Prisma Sains: Jurnal Pengkajian Ilmu dan Pembelajaran Matematika dan IPA IKIP Mataram
https://e-journal.undikma.ac.id/index.php/prismasains/index
e-mail: prismasains.pkpsm@gmail.com

October 2026. Vol. 14, No. 4
p-ISSN: 2338-4530
e-ISSN: 2540-7899
pp. 2666-2687

A Bibliometric Review of Gender, Sustainable Development, and Mathematics Education: Trend Mapping and Co-Authorship and Keyword Co-Occurrence Analysis

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Received: January 2026; Revised: February 2026; Published: October 2026

Abstract

This study maps publication trends, collaboration networks, and thematic structures at the intersection of mathematics education, gender, and sustainable development using a bibliometric review approach. Following the PRISMA 2020 protocol, 100 peer-reviewed journal articles (2015–2025) were extracted from Google Scholar via Publish or Perish and analyzed through VOSviewer 1.6.20 using co-authorship and keyword co-occurrence techniques. The corpus accumulated 2,766 citations (average 27.66/article), with an h-index of 26 and g-index of 45. Results reveal a sharp publication surge since 2020 (peak: 42 articles in 2024) and a highly centralized collaboration network anchored by Àngel Alsina. Thematic analysis identified three clusters: (1) Digital Innovation & Pedagogy (AI, ICT, teacher training), (2) Sustainability Competence (ESD, critical thinking, 21st-century skills), and (3) Foundational Equity (gender, STEM). Critically, weak link strength between digital technology and gender/sustainability keywords (e.g., AI–gender link strength ratio <0.3) evidences persistent fragmentation. This evidence map highlights research gaps for agenda-setting particularly integrative studies bridging AI-mediated pedagogy, ethnomathematics, and gender-responsive sustainability education rather than prescribing direct policy interventions.

Keywords: Bibliometric analysis; Gender; Mathematics education; Sustainable development; VOSviewer.

How to Cite: Muntazhimah, M., Putri, R. M., Muntaz, N. Y., Mahadryanie, A., Rahmadhar, F., Amperadi, R., … Zahrah, A. (2026). A Bibliometric Review of Gender, Sustainable Development, and Mathematics Education: Trend Mapping and Co-Authorship and Keyword Co-Occurrence Analysis. *Prisma Sains: Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, *14*(4), 2666–2687. https://doi.org/10.33394/j-ps.v14i4.19201

https://doi.org/10.33394/j-ps.v14i4.19201

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INTRODUCTION

Mathematics education globally is undergoing a fundamental paradigm shift, from merely mastering arithmetic algorithms to developing systemic literacy capable of responding to the complex challenges of the 21st century. As an essential tool for modeling and decision-making, mathematics plays a central role in mapping solutions to environmental crises and social inequality (Rojas et al., 2026; Skovsmose, 2023). Rather than treating numbers as abstract entities detached from reality, contemporary scholarship emphasizes critical mathematics education, where learners utilize quantitative reasoning to interrogate systemic injustices, climate vulnerabilities, and resource distribution (Gutstein, 2006; Suh et al., 2026). By framing real-world dilemmas through mathematical modeling, students cultivate deep analytical capabilities that connect classroom concepts directly to societal welfare, sustainability metrics, and civic engagement (Anhalt et al., 2021; Vogelsanger et al., 2025).

This paradigm evolution is firmly aligned with international mandates asserting that

education must equip students with the competence to understand the interrelationship between local actions and global impacts through the lens of economics, ecology, and social justice (UNESCO, 2020). To achieve this transformative vision, curricular frameworks must integrate culturally responsive pedagogies and data literacy, enabling learners to navigate digital environments ethically and act as agents of equity (Lestari et al., 2025; Stinson et al., 2011). Consequently, teacher professional development and instructional design must pivot toward problem-posing models that foster mathematical citizenship, preparing the next generation to deploy rigorous mathematical thinking toward building resilient, inclusive, and sustainable global communities.

