network from the topics

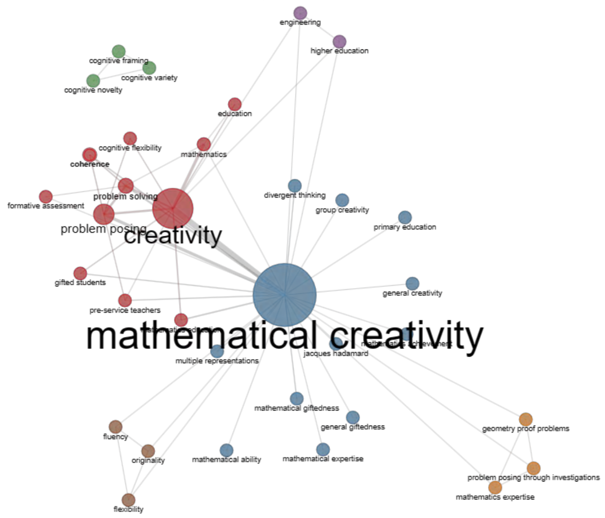
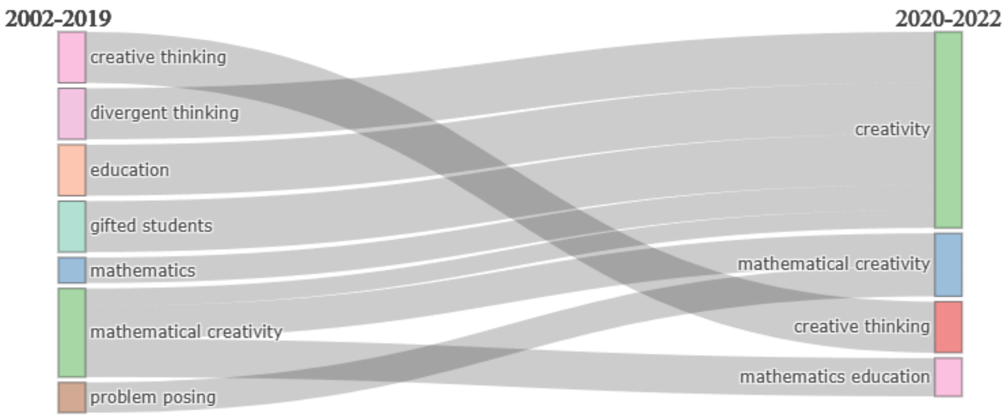


Figure 10 depicts a cluster analysis based on the frequency of co-occurrence of keywords, which utilizes statistical methods to simplify the complex relationships between keyword networks by forming subgroups and visualizing them to identify the research theme groups. The magnitude of the nodes on the map indicates the occurrence of particular keywords. The proximity of the two dots and the width of the line between them indicate the strength of co-occurrence between keyword pairings. The color of the nodes represents groups of keywords, which frequently consist of co-occurring words and can be interpreted as a widespread research topic in the field (Hernandez-Torrano & Ibrayeva, 2020).

There are at least six research themes depicted on the map (Figure 10) regarding mathematical creativity. In the first cluster (blue), the studied topics concentrated on the theme of mathematical creativity and mathematics education in general, as indicated by terms such as "general creativity", "mathematical giftedness", "general giftedness", and "group creativity". The words "mathematics," "education," "problem posing," "problem-solving," "gifted students," and "formative assessment" frequently occur together, suggesting that the second cluster (red color) has a theme related to mathematics curriculum and learning. The third cluster (green color) concentrates on mathematical creativity in terms of psychological aspects, specifically cognitive psychology, which is characterized by terms such as "cognitive framing", "cognitive variety", and "cognitive novelty". The fourth cluster (purple color) concentrates on the study of mathematical creativity at the engineering and higher education levels, giving rise to words such as "engineering" and "higher education." The fifth cluster (orange color) represents the study of mathematical creativity within the field of mathematics, as represented by terms like "geometry proof problems," "problem posing through investigations," and "mathematics expertise." The sixth cluster (brown) represents an in-depth study of indicators for measuring and assessing mathematical creativity, giving birth to terms such as "fluency," "flexibility," and "originality."

