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A Bibliometric Analysis of Studies on Sustainability in Mathematics Education Based on Web of Science Database

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ABSTRACT

This research aims to conduct a bibliometric analysis of studies on sustainability in mathematics education found in the Web of Science database. It is believed that this study will make a significant contribution to the literature on sustainability in mathematics education, serving as a valuable resource for researchers considering work in this field. To analyze the obtained data, the bibliometric analysis method, a quantitative research model, has been utilized. Through this method, targeted research has been conducted by scanning the Web of Science database using relevant keywords, resulting in the examination of 296 works published from 1997 to the present. The distribution of selected studies has been detailed according to publication years, categories, authors, institutions, countries, types, subject areas, and the most cited works. Additionally, network maps illustrating co-authorship relationships among authors, co-authorship relationships among countries, common keywords, citation matching by institutions, co-citation networks based on cited works, co-citation networks of cited journals, and co-citation networks of cited authors have been provided in the findings section. The results indicate that various aspects of sustainability in mathematics education have been addressed through numerous studies conducted from 1997 to the present.

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INTRODUCTION

In recent years, the concept of sustainability has gained significant importance as a means of addressing issues such as climate change, environmental degradation, and societal challenges. Sustainability refers to meeting present needs without compromising the ability of future generations to meet their own needs. Achieving and maintaining sustainability requires a broad transformation in consumption patterns, production perspectives, and social structures (Maniatis, 2023). Since the recognition of the necessity of these changes, the concept of sustainable development has come to the forefront (Aghion & Howitt, 1997).

Education for Sustainable Development (ESD) is essential for fostering the social transformation required to build a peaceful, prosperous, and sustainable world, as well as for nurturing individuals who can take active roles and act responsibly toward both themselves and society (United Nations Educational, Scientific and Cultural Organization, 2020). Education plays a crucial role in raising awareness and fostering a new perspective on sustainable development in all aspects of individuals' and communities' lives (Bulut & Polat, 2019). At this point, there is a significant relationship between sustainability and education, as educational activities aim to create a more sustainable future for society by following a sustainable path (Öztürk, 2017; Çoruk & Turhan, 2024).

The presence of sustainability and sustainable development in mathematics education has been evident in various parts of the mathematics curriculum (Vásquez et al., 2021). Issues arising from social, economic, and environmental challenges, as well as their solutions, can be better understood through mathematics (National Council of Teachers of Mathematics, 2000). Integrating the concept of sustainability into mathematics education not only deepens students' mathematical understanding but also strengthens their ability to transfer and apply these skills across different disciplines. Additionally, fostering sustainability awareness among students equips them with the necessary tools to face future environmental, economic, and social challenges. In this context, addressing mathematics education through a sustainability perspective contributes to the development of students as more conscious and responsible individuals (Serow, 2015). It plays a critical role in helping students connect real-life problems with their own environments, thereby highlighting the importance and role of sustainability in mathematics education (Renert, 2011).

Numerous studies have explored the relationship between sustainability and mathematics education, highlighting its importance (Li & Tsai, 2021; Petocz & Reid, 2003; Renert, 2011; Wals & Corcoran, 2004). In their research, Petocz and Reid (2003) examined how the concept of sustainability can be understood and applied within mathematics education. The researchers emphasized that mathematical thinking is a crucial tool for understanding and addressing sustainability issues. Their study demonstrates how integrating the concept of sustainability into mathematics education can enhance students' mathematical skills while also fostering greater awareness of sustainability. The research offers recommendations for sustainability-based mathematics education, arguing that the integration of these two disciplines can raise both academic and societal awareness among students.

In his research, Renert (2011) argues that mathematics education should be reconsidered through a sustainable approach. The researcher emphasizes the need to relate mathematics more meaningfully to daily life, as this could help students develop more positive attitudes toward the subject. Renert also highlights that sustainable mathematics education should not solely focus on technical knowledge but should enable students to develop critical thinking, problem-solving skills, and social responsibility. The study suggests new pedagogical approaches to make mathematics education more relevant and integrated into students' lives.

Li and Tsai (2021), in their study, examined how Education for Sustainable Development (ESD) can be integrated into the context of mathematics education. The researchers stressed the crucial role of mathematical thinking and problem-solving skills in achieving sustainable development goals. Their

research provided a theoretical framework for integrating ESD into mathematics education, focusing on pedagogical strategies and practical applications. Additionally, they addressed the challenges encountered during this integration process and proposed solutions to overcome these obstacles. The study offers a roadmap that can help students gain a deeper understanding of both mathematical and sustainability-related concepts.

Research provides an in-depth overview of the general state of the literature, revealing current trends and developments. These studies not only help us track the latest innovations in the field but also build upon the knowledge accumulated from previous research. As such, they serve as a guide for researchers in determining the direction of future studies. Additionally, these studies help identify gaps in the field and determine which topics should be prioritized. Scientific reviews conducted on specific topics play a critical role in establishing a solid foundation for future research, helping to define trends and priorities (Falkingham & Reeves, 1997). Yıldırım and Şimşek (2021) also emphasized in their research that synthesizing studies is important, offering a reliable and practical resource for future work. In the literature, various studies that analyze and synthesize research on different topics are observed (Çelik et al., 2018; Kaya & Dinçer, 2023; Sandelowski & Barroso, 2003; Saraçoğlu & Aşılıoğlu, 2022; Techentin et al., 2014). However, upon reviewing the literature, it is evident that a bibliometric analysis of studies on sustainability in mathematics education within the Web of Science database has not yet been conducted.

Therefore, this study aims to conduct a bibliometric analysis of research on sustainability in mathematics education, based on the Web of Science database. It is anticipated that this study will make a significant contribution to the literature on sustainability in mathematics education and offer a comprehensive literature review by compiling existing research in the field. Through this approach, researchers interested in focusing on sustainability in mathematics education will be able to assess the current state of the field and shape their own studies accordingly. The sub-problems identified within this framework are presented below. These problems will guide researchers and provide support in determining the direction of their work.

In the Web of Science database, studies on sustainability in mathematics education:

What is the distribution of studies on sustainability in mathematics education, in the Web of Science database, based on the following: year, category, author, institution, country, type, subject area, journal, and most-cited works?

What does the network map look like for the following aspects of studies on sustainability in mathematics education in the Web of Science database: co-authorship relationships by authors, co-authorship relationships by countries, common keywords, bibliographic coupling by institutions, co-citations by cited works, co-citations by cited journals, and co-citations by cited authors?

METHOD

Research design

This study aims to conduct a bibliometric analysis of research on sustainability in mathematics education based on the Web of Science database. Advances in information technology have facilitated faster, easier, and more economical access to information, leading to a substantial increase in the volume of accessible data. In this context, evaluating the obtained information, ensuring the reliability and currency of sources, and preventing the formation of useless data piles are critical. Therefore, analyzing data by classifying it, rather than handling it in bulk, makes it possible to obtain accurate, reliable, and sufficient information. Bibliometric analysis is one method that can be used for this purpose. Bibliometric studies are important works that examine the existing literature in a specific scientific field to reveal the current state, trends, and development processes of the field (Üsdiken & Pasadeos, 1993). Similarly, bibliometric analysis is a method widely used across various disciplines today, applied to examine the

structure and dynamics of academic and scientific work within a particular field. This technique has become an indispensable tool for understanding the development of a discipline and evaluating emerging research trends in that area. Additionally, this analytical method provides insights into the general state of the field and helps determine future research directions (Borgman & Furner, 2002). Based on this information, data will be analyzed through the creation of tables and scientific field maps, focusing on publication years, sources, authors, connections, countries, types, subject areas, co-authorship, common keywords, bibliographic coupling, and co-citation.

Data Collection

In accordance with the objective of the study, the scope of research on sustainability in mathematics education in the literature has been determined through a bibliometric analysis of studies published in the Web of Science database.