However, the integration of sustainable development values in mathematics learning in the field is often hampered by the rigidity of the curriculum and the dominance of an evaluation system that is oriented solely towards high-stakes testing. Although the use of real-world problem-based learning models can improve students' soft skills and ethical awareness, its implementation tends to be sporadic and structurally under-integrated (Gravemeijer et al., 2017; Vásquez et al., 2023)). This gap creates a disconnect between progressive mathematics pedagogy theory and classroom reality, where sustainability and inclusivity dimensions are often sidelined in favor of pursuing technical material mastery.

The gap between the idealism of the curriculum and its practical application in the field calls for a profound reorientation of how mathematics is positioned in the classroom (Pais & Valero, 2012). Mathematics can no longer be viewed as a value-neutral subject, but must be recognized as an intellectual tool capable of constructing students' understanding of justice and equality. In this context, mathematics education is currently at a crucial crossroads in supporting the global agenda outlined in the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 5 (Gender Equality) (UNESCO, 2022). The integration of Education for Sustainable Development (ESD) into the curriculum is expected to not only build cognitive abilities, but also critical awareness of marginal issues, as systematically documented in recent reviews of mathematics education and sustainability (Lina & Johar, 2025).

This structural unpreparedness is not only reflected in instructional practices but also rooted in an academic discourse that is not yet fully integrated. Although studies on sustainability and gender have developed separately, the synthesis between the two in the context of mathematics education still leaves a wide theoretical gap (Makramalla et al., 2025; Nurlu, 2025). This indicates a misalignment between global policy demands and the current research roadmap, where research often focuses on the effectiveness of technical teaching but ignores the interconnection of broader sociopolitical aspects (Widodo et al., 2025)

In Indonesia, this weak integration has also been identified, reflecting a mismatch between global policy demands and the current research roadmap. Studies reveal that research often prioritizes technical teaching effectiveness while overlooking broader sociopolitical interconnections, resulting in a lack of literature that holistically links mathematical literacy with issues of marginalization. For instance, Nurhikmayati et al. (2024) found significant geographical disparities in students' critical thinking skills, with urban students outperforming those in border and highland areas due to unequal access to resources and socioeconomic factors. Similarly, Sholikhakh et al. (2025) identified epistemic gaps in Indonesian first-grade mathematics textbooks, where weak micro-level task design creates learning obstacles, particularly for underprivileged students. These findings underscore how geographical marginalization and curricular design perpetuate inequalities in mathematics education.

The main problem in current literature is thematic fragmentation. In line with standard bibliometric indicators (Donthu et al., 2021; Ng et al., 2025), this fragmentation can be operationalized through metrics such as low co-occurrence link strength and weak thematic centrality. As Donthu et al. (2021) outline, bibliometric analysis provides a rigorous framework for uncovering the evolutionary nuances of a research field and identifying emerging areas—a

framework that underpins the methodological approach of the present study. Cobo et al. (2011) pioneered approaches for detecting and visualizing the evolution of research fields through co-word analysis and bibliometric mapping, providing methodological foundations for identifying thematic fragmentation—a central concern of the present study. Our analysis reveals these conditions specifically between gender issues and the fields of digital technology (AI/ICT) and sustainability curriculum. Research clusters tend to be isolated; for example, discussions on gender equality often run parallel without significantly intersecting with Artificial Intelligence (AI) innovation or critical pedagogy in mathematics. In fact, in this era of disruption, understanding how AI algorithms can reproduce gender bias is highly dependent on critical mathematical literacy (Pethig & Kroenung, 2023). Recent scholarship in engineering education further confirms that AI systems can preserve or even intensify existing societal gender biases, underscoring the urgent need to integrate gender bias mitigation strategies into technical curricula, including mathematics education (Borges et al., 2025). Without strong integration between these elements, the potential of mathematics education as a driver of solutions to global challenges will not be optimally achieved.