Figure 11
Flow diagram of longitudinal thematic evolution



Moreover, through thematic evolution analysis, it is possible to demonstrate development trends and dynamic shifts in research themes on mathematical creativity. Figure 11 depicts the evolution of keywords from 2002 to 2019 and from 2020 to 2022. On the page's left-hand side, you will find a list of the most popular search terms for mathematical creativity research. These keywords are "creative thinking," "divergent thinking," "education," "gifted students," "mathematics," "mathematical creativity," and "problem-solving." On the right are enumerated prominent search terms such as "creativity", "mathematical creativity", "creative thinking", and "mathematics education". The connection between the two keyword lists signifies an evolution in the concept's research (Xu et al., 2022). The keywords "divergent thinking," "education," "gifted students," and "mathematics" coalesced into a single overarching theme: creativity. The keyword "problem-posing" then emphasizes the development of "mathematical creativity" as a theme. While "mathematical creativity" is a widely researched topic, "mathematics education" is a topic that receives less attention. Consequently, the visualization of research trends in mathematical creativity illustrates how creativity has emerged as an essential topic in the field of education, particularly mathematics education. Specifically, the field of mathematics education encourages the growth of mathematical creativity, which has become an important research topic in the broader field of education.

4. Discussion

In this section, we will discuss research findings and their implications for future practice and study.

4.1. Research on Mathematical Creativity in Several Countries

Figure 3 depicts a three-field plot depicting the structure, description, and development of research in this area to ascertain the evolution of research on mathematical creativity. In this figure, we exhibit a three-field plot of the author's country, the author's name, and keywords describing the research topic. While Figures 4, 5, and 6 illustrate the productivity of the author's institution, including the productivity of publication sources and authors who investigate mathematical creativity, as well as collaboration profiles between authors' publications. From these elements, we can deduce several factors that support the development and trends of the themes being investigated by mathematical creativity researchers.

This study's bibliometric analysis generated some intriguing results. This study found that both in Israel and the United States, the study of mathematical creativity is gaining importance in the field of education. Mathematical creativity is the aim and foundation of mathematics education in both countries (Hadar & Tirosh, 2019; Leikin & Lev, 2012; Kozlowski & Si, 2019; Mann, 2009). In addition, the publications published by the two nations have a significant impact on research into mathematical creativity. The development of students' mathematical creativity in secondary schools through the use of a multiple-solution task (MST) is discussed in significant works such as the Israeli publication Leikin (2009). The research revealed that students' mathematical creativity can be demonstrated by solving problems in diverse ways, such as different in terms of the representation of mathematical concepts employed, different in terms of the use of properties (definitions or theorems) of mathematical objects in the field of mathematics, and different in terms of the characteristics of mathematical objects. Then, U.S.-based publications by Bicer (2021a) had a significant impact on the development of the study of mathematical creativity, particularly those about learning practices related to creativity. General instructional practices (such as teaching students that they can learn from their mistakes) and discipline-specific instructional practices (such as problem-solving and problem-posing) can foster creativity in learning, according to this study. These two articles have served as the cornerstone for the development of research tendencies in mathematical creativity up until this point.

Nonetheless, over the past two decades, researchers from a variety of countries have primarily focused on implementing discipline-specific instructional strategies through the use of a variety of learning strategies. Multiple solution tasks (MSTs) (Leikin, 2009; Levav-Waynberg & Leikin, 2012; Leikin & Lev, 2013), open-ended problems (Kwon et al., 2006), multiple representations and/or visualizations tasks (Bicer, 2021b), model-eliciting activities (Gilat & Amit, 2014), and visualization with technology integration tasks (Idris & Nor, 2010) are some of the learning approaches used to develop mathematical creativity. While several other researchers conducted studies on mathematical creativity on the topic of general instructional practices, such as justice (Luria et al., 2017), making errors (Shriki, 2009), and taking risks (Sriraman, 2017), others examined the relationship between mathematical creativity and specific instructional practices. Compared to the broad instructional practices theme, discipline-specific instructional themes, such as problem-solving and problem-posing, comprise the majority of the keywords.