Web of Science is a multidisciplinary database that serves as an indispensable information resource for researchers, academics, and scientists worldwide. Initially launched in the 1960s by the Institute for Scientific Information (ISI) and currently operated by Clarivate Analytics, Web of Science allows for the systematic indexing of academic works published across a broad range of fields, including science, technology, social sciences, arts, and humanities. The platform offers a rich database containing millions of journal articles, conference papers, books, patents, and other academic resources. One of Web of Science's most powerful features is its citation analysis and research performance metrics. These tools enable the examination of a work's impact within the scientific community, its relationship with other studies, and citation counts. As a result, researchers can track the most current and influential works in their fields, monitor scientific trends, and better position their own research. Web of Science also provides capabilities for broader analyses, such as research funding, institutional performance, and scientific collaborations. Researchers can gain in-depth information on specific topics, authors, institutions, or journals, using this information to enhance literature reviews, identify future research topics, and shape academic publishing strategies. The comprehensive data and analytical tools offered by Web of Science make it a reference point within the global academic community (Clarivate, 2024).

To identify studies for the bibliometric analysis research method, a comprehensive literature review was conducted at the beginning of the research process based on the defined research questions. As a result of this review, relevant studies from the Web of Science database were selected. During the data collection phase, content analysis was performed to determine which studies to include, and consultations were held with experts in the field regarding the selection of keywords. Based on the feedback from these experts, keywords were established, and the research was refined using these keywords. In reviewing the literature, searches were conducted using the keywords "Sustainability in Mathematics Education," "Sustainability and Mathematics Education," "Sustainable Development in Mathematics Education," and "Sustainable Development and Mathematics Education." Studies that contained these keywords in their titles, keywords, or abstracts were identified and examined. As a result, all studies from the past to the present, across all indices, document types, publishers, institutions, authors, languages, and Web of Science categories were included in the research, leading to a total of 296 studies. The selected studies were then exported for the analysis phase.

Data Analysis

VOSviewer is a software tool designed for constructing and visualizing bibliometric networks (Eck & Waltman, 2017). This software is developed to analyze relationships between scientific publications and citations, presenting these relationships in visual maps. VOSviewer excels in visualizing concept networks, co-citation analyses, author collaborations, and the evolution of terms over time, particularly when working with large datasets. Its user-friendly interface allows researchers to easily examine the overall structure and dynamics of literature across different disciplines, identify research trends and gaps. Additionally, the maps created with VOSviewer contribute to a better understanding of academic work

and reveal significant connections and interactions in the literature. Consequently, VOSviewer has become a widely preferred tool in bibliometric analyses (Eck & Waltman, 2010).

In this study, the Web of Science database, which provides extensive global academic content, was utilized as a key resource. During the research process, the bibliometric mapping feature of VOSviewer software was employed to conduct the required analyses, enabling the creation of detailed maps for in-depth examination. Findings related to the questions posed were directly obtained from the database in tabular form and analyzed. This process integrated both the tabular analyses conducted through the Web of Science database and the bibliometric maps generated using VOSviewer, with results being carefully interpreted. All these findings are presented comprehensively and in detail in the results section. This approach has expanded the scope of the research and allowed for a more profound analysis of the findings.

Validity and Reliability of the Study

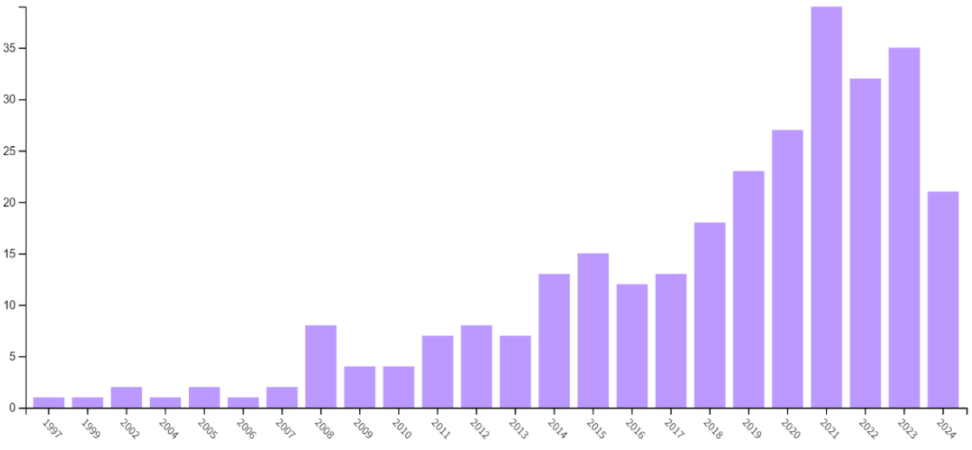
In this bibliometric analysis study, the literature review process was conducted meticulously. The objectives included identifying relevant studies on the topic, clarifying research questions, examining these studies under specific categories in detail, compiling them, and presenting a comprehensive report. The study's aims and research questions were clearly articulated, thereby defining the focus of the work.

Ensuring the reliability of the research is crucial not only in the selection of studies but also in verifying their accuracy and validity. In this context, extensive reviews were carried out over a prolonged period to process the studies without errors, and continuous communication was maintained with experts in the field. The selection of studies and the determination of keywords, based on expert opinions, enhanced the depth and accuracy of the research. Additionally, the processes of data export and cleaning were executed with great care, minimizing error margins during the analysis phase and maximizing the reliability of the findings. This process plays a critical role in enhancing the scientific contribution of the research and the value it adds to the literature.

FINDINGS

In alignment with the research focus, the distribution of studies in the Web of Science database was analyzed according to their publication years, sources, authors, connections, countries, types, and subject areas. Subsequently, network analyses were conducted for co-authorship (authors, countries), co-occurrence of keywords, bibliographic coupling (authors, journals, countries), and co-citation (authors, studies, journals).

The distribution of published studies on sustainability in mathematics education by year is presented below.



Graph 1. *Distribution of articles by year*

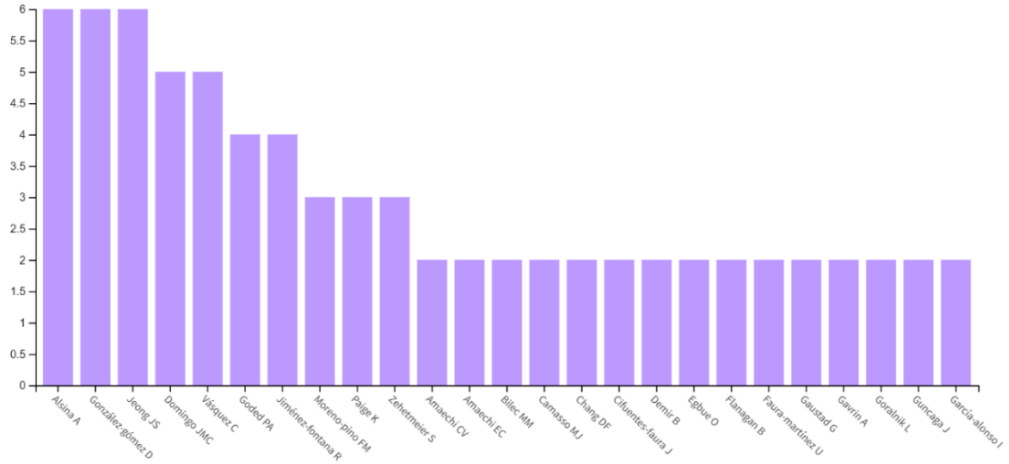
Upon examining Graph 1, it can be observed that studies on sustainability in mathematics education began in 1997 and generally increased up until 2021. The highest number of studies was conducted in 2021 (n=39). Following this, although the number of studies published remained higher than in previous years, it was lower compared to 2021. Interest in this topic has evidently increased since 1997. While a decline is observed in 2024, the number of studies in the graph only reflects the first seven months of the year.