This study offers novelty in two main aspects. First, it is the first study to comprehensively map the triadic intersection between mathematics education, sustainability (ESD), and gender using co-occurrence cluster analysis and trend overlay for the period 2015–2025. Second, this study identifies disconnected themes, particularly between AI/ICT, SDGs, and gender, by including empirical evidence in the form of link strength and density, rather than merely descriptive narrative analysis. The use of link strength and density as quantitative indicators follows methodological precedents in bibliometric research, such as Wei et al. (2024), who employed VOSviewer-based co-occurrence analysis with link strength metrics to map thematic structures in sustainability research.

To achieve this objective, this study analyzed 100 final documents that had undergone a rigorous curation process (from a total of 200 initial documents extracted using Publish or Perish via Google Scholar). This review was conducted to answer the following four research questions (RQs):

- RQ1. What is the annual growth trend of publications on this topic during the period 2015–2025?
- RQ2. Who are the core authors and what is the structure of the collaboration network that has been formed?
- RQ3. What are the main thematic clusters and emerging topics based on the overlay visualization?
- RQ4. What gaps were found in the connectivity between gender issues, ESD, and digital technology in the current intellectual map?

Through the answers to these questions, it is hoped that this research can provide an epistemic basis for policymakers and researchers to develop a mathematics curriculum that is more integrative, inclusive, and relevant to future challenges.

METHOD

Research Design

This study employs a descriptive bibliometric analysis designed to map publication trends, author collaboration networks, and thematic clusters within the intersection of mathematics education, gender, and sustainable development. The bibliometric approach was selected to provide a quantitative and structural overview of the field (Donthu et al., 2021; Kataeva et al., 2025; Zupic & Čater, 2015), identifying central contributors and evolving research gaps over the 2015–2025 period.

Data Collection and Literature Screening

Data was collected from the Google Scholar database due (Martín-Martín et al., 2021) to its extensive coverage of global academic literature. The metadata search process was

conducted using Publish or Perish (PoP) software version 8 (Harzing, 2007). The data search protocol was implemented on December 16, 2025, with the search query: "mathematics education" AND "sustainable development" AND gender. To ensure adequate coverage, the year range was set to 2015–2025 and the maximum results were set to 200 documents. All results were exported in RIS format for further processing. The literature screening process followed the PRISMA 2020 protocol (Page et al., 2021). The initial search through Publish or Perish yielded 200 article metadata. After the identification stage, strict data cleaning was performed according to the predetermined inclusion and exclusion criteria (Table 1). A total of 3 duplicate documents were removed after checking using Mendeley. A total of 37 documents that did not go through the peer-review process, such as those from ResearchGate and Academia.edu, were excluded after manual verification. A total of 20 documents with incomplete metadata were excluded. A total of 8 documents without full text access were discarded. In addition, 18 books and 14 conference papers or proceedings were excluded because they did not meet the inclusion criteria for journal articles. After the entire screening process, a total of 100 valid and relevant documents were included in the final analysis (n = 100) as shown in Figure 1.

Table 1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Document Type	Peer-reviewed journal articles indexed in reputable databases (e.g., Scopus, WoS, SINTA)	Books, book chapters, theses, dissertations, conference proceedings, preprints, duplicates
Time Range	2015 – 2025	Before 2015
Topic Relevance	Explicit intersection of mathematics education, gender, and sustainable development/SDGs.	Articles that only mention keywords in references, or focus on biological/chemical sustainability without clear educational context.
Accessibility	Full text accessible for content verification.	Abstracts only, broken links, or publications behind paywalls without institutional access.
Peer-Review Status	Peer-reviewed documents only.	Non-peer-reviewed materials such as preprints, blogs, lecture notes, or self-archived articles without formal review.