In addition, the dominance of articles on mathematical creativity published in the United States has become the most referenced set of keywords in comparison to other countries. Nevertheless, we cannot rule out the possibility of significant contributions from several Asian nations, including Indonesia and Korea (see Figures 3 and 4). The fact that not only Western researchers but also Asian researchers contribute to the study of mathematical creativity is a very positive development. The only thing that requires further clarification is whether or not these experts' research affects a student's ability to develop mathematical creativity as a whole. Has mathematical creativity been extensively studied and contrasted with the dimensions of students' creative personality traits? This issue requires a comprehensive analysis and critique.

Western researchers have long studied the theoretical underpinnings of how creativity in mathematics might be cultivated (see Aiken, 1973; Haylock, 1987), with a focus on mathematical creativity for gifted students (Leikin & Pitta-Pantazi, 2012; Sriraman et al., 2013). Several researchers from various nations have also referred to these findings, particularly when discussing how learning mathematics fosters mathematical creativity in students. Numerous researchers from all over the world have been captivated thus far by the study of mathematical creativity in children with exceptional abilities. Therefore, future research should focus on both mathematically inclined students and those who are not. This is necessary because it is necessary to develop mathematical creativity as part of children's mathematical abilities, such as through mindset intervention (Boaler, 2015) for children who are not or are only moderately talented in mathematics. In addition, it is anticipated that future research on mathematical creativity will focus more on how it influences various aspects of the creative characteristics of students.

4.2. Research on Mathematical Creativity in Learning Mathematics

According to the results of the bibliometric analysis, the research document data is divided into four groups: author keywords, keyword plus phrases, title words, and abstract words. According to this analysis, the most frequently occurring keywords are "creativity", "problem-posing", "mathematics", "problem-solving", "teaching", "learning", "cognition", "e-learning", "creative", "education", "task", and "thinking". This set of keywords shows the meaning that creativity in mathematics or mathematics creativity in the learning and teaching process of mathematics can be developed through problem-solving (Moore-Russo & Demler, 2018), problem-posing (Van Harpen & Sriraman, 2013), multiple solution tasks (MSTs) (Leikin, 2009; Leikin & Lev, 2013; Levav-Waynberg & Leikin, 2012), and technology/e-learning (Yuniawati et al., 2020). In addition, when students use creative processes to solve mathematical problems, their cognitive styles, such as spatial, object, and verbal cognitive styles, allow them to comprehend the outcomes (Pitta-Pantazi et al., 2012).

Reviewing the definition reveals the definition of mathematical creativity using Rhodes's (1961) 4P model framework, which includes product, person, process, and press or environment, according to the researchers, who discovered this through keyword analysis. The product of creativity can be observed in the emergence of original, practical, diverse, expansive, and novel methods for solving mathematical problems. The growth of mathematical creativity is centered on the creative individual in terms of cognitive abilities, personality traits, and life events. The creative process is the review of mathematical creativity research that is used to generate creative works. Leikin and Pitta-Pantazi's (2012) and Pitta-Pantazi et al.'s (2018) study on mathematical creativity, titled the creative environment, examines the conditions under which original ideas emerge.

Some mathematical creativity researchers focus on the creative product that is evident from the mathematical creativity product's characteristics. Some of these researchers use originality, fluency, and flexibility to evaluate mathematical creativity (Leikin & Lev, 2007; Pitta-Pantazi et al., 2011). Other researchers evaluate mathematical creativity using Torrance's (1974) four criteria: originality, fluency, flexibility, and elaboration. In general, however, researchers of mathematical creativity believe it is sufficient to evaluate the product of mathematical creativity based on three characteristics: originality, fluency, and flexibility.