The distribution of published studies on sustainability in mathematics education according to the top 25 categories in the Web of Science is presented below.

Figure 1. *Tree map of studies by the top 20 wos categories*

Upon examining Figure 1, it can be observed that in the Web of Science categories related to sustainability in mathematics education, Education & Educational Research ranks first (n=145). It is followed by Green & Sustainable Science & Technology (n=61), Environmental Sciences (n=58), Education & Scientific Disciplines (n=52), Environmental Studies (n=51), Engineering Multidisciplinary (n=18), Engineering Electrical & Electronic (n=9), Mathematics (n=9), Computer Science Interdisciplinary Applications (n=7), Psychology Educational (n=7), and Engineering Environmental (n=5).

The distribution of published studies on sustainability in mathematics education by the top 25 authors with the highest number of publications is presented below.



Graph 2. *Distribution by the top 25 authors with the most publications*

Upon examining Graph 2, it can be observed that the authors with the highest number of studies on sustainability in mathematics education are Angel Alsina (n=6), David Gonzalez Gomez (n=6), and Jin Su Jeong (n=6). They are followed by José María JMCD Cardeñoso Domingo (n=5), Claudia Vásquez (n=5), Pilar PAG Azcárate Goded (n=4), Rocío RJF Jiménez-fontana (n=4), Francisco Manuel Moreno-Pino (n=3), Kathryn Paige (n=3), and Stefan Zehetmeier (n=3).

The distribution of published studies on sustainability in mathematics education by the top 25 institutions is presented below.

Figure 2. *Distribution of studies according to the top 25 institutions*

Upon examining Figure 2, it can be observed that the institution with the highest number of publications on sustainability in mathematics education is Universitat De Girona (n=8). It is followed by Pontificia Universidad Catolica De Chile (n=7), Universidad De Cadiz (n=7), Universidad De Extremadura (n=7), University Of California System (n=5), University System Of Georgia (n=5), Oregon State University (n=4), Pennsylvania Commonwealth System Of Higher Education (PCSHE) (n=4), State University System Of Florida (n=4), Sungkyunkwan University (SKKU) (n=4), Universidad De La Laguna (n=4), Universiti Kebangsaan Malaysia (n=4), University Of California, Berkeley (n=4), and University Of Pittsburgh (n=4).

The distribution of published studies on sustainability in mathematics education by the top 25 countries is presented below.

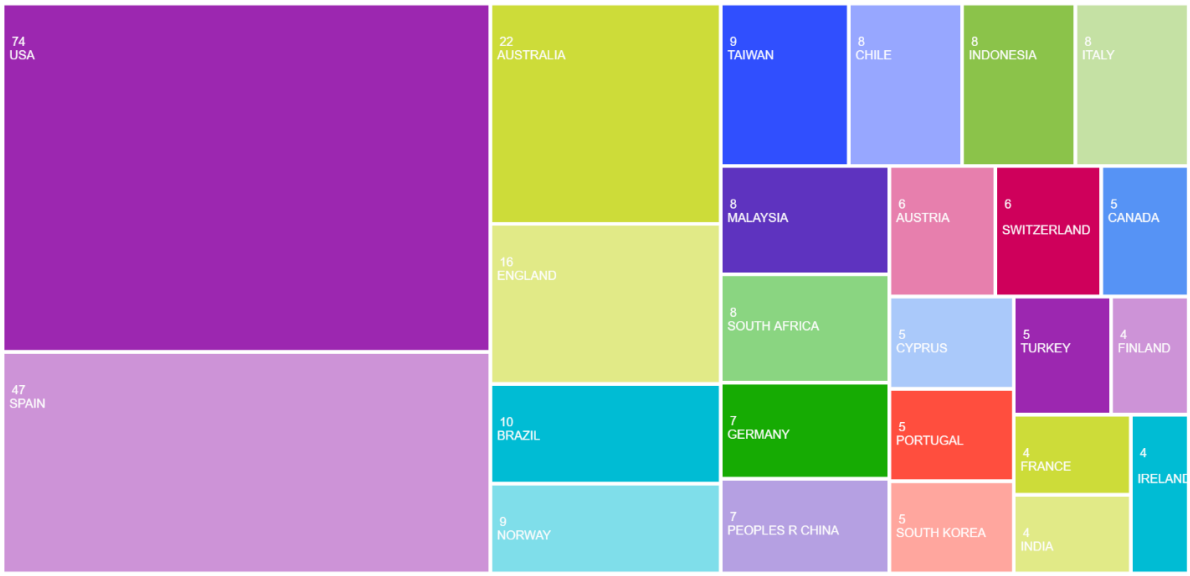


Figure 3. *Distribution by the top 25 countries*

Upon examining Figure 3, it can be observed that the country with the highest number of studies on sustainability in mathematics education is the United States (n=74). This is followed by Spain (n=47), Australia (n=22), United Kingdom (n=16), Brazil (n=10), Norway (n=9), Taiwan (n=9), Chile (n=8), Indonesia (n=8), Italy (n=8), Malaysia (n=8), South Africa (n=8), Germany (n=7), China (n=7), Austria (n=6), Switzerland (n=6), Canada (n=5), and Turkey (n=5).

The distribution of published studies on sustainability in mathematics education by type is presented below.

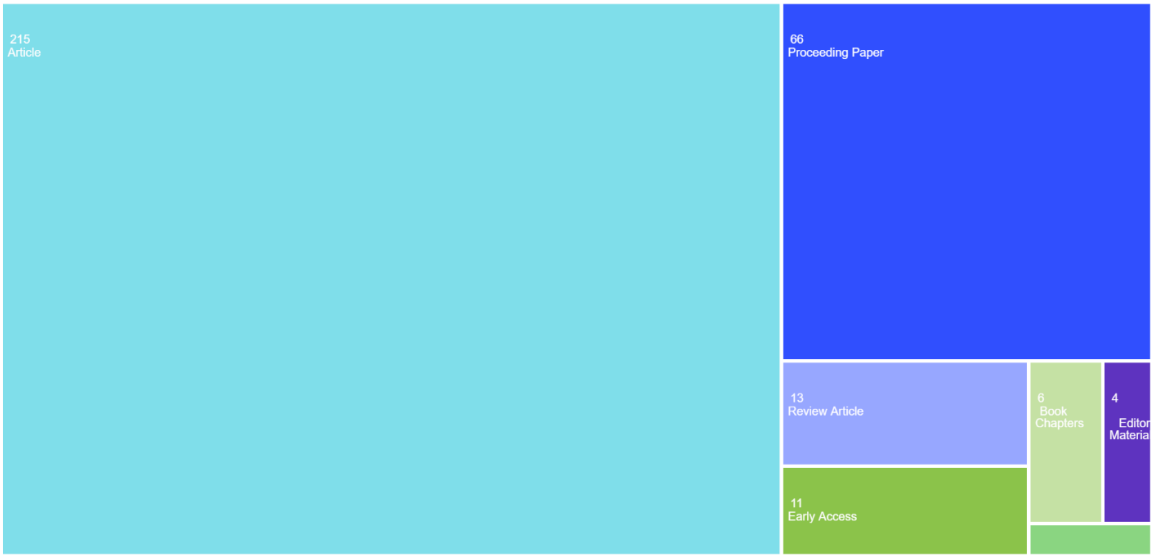


Figure 4. *Distribution by type of studies*

Upon examining Figure 4, it can be observed that the highest number of publications on sustainability in mathematics education is in the form of articles (n=215). This is followed by conference papers (n=66), review articles (n=13), early access publications (n=11), book chapters (n=6), editorial materials (n=4), and meeting abstracts (n=2).

The distribution of published studies on sustainability in mathematics education by subject area is presented below.