Next, researchers of mathematical creativity investigate the cognitive characteristics and distinctive creative personalities of creative individuals (Leikin & Pitta-Pantazi, 2012). Runco (2007), Kleiman (2005), Sternberg (2006b), Andiliou and Murphy (2010), Beghetto (2010), Bereczki and Kárpáts (2018), and Bereczki and Kárpáts (2018) are examples of researchers who have researched creativity in general. Sriraman (2009, 2017) and Mann (2006) are two researchers who have researched mathematical creativity. The researchers identified general personality traits associated with creative personalities, such as a growth mindset (Sheffield, 2018), self-confidence (Regier & Savic, 2019), straightforward thinking, high curiosity, intuitiveness, tolerance for ambiguity, persistence, openness to experience, broad interests, self-determination, and openness (Leikin & Pitta-Pantazi, 2012).

In general, researchers of mathematical creativity concentrate solely on creativity products, but several other researchers present creative processes for achieving these products. Several studies have examined both creative products and processes, including research on the relationship between mathematical ability and mathematical creativity (Kattaou et al., 2013), the influence of cognitive style on mathematical creativity (Pitta-Pantazi et al., 2012), and the relationship between the level of mathematical ability and mathematical creativity (Leikin & Lev, 2012; Tubb et al., 2020).

In addition to focusing on the creative process, researchers studying mathematical creativity in educational settings also consider the creative environment, as there is a correlation between an individual's creativity and their environment. Leikin and Pitta-Pantazi (2012) state that the characteristics of an educational environment conducive to the production of creative products and processes are facilitated by the use of instructional designs, the selection of appropriate assignments, authentic assessment, and the incorporation of technology. The majority of researchers focus on the relationship between mathematical creativity and its environment, such as developing mathematical creativity with open lessons (Schoevers et al., 2022), technology (Abramovich & Freimen, 2022), learning design related to creativity tasks (Bicer et al., 2022), and assessing mathematical creativity with natural language processing (Marrone et al., 2022).

The four approaches used in the research on mathematical creativity—creative person, creative process, creative product, and creative environment—are regarded as a unit and cannot be separated. The four approaches can mutually complement and interact with one another. Leikin and Elgrably (2022) conducted one of the most recent studies on mathematical creativity that links the four approaches, focusing on the mathematical creativity of Problem Posing through Investigation (PPI) experts. According to him, this study concentrates solely on the creative process, specifically the creative process in PPI and product creativity in the form of creative solutions. A closer examination reveals that the two researchers recruited mathematicians with creative personalities (creative persons) and PPI tasks (creative press) to map the creative products and processes of these mathematicians.

In conclusion, keyword analysis reveals that research on mathematical creativity contains a greater number of keywords that contribute to the creative process, product, and press/environment approaches. In contrast, research on mathematical creativity that leads to a creative person approach, including the combination or integration of the four approaches, has not been studied extensively. The majority of research on mathematical creativity is conducted on the topic of discipline-specific instructional practices, as opposed to general instructional practices. Mathematical creativity is one of the most essential mathematical skills that students must possess to succeed in the future, so all methods for studying it must be implemented. Researchers must continue to conduct studies employing a variety of methodologies so that the findings can enhance good practices in the development of mathematical creativity in mathematics education.

4.3. Research on Mathematical Creativity on Several Research Themes

The cultivation of creativity (mathematics) in education is a crucial component of student preparation. Creativity in solving life's complex problems is a crucial skill/competency of the 21st century that is unquestionably necessary today, especially in light of the increasingly complex developments of the era and the rapid development of the digital transformation era. Schools must be able to manage the interactions between people, processes, products, and the environment that fosters creativity in students and instructors (Tubb et al., 2020) to meet the challenge of developing these abilities. Moreover, it is hoped that by cultivating these creative aspects, not only the cognitive aspects of mathematics, but also the affective aspects of the impact of mathematical activities, such as motivation, involvement, beliefs, attitudes, values, emotions, feelings, moods, and self-efficacy, will be achieved (Cai & Leikin, 2020). This is the primary reason for the shift in research themes on mathematical creativity from those that initially focused heavily on mathematical creativity in problem-solving and problem-posing in the field of mathematics to those that concentrate more broadly on mathematical creativity and mathematics education.