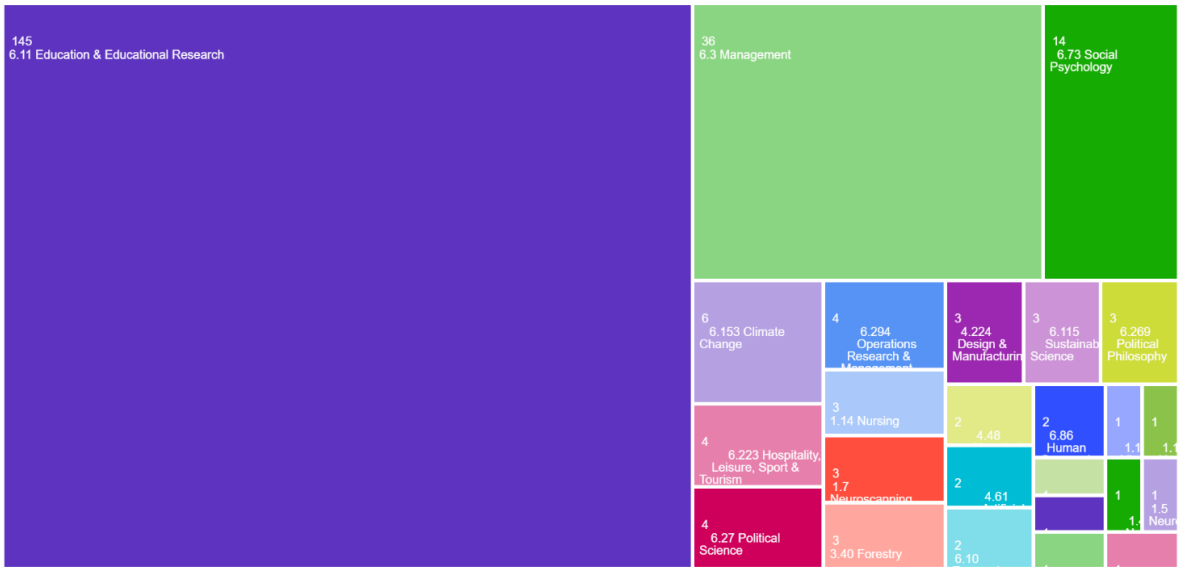


Figure 5. *Distribution by subject area of studies*

Upon examining Figure 5, it can be observed that the category with the highest number of studies related to sustainability in mathematics education is Education and Educational Research (n=145). This is followed by Management (n=36), Social Psychology (n=14), Climate Change (n=6), Hospitality (n=4), Leisure (n=4), Sport and Tourism (n=4), Political Science (n=4), Operations Research and Management Science (n=4), Nursing (n=3), Neuroscanning (n=3), Forestry (n=3), Design and Manufacturing (n=3), Sustainability Science (n=3), and Political Philosophy (n=3).

The distribution of published studies on sustainability in mathematics education in the Web of Science database by the top 25 journals is presented below.

Figure 6. *Distribution by the top 25 journals*

Upon examining Figure 6, it can be observed that the journal with the highest number of publications on sustainability in mathematics education is MDPI (n=71). This is followed by Springer Nature (n=37), Taylor and Francis (n=20), Elsevier (n=18), IATED-Int Assoc Technology Education and Development (n=11), Emerald Group Publishing (n=10), American Society for Engineering Education (n=9), IEEE (n=9), Wiley (n=7), Sociedad Española de Investigación y Educación Matemática (SEIM) (n=6), Frontiers Media SA (n=4), IATED-Int Assoc Technology Education and Development (n=4), SAGE (n=4), Anadolu University (n=3), IOP Publishing Ltd (n=3), and University of Cadiz, Department of Didactics (n=3).

In the studies published on sustainability in mathematics education within the Web of Science database, the category with the highest number of research articles is Education & Educational Research (n=145). The top 10 most cited studies in this category are presented below.

Table 1. *Top 10 most cited studies in the education & educational research category*

	Name of the Study	Author Name	Year of Publication	Number of Citations	Number of References
1	Decolonizing Methodologies And İndigenous Knowledge: The Role Of Culture, Place And Personal Experience In Professional Development	Pauline W. U. Chinn	2007	86	64
2	The Adoption Of Open Educational Resources By One Community College Math Department	John Levi Hilton Donna Gaudet Phil Clark Jared Robinson David Wiley	2013	80	14
3	Subject Teachers As Educators for Sustainability: A Survey Study	Anna Uitto Seppo Saloranta	2017	60	29
4	Global Citizenship Education, School Curriculum And Games: Learning Mathematics, English And Science As A Global Citizen	Cher Ping Lim	2008	57	31
5	Developing A Communal İdentity As Beginning Teachers Of Mathematics: Emergence Of An Online Community Of Practice	Merrilyn E. Goos Anne Bennison	2008	53	19
6	Ways Of Promoting The Sustainability Of Mathematics Teachers' Professional Development	Stefan Zehetmeier Konrad Krainer	2011	41	69
7	Online Mathematics Teacher Education: Overview Of An Emergent Field Of Research	Marcelo de Carvalho Borba Salvador Llinares	2012	37	25
8	Moving Towards Transdisciplinarity: An Ecological Sustainable Focus For Science And Mathematics Pre-Service Education In The Primary/Middle Years	Kathryn Paige David Lloyd Mike Chartres	2008	37	56
9	Evidence-Based CPD: Scaling Up Sustainable Interventions	Bettina Roesken-Winter Celia Hoyles Sigrid Blömeke	2015	36	82
10	Reforming Mathematics Learning In Indonesian Classrooms Through RME	Robert K. Sembiring Sutarto Hadi Maarten Dolk	2008	35	30

Upon examining Table 1, the most cited study in the field of sustainability in mathematics education is “Decolonizing Methodologies and Indigenous Knowledge: The Role of Culture, Place, and Personal Experience in Professional Development” published by Pauline W. U. Chinn in 2007 (citation count = 86). This is followed by the study “The Adoption of Open Educational Resources by One Community College Math Department” by Hilton et al. (2013) (citation count = 80), “Subject Teachers as Educators for Sustainability: A Survey Study” by Uitto et al. (2017) (citation count = 60), “Global Citizenship Education, School Curriculum and Games: Learning Mathematics, English and Science as a Global Citizen” by Lim (2008) (citation count = 57), “Developing a Communal Identity as Beginning Teachers of Mathematics: Emergence of an Online Community of Practice” by Goos et al. (2008) (citation count = 53), “Ways of Promoting the Sustainability of Mathematics Teachers' Professional Development” by

Zehetmeier et al. (2011) (citation count = 41), "Online Mathematics Teacher Education: Overview of an Emergent Field of Research" by Borba et al. (2012) (citation count = 37), "Moving Towards Transdisciplinarity: An Ecological Sustainable Focus for Science and Mathematics Pre-Service Education in the Primary/Middle Years" by Paige et al. (2008) (citation count = 37), "Evidence-Based CPD: Scaling Up Sustainable Interventions" by Winter et al. (2015) (citation count = 36), and "Reforming Mathematics Learning in Indonesian Classrooms Through RME" by Sembiring et al. (2008) (citation count = 35).

The network map showing the co-author relationship of the studies published on sustainability in mathematics education according to the authors is given below.

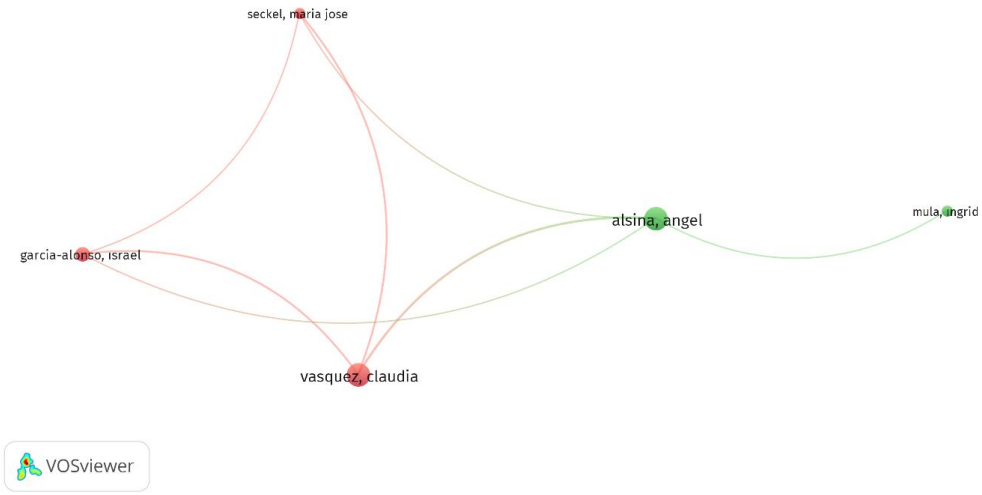


Figure 7. *Co-authorship network map of authors in the studies*

Upon examining Figure 7, it can be observed that to identify the co-authorship network of authors in studies on sustainability in mathematics education, the minimum publication count for an author was set to two, as was the minimum citation count. Based on these criteria, the total number of authors cited in the studies is 46, with the largest cluster consisting of 5 authors. The analyses revealed that the most connected author group comprises 2 clusters (connection count: 7, total connection strength: 11). Each of these clusters contains at least 2 and at most 3 authors. The prominent authors within these clusters include Angel Alsina (connection count: 4, total connection strength: 6, document count: 6), Claudia Vásquez (connection count: 3, total connection strength: 7, document count: 6), Maria Jose Seckel (connection count: 3, total connection strength: 4, document count: 2), and Israel Garcia-Alonso (connection count: 3, total connection strength: 4, document count: 3).

The network map illustrating the co-authorship relationships among countries in studies published on sustainability in mathematics education is presented below.

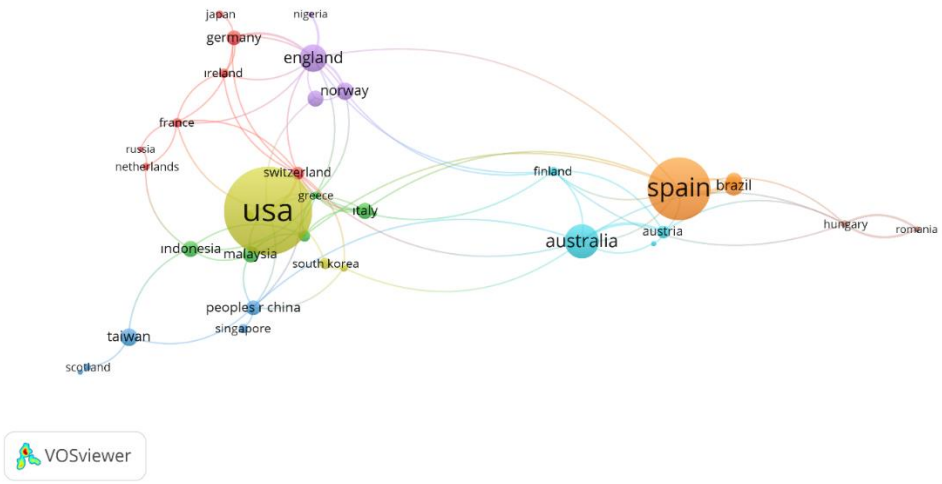


Figure 8. *Co-authorship network map by country in the studies*

Upon examining Figure 8, it can be observed that to identify the co-authorship network of countries in studies published on sustainability in mathematics education, the minimum publication count for an author was set to two, as was the minimum citation count. Based on these criteria, the total number of countries cited in the studies is 43, with the number of countries forming a large cluster identified as 37. The analyses revealed that the most connected group of countries consists of 8 clusters (connection count: 79, total connection strength: 95). Each of these 9 distinct clusters contains at least 3 and at most 7 co-authoring countries. Among these countries, the United States (connection count: 10, total connection strength: 11, document count: 74), Spain (connection count: 9, total connection strength: 15, document count: 47), Australia (connection count: 8, total connection strength: 10, document count: 21), United Kingdom (connection count: 10, total connection strength: 13, document count: 16), and Indonesia (connection count: 5, total connection strength: 5, document count: 8) stand out prominently.

The network map illustrating the co-occurring keywords in studies published on sustainability in mathematics education is presented below.

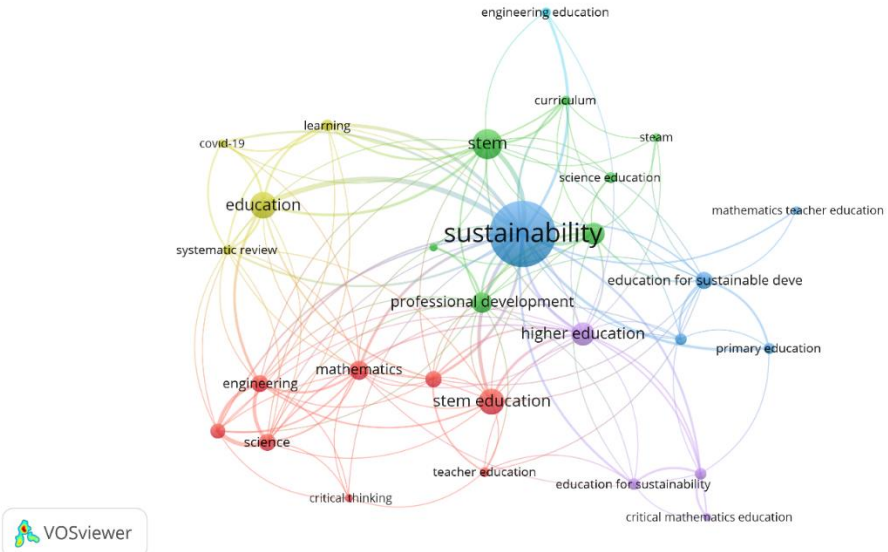


Figure 9. *Co-occurrence network map of keywords in the studies*

Upon examining Figure 9, it can be observed that the minimum count for co-occurring keywords in studies published on sustainability in mathematics education has been set to five. The total number of keywords analyzed is 29. The analysis revealed that the most connected group of co-occurring keywords consists of 6 clusters (connection count: 138, total connection strength: 269). Each of these 6 distinct clusters contains at least 1 and at most 8 common keywords. Among these shared keywords, the one with the highest connection strength is sustainability (connection count: 24, total connection strength: 87). This is followed by higher education (connection count: 19, total connection strength: 31), STEM (connection count: 18, total connection strength: 35), professional development (connection count: 14, total connection strength: 22), mathematics (connection count: 14, total connection strength: 21), education for sustainable development (connection count: 13, total connection strength: 19), and education (connection count: 10, total connection strength: 13) as the other commonly used keywords.

The network map illustrating the bibliographic coupling of institutions in studies published on sustainability in mathematics education is presented below.

Figure 10. *Bibliographic coupling network map of institutions in the studies*

Upon examining Figure 10, it can be observed that in the bibliographic coupling of institutions in studies published on sustainability in mathematics education, the minimum publication count for an institution was set to two, and the citation count for the works produced by these institutions was also set to a minimum of two. Based on these criteria, out of 58 institutions, 16 meet the specified requirements. These 16 institutions are organized into 3 clusters (connection count: 21, total connection strength: 23), with each cluster containing at least 4 and at most 7 institutions. Among these institutions, the following stand out: Univ Klagenfurt (connection count: 6, total connection strength: 7), Middle East Technical University (connection count: 4, total connection strength: 5), Comenius University (connection count: 4, total connection strength: 4), George Emil Palade University - Comenius University (connection count: 4, total connection strength: 4), Univ Jyväskylä (connection count: 4, total connection strength: 4), and Univ Miskolc (connection count: 4, total connection strength: 4).