As shown in Figures 8, 9, and 10, the initial themes of research on mathematical creativity concentrated on problem-solving and problem-posing by involving each in the processes and products of creativity (cognitive), giftedness (creative person), and environment. In the meantime, few researchers have conducted research on mathematical creativity that examines the interplay of these four factors comprehensively. Figure 9 demonstrates that the themes of mathematical creative thinking ability and self-confidence, as well as the theme of general instructional practices that has an impact on strengthening the cognitive and affective aspects of mathematics learning in students, require further investigation. Consequently, the current trend of mathematical creativity research themes (Figure 10) continues to shift from themes that focus exclusively on discipline-specific instructional practices to general instructional practices themes that involve more person, process, product, and press/environment creativeness. Future researchers will have the opportunity to investigate research topics such as these to promote the development of creativity in schools in general and the development of students' mathematical creativity in particular when learning mathematics.

5. Conclusion, Limitations, and Implications

This study uses bibliometric analysis to construct a comprehensive picture of the last two decades (2002–2022) of research on mathematical creativity, particularly in the field of mathematics education. All of the 162 journal articles analyzed in this study are indexed in the Scopus database. The following are the major findings of the study: First, despite a decline in citations, the quantity of papers on mathematical creativity has rapidly increased over the past two decades. The University of Haifa and the United States are the most productive and influential universities in terms of publication output, respectively. The authors and journals Bicer (United States) and ZDM-Mathematics Education are highly productive and influential. Fourth, "creativity" has been the most prominent keyword over the past two decades as the primary research topic. Future research trends will encourage researchers of mathematical creativity to focus not only on the topic of discipline-specific instructional practices, but also on the topic of general instructional practices that incorporate more person, process, product, and press/environment creative approaches.

This study has a variety of research limitations. The researcher searches for relevant document titles with scope restrictions or other criteria to exclude pertinent information from the current study. Second, no other databases were combined with the data used for this analysis, which consisted solely of Scopus database information. Thirdly, the bibliometric analysis in this study is limited to analysis of the author's keywords and does not include analysis of the entire text, so it is conceivable that the development of the themes differs.

In light of the limitations of this study, additional bibliometric research with recommendations is required. First, the scope of the data can be broadened by incorporating additional databases, allowing for the identification of trends in the evolution of the field of study at various stages. For instance, the data used originates from the Web of Science database. Future studies are anticipated to be able to use an analytical unit with a larger database to obtain a comprehensive portrait of the trends in the research on mathematical creativity. To serve as a resource for researchers, educators, schools, curriculum developers, and the government, the study's findings can provide information and literature on the development of the study of mathematical creativity. Given the importance of the study of mathematical creativity, it is anticipated that researchers will be able to refer to this study when researching mathematical creativity related to various themes and fields using a variety of suitable research methods. This study can provide instructors with an overview of the development trend in the study of mathematical creativity for use as a reference in the classroom learning process. This study can serve as a foundation for schools to formulate policies regarding the significance of mathematical creativity in the classroom, allowing students to reach their full potential. This study can serve as a basis for curriculum designers to establish curriculum policies that make mathematical creativity a learning objective. Lastly, for the government, this study can serve as the premise for mapping developments and trends in creativity studies (in mathematics) so that they can be incorporated into regional or national educational policies.

Acknowledgments: Researchers would like to thank the Directorate General of Higher Education, Research and Technology, Ministry of Education, Culture, Research and Technology of the Republic of Indonesia to fund this research through a Doctoral Dissertation Research Grant, Contract Number 042/E5/PG.02.00.PL/2023.

Author contributions: All authors are agreed with the results and conclusions.

Declaration of interest: No conflict of interest is declared by the authors.

Ethics declaration: This study does not require an ethical approval, because it only analyzes the data from published literature.

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