The network map illustrating the co-citation relationships of cited works in studies published on sustainability in mathematics education is presented below.

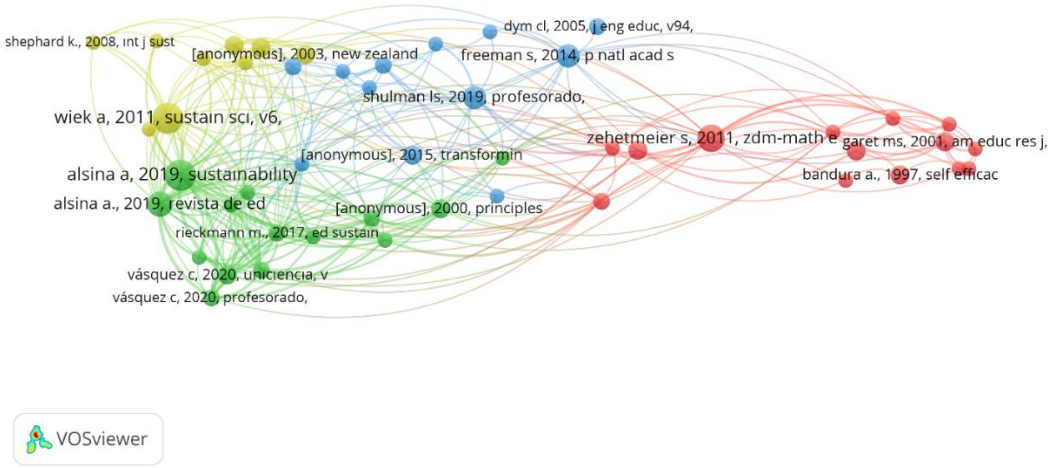


Figure 11. *Co-citation network map of cited works in the studies*

Upon examining Figure 11, it can be observed that the minimum co-citation count for the cited works in studies published on sustainability in mathematics education has been set to five. Accordingly, the total number of cited works is 12,077, with 49 works meeting the specified criteria. The analysis indicates that the network map comprises a total of 4 clusters (connection count: 288, total connection strength: 411), with each cluster containing a minimum of 9 and a maximum of 14 cited works. The most frequently cited works in these studies include Angel Alsina, Sustainability-Basel (2019) (connection count: 26, total connection strength: 54), Angel Alsina, Revista de Educación Ambiental y Sostenibilidad (2019) (connection count: 23, total connection strength: 46), Stefan Zehetmeier, ZDM - Mathematics Education (2011) (connection count: 19, total connection strength: 25), and Claudia Vásquez, Profesorado (2020) (connection count: 16, total connection strength: 33).

The network map illustrating the co-citation relationships of cited journals in studies published on sustainability in mathematics education is presented below.

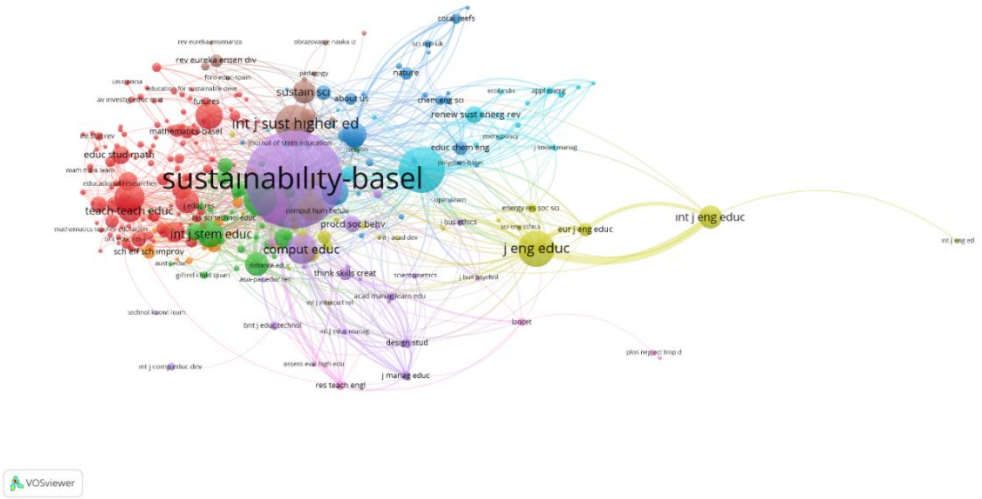


Figure 12. *Co-citation network map of cited journals in the studies*

Upon examining Figure 12, it can be observed that the minimum co-citation count for the cited journals in studies published on sustainability in mathematics education has been set to five. Accordingly, the total number of cited journals is 7,599, with 315 journals meeting the specified criteria. The analysis indicates that the network map comprises a total of 6 clusters (connection count: 1,056, total connection strength: 15,045), with each cluster containing a minimum of 3 and a maximum of 13 cited journals. Among these journals, the following stand out: Sustainability-Basel (connection count: 265, total connection strength: 7,629), Journal of Cleaner Production (connection count: 213, total connection strength: 3,418), Journal of Engineering Education (connection count: 143, total connection strength: 2,705), Educational Sciences (connection count: 231, total connection strength: 1,859), and Science (connection count: 204, total connection strength: 1,166).

The citation network map of authors in studies published on sustainability in mathematics education is presented below.

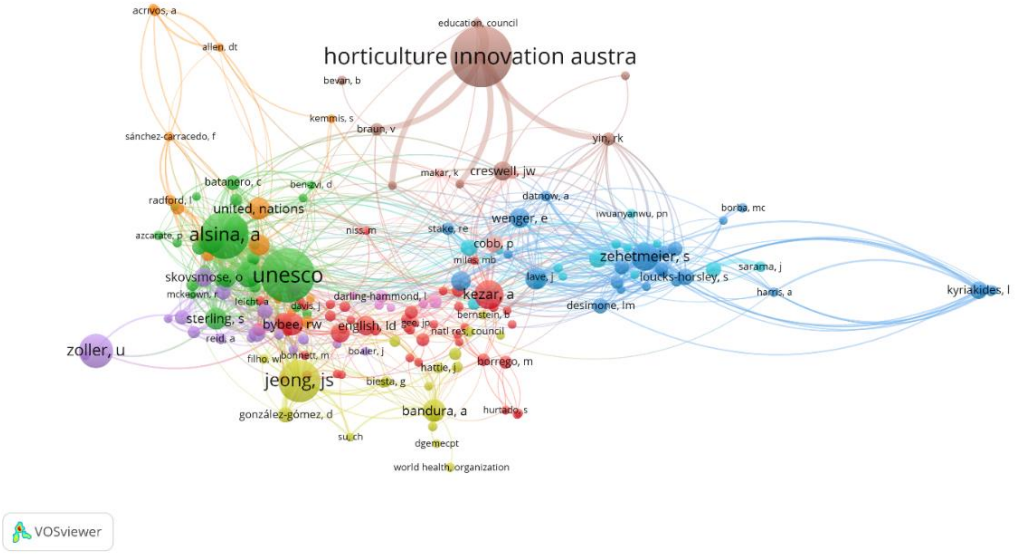


Figure 13. *Co-citation network map of cited authors in the studies*

Upon examining Figure 13, it has been determined that in studies published on sustainability in mathematics education, the number of citations for the referenced authors is set at a minimum of five. Accordingly, the total number of cited authors is 9,120, and the number of journals meeting this criterion is 194. The analysis reveals that the network map consists of a total of 10 clusters (number of connections: 2,539; total connection strength: 8,223), with each cluster comprising a minimum of 4 and a maximum of 46 cited authors. Among these authors are UNESCO (number of connections: 99; total connection strength: 636), Angel Alsina (number of connections: 70; total connection strength: 560), Horticulture Innovation Australia (number of connections: 6; total connection strength: 462), Stefan Zehetmeier (number of connections: 66; total connection strength: 389), Jin Su Jeong (number of connections: 41; total connection strength: 305), and Claudia Vásquez (number of connections: 57; total connection strength: 298).

DISCUSSION, CONCLUSION, RECOMMENDATIONS

It can be argued that sustainability in mathematics education provides conducive conditions for students to learn concepts related to sustainable development and to comprehend and solve the problems they encounter in their environment (Li & Tsai, 2021). Furthermore, by integrating sustainability, the various social, economic, and environmental issues that arise can be better understood through mathematics, along with potential solutions (National Council of Teachers of Mathematics, 2000).

The concept of sustainability plays a significant role in mathematics education (Renert, 2011). In this context, a bibliometric analysis of studies conducted on sustainability in mathematics education has been carried out using the Web of Science database. The data from Web of Science, encompassing studies on sustainability in mathematics education from 1997 to the present, have been examined, and a bibliometric analysis of research in this field has been conducted. It is anticipated that these analyses will provide important contributions to the field and that experts wishing to conduct research on this topic will identify gaps in the literature, allowing them to plan their future studies accordingly.

In the scope of this research, searches were conducted using the keywords "Sustainability in Mathematics Education," "Sustainability and Mathematics Education," "Sustainable Development in Mathematics Education," and "Sustainable Development and Mathematics Education." Studies that included these terms in their titles, keywords, or abstracts were identified and examined. The search resulted in the inclusion of all studies from the past to the present across all indexes, document types, publishers, institutions, authors, and published languages, as well as all categories in the Web of Science. This comprehensive search yielded a total of 296 studies.

An analysis of the number of studies by year reveals that research on this topic has been conducted since 1997, with a noticeable increase in the volume of work over the years. This rise can be attributed to the growing interest in sustainability in mathematics education, aligned with global sustainability goals, as mathematical thinking plays a critical role in addressing environmental, economic, and social issues (United Nations, 2015). Additionally, interdisciplinary approaches assist mathematics students in developing analytical thinking and data analysis skills, enabling them to tackle complex sustainability challenges (Barwell, 2018). Furthermore, the importance of fostering critical thinking and the ability to generate sustainable solutions has gained traction as part of 21st-century skills (Keitel et al., 2004). Another reason for this increased focus is the urgent nature of issues such as the climate crisis and the depletion of natural resources, which necessitate mathematical modeling (Sterling, 2001). The universal language of mathematics has also provided a foundation for global collaboration (Organisation for Economic Co-operation and Development, 2019). Reviewing the starting year of studies related to this topic and the number of studies conducted suggests that the significance of the subject has only recently begun to be recognized, resulting in a relatively low number of studies initially. Nevertheless, despite fluctuations over the years, a general upward trend has been observed. While a decline is noted for 2024, it is important to note that the data presented in the graph covers only the first seven months of that year.

When examining the distribution of published studies on sustainability in mathematics education across Web of Science categories, the top category is "Education Educational Research." This is followed by "Green Sustainable Science Technology," "Environmental Sciences," "Education Scientific Disciplines," "Environmental Studies," "Engineering Multidisciplinary," "Engineering Electrical Electronic," "Mathematics," "Computer Science Interdisciplinary Applications," "Psychology Educational," and "Engineering Environmental." This categorization indicates that the majority of research is concentrated in the field of education, followed by various studies in areas such as the environment, technology, engineering, and multidisciplinary fields.

Since 1997, the authors with the most publications on sustainability in mathematics education are Angel Alsina, David González Gómez, and Jin Su Jeong. Angel Alsina is an academic specializing in mathematics education. His work focuses particularly on mathematics education in early childhood and the development of problem-solving skills during this period. Alsina is developing pedagogical approaches for integrating concepts of sustainability into mathematical processes. In this context, he works on teaching methods that help students enhance their critical thinking and mathematical analysis skills, thereby fostering sustainable thinking capabilities. David González Gómez is a researcher specializing in educational technologies and science-mathematics education. He focuses on the integration of educational technologies, particularly online platforms and digital tools, into educational processes in connection with sustainable development goals. His research explores how mathematics

education can be made more effective in online learning environments and how these processes contribute to sustainable educational objectives. Jin Su Jeong is an academic specializing in teacher education and sustainability in mathematics teaching. He conducts research on the use of innovative teaching methods and technologies in education aligned with sustainable development goals. Jeong works on integrating sustainability concepts into the mathematics curriculum to enhance students' environmental awareness. Additionally, he develops educational materials to provide guidance for teachers in this process. As seen in the analyses, these authors have made significant contributions to the relationship between sustainability in education and mathematics teaching, thereby advancing the development of pedagogical approaches in this field.

The institution with the highest number of publications on sustainability in mathematics education is the Universitat de Girona. Following this, the order of institutions is as follows: Pontificia Universidad Católica de Chile, Universidad de Cádiz, Universidad de Extremadura, University of California System, University System of Georgia, Oregon State University, Pennsylvania Commonwealth System of Higher Education (PCSHE), State University System of Florida, Sungkyunkwan University (SKKU), Universidad de La Laguna, Universiti Kebangsaan Malaysia, University of California, Berkeley, and the University of Pittsburgh. When examining the countries with the most research conducted on sustainability in mathematics education, the United States ranks first. It is followed by Spain, Australia, the United Kingdom, Brazil, Norway, Taiwan, Chile, Indonesia, Italy, Malaysia, South Africa, Germany, China, Austria, Switzerland, Canada, and Turkey. These analyses indicate that sustainability in mathematics education is being addressed in various regions around the world, and significant research is being conducted on this topic.

In the field of sustainability in mathematics education, the majority of publications are in the form of articles. Following this, other types of publications include conference papers, review articles, early access articles, book chapters, editorial materials, and meeting summaries. One of the reasons for the predominance of article-type research on sustainability in mathematics education is its ability to facilitate rapid information sharing and respond to current issues. Articles allow for a focused exploration of specific aspects of the relationship between sustainability and mathematics education, offering opportunities to examine topics in depth, such as the contributions of teaching methods to sustainability. Additionally, articles provide new strategies through interdisciplinary collaborations and serve as valuable resources for educators.

In terms of categories, the "Education and Educational Research" category ranks first in sustainability in mathematics education. This is followed by categories such as Management, Social Psychology, Climate Change, Hospitality, Leisure, Sport and Tourism, Political Science, Operations Research and Management Science, Nursing, Neuroscanning, Forestry, Design and Manufacturing, Sustainability Science, and Political Philosophy. Analyzing the distribution of studies by subject area reveals that the majority of research is conducted in the field of education, while a variety of other subject areas are also represented.

The journal with the highest number of publications on sustainability in mathematics education is MDPI. Following MDPI are Springer Nature, Taylor and Francis, Elsevier, IATED-International Association of Technology Education and Development, Emerald Group Publishing, American Society for Engineering Education, IEEE, Wiley, Sociedad Española de Investigación y Educación Matemática (SEIEM), Frontiers Media SA, IATED-International Association of Technology Education and Development, Sage, Anadolu University, IOP Publishing Ltd., and the University of Cádiz Department of Didactics. An examination of the journals publishing research on sustainability in mathematics education indicates that most of them possess a substantial readership and have a strong publishing presence.

In the Web of Science database, the ten most cited studies within the "Education Educational Research" category related to sustainability in mathematics education are as follows: The study titled "Decolonizing Methodologies and Indigenous Knowledge: The Role of Culture, Place, and Personal Experience in Professional Development" by Pauline W. U. Chinn (2007) ranks first with 86 citations. This study has made significant contributions to the field by emphasizing the importance of indigenous knowledge and cultural contexts in education. It advocates for the inclusion of indigenous knowledge systems in educational practices, supporting the process of decolonization, and discusses the influence of culture and place on professional development. Moreover, in the context of teacher education and sustainability, it promotes a more inclusive and critical approach to education by integrating diverse knowledge systems.

It is followed by "The Adoption of Open Educational Resources by One Community College Math Department" authored by John Levi Hilton et al. (2013), which has received 80 citations. This study has made significant contributions to sustainability in mathematics education through the use of Open Educational Resources (OER). By promoting the low-cost and accessible nature of OER, the study supports economic sustainability in education while fostering environmental sustainability through the reuse and sharing of resources. Additionally, the adoption of OER enhances educational equity by enabling broader access to mathematical knowledge for more students, contributing to the development of a long-term, sustainable learning ecosystem. In this way, the study serves as a guide for transforming mathematics education into a more sustainable and inclusive framework.

The third study, "Subject Teachers as Educators for Sustainability: A Survey Study," by Anna Uitto et al. (2013), has garnered 60 citations. This study examines the role of teachers in sustainability education, indirectly contributing to the field of mathematics education. It emphasizes the potential for mathematics teachers to integrate sustainability principles into their lessons, highlighting the need to raise teachers' awareness and support interdisciplinary approaches. In this context, the study provides an important perspective on how mathematics lessons can help develop sustainability awareness through real-world problem-solving.

Additionally, "Global Citizenship Education, School Curriculum, and Games: Learning Mathematics, English, and Science as a Global Citizen" by Cher Ping Lim (2008) has 57 citations. The study integrates global citizenship education with mathematics lessons, exploring ways to equip students with knowledge about sustainability, environmental awareness, and global issues. By developing mathematical thinking skills in a global context, it offers a critical approach to problem-solving for worldwide challenges and highlights the role of education as a key tool in achieving sustainable development goals.

The fifth study, "Developing a Communal Identity as Beginning Teachers of Mathematics: Emergence of an Online Community of Practice," by Merrilyn E. Goos et al. (2008), has achieved 53 citations. The study promotes the sharing of experiences and knowledge among teachers through an online community, supporting continuous learning and professional development. This process helps teachers develop innovative and sustainable approaches to mathematics education, strengthens the culture of collaboration and partnership in education, and contributes to the creation of a long-term teaching practice ecosystem.

Following this, "Ways of Promoting the Sustainability of Mathematics Teachers' Professional Development" by Stefan Zehetmeier et al. (2011) has 41 citations. The study "Online Mathematics Teacher Education: Overview of an Emergent Field of Research" by Marcelo de Carvalho Borba et al. (2012) has received 37 citations, the same as "Moving Towards Transdisciplinarity: An Ecological Sustainable Focus for Science and Mathematics Pre-Service Education in the Primary/Middle Years" by Kathryn Paige et al. (2008). Moreover, "Evidence-Based CPD: Scaling Up Sustainable Interventions" by Bettina Roesken-Winter et al. (2015) has 36 citations, and lastly, "Reforming Mathematics Learning in Indonesian Classrooms Through RME" by Robert K. Sembiring et al. (2008) has 35 citations.

An analysis of the co-authorship network among authors of studies published on sustainability in mathematics education reveals a total of 46 identified authors. Among these, Angel Alsina, Claudia Vásquez, María José Seckel, and Israel García-Alonso are particularly prominent. The commonality among these authors lies in their collaborative focus on sustainability within the contexts of sustainable development, education, and, specifically, mathematics education. In their work, these authors investigate strategies for integrating sustainability principles into educational systems, methods for fostering sustainability awareness among students, and approaches for creating environmental consciousness in education.

An analysis of the co-authorship network of countries involved in studies on sustainability in mathematics education identifies a total of 43 countries. Among these, the United States, Spain, Australia, the United Kingdom, and Indonesia are notable. This ranking indicates that research on sustainability in mathematics education is being conducted by researchers in various locations and institutions around the world.

Additionally, an examination of the common keywords used in studies related to sustainability in mathematics education reveals that the most frequently used keyword is "sustainability." This is followed by keywords such as "higher education," "STEM," "professional development," "mathematics," "education for sustainable development," and "education." The prevalence of these keywords suggests that the concepts of sustainability and education are interrelated and intertwined. Furthermore, it is anticipated that by engaging with these concepts, researchers will be able to conduct clearer and more accessible studies related to the topic.

In the bibliographic matching of institutions involved in studies on sustainability in mathematics education, a total of 16 institutions have been identified based on the required criteria. Notable among these institutions are the University of Klagenfurt, Middle East Technical University, Comenius University, George Emil Palade University of Medicine, Comenius University, the University of Jyväskylä, and the University of Miskolc. The analysis of these institutions indicates that they are actively collaborating on research related to sustainability in mathematics education across various regions of the world. This further underscores the value of investigating this topic.

An analysis of the co-citation network of studies published on sustainability in mathematics education reveals the most frequently cited works, including Angel Alsina's Sustainability-Basel (2019), Angel Alsina's Revista de Educación Ambiental y Sostenibilidad (2019), Stefan Zehetmeier's ZDM-Math Educ (2011), and Claudia Vásquez's Profesorado (2020). These studies address the relationship between sustainability and mathematics education from various perspectives. Angel Alsina’s Sustainability-Basel (2019) examines how sustainability education can be integrated during early childhood. It emphasizes the critical role of mathematical thinking and education in fostering environmental awareness among children. The study discusses strategies and practical examples for incorporating sustainability awareness into mathematics education at an early age. Similarly, another work by Angel Alsina, published in Revista de Educación Ambiental y Sostenibilidad (2019), explores the integration of environmental education with mathematics education, offering recommendations on how mathematical concepts can be taught within the context of sustainability. It also aims to enhance students' sensitivity to environmental issues alongside the development of mathematical skills. Stefan Zehetmeier’s study in ZDM-Math Educ (2011) focuses on teacher education within the context of sustainable professional development. The work presents models for how mathematics teachers can sustainably advance their professional growth, while also investigating the long-term effects of such programs on educators. Claudia Vásquez’s study in Profesorado (2020) centers on how teachers shape mathematical pedagogy within the framework of sustainability education. It provides examples and practices regarding how sustainability themes are addressed in mathematics classes, with the aim of enhancing teaching methods in this context. Overall, the analyses highlight how the topics of mathematics education and sustainability are interconnected and how these two areas can mutually support each other in educational settings.

An analysis of the co-citation network of studies published on sustainability in mathematics education reveals that there are a total of 315 journals that meet the established criteria. Notable among these journals are Sustainability-Basel, Journal of Cleaner Production, Journal of Engineering Education, Educational Studies in Mathematics, and Science. The examination of these journals indicates that they publish research on a variety of topics, possess high impact factors, and ensure that the published studies undergo a rigorous peer-review process. Furthermore, it is noteworthy that international authors collaborate to produce joint works.

In the co-citation network analysis of authors cited in studies on sustainability in mathematics education, prominent figures include UNESCO, Angel Alsina, Horticulture Innovation Australia, Stefan Zehetmeier, Jin Su, and Claudia Vásquez. The works of these authors have significantly contributed to the field of sustainability in mathematics education.

In conclusion, this study presents a bibliometric analysis of research on sustainability in mathematics education published in the Web of Science database from 1997 to the present. This research exclusively includes studies published within the Web of Science database and provides an analysis of them. The findings indicate that the topic of sustainability in mathematics education has only recently begun to be explored, with a limited number of studies conducted. Researchers can examine this study to understand what has been explored in this field and how the research has been conducted, thereby gaining insights for their own investigations. Additionally, they may explore other databases to conduct more comprehensive bibliometric analyses. It is anticipated that this research will serve as a valuable data source for researchers interested in the topic and help them gain a deeper understanding of its nuances.

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