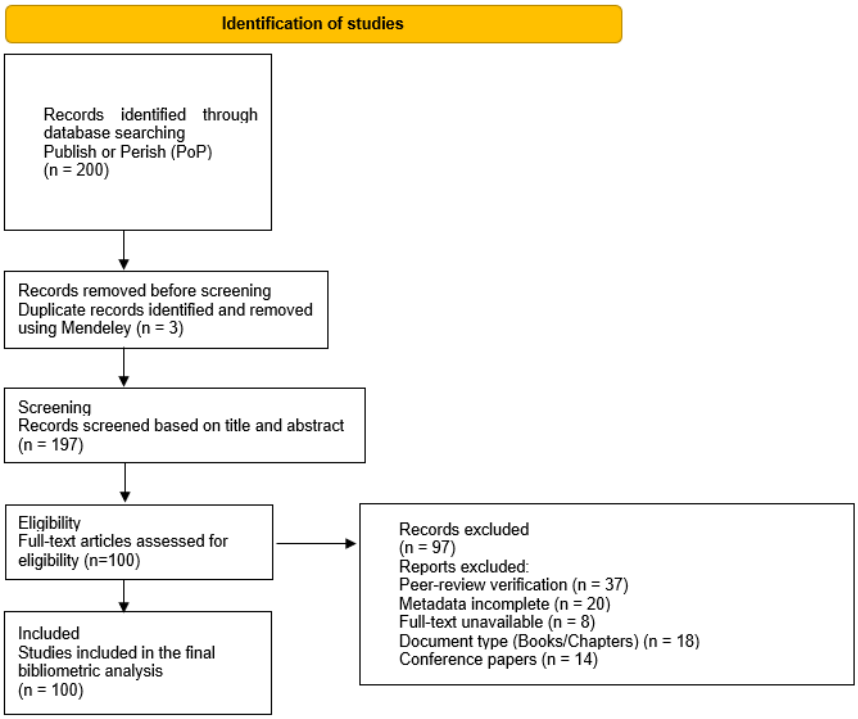


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020

Search Strategy and Metadata Extraction

Transparency in search strategies is essential for the replicability of bibliometric studies (Gusenbauer & Haddaway, 2020). Table 2 details the search configuration used in the Publish or Perish software (Harzing, 2007), a widely adopted tool for bibliometric data retrieval (Mingers & Meyer, 2017; Nawi et al., 2024). The search was conducted using the query string "mathematics education" AND "sustainable development" AND "gender" in the Google Scholar database to ensure broad and global literature coverage (Martín-Martín et al., 2021). While Google Scholar offers superior coverage in the social sciences compared to Scopus and Web of Science, it requires careful data validation due to metadata reliability issues ((Mingers & Meyer, 2017)). Metadata extraction was performed on December 16, 2025, with a publication range from 2015 to 2025. The maximum number of results was limited to 200 documents as initial results before undergoing screening and cleaning following PRISMA guidelines (Page et al., 2021). The search results were then exported in RIS format for further processing.

Table 2. Search Strategy Configuration

Parameters	Settings / Details
Database	Google Scholar
Software	Harzing's Publish or Perish (Version 8)
Keywords (Query)	"mathematics education" AND "sustainable development" AND "gender"
Year Range	2015 – 2025
Maximum Initial Results	200 documents
Metadata Extraction Date	December 16, 2025
Export Format	RIS (Research Information Systems)
Initial Cleaning	Manual verification of titles and abstracts, removal of duplicate results and entries without physical documents

Keyword Standardization and Data Preprocessing

To address variations in keyword spelling that can cause pseudo-cluster fragmentation in VOSviewer analysis, for example, an artificial separation between “SDG” and “Sustainable Development Goals” is applied to the standard thesaurus file (thesaurus.txt) as part of data pre-processing (Eck & Waltman, 2023). This step is crucial to ensure accuracy in calculating term frequencies and link strength between concepts. The unification process is performed on key terms, synonyms, and spelling variants commonly found in the corpus. Table 3 presents examples of label mapping performed to standardize terms prior to co-occurrence analysis (Nowakowska, 2025).

Table 3. Example of Thesaurus Label Mapping (Keyword Unification)

Standardized Label	Unified Term Variants (Input)
Sustainable development	Sustainable development, Sustainable Development, sustainable development
Gender equality	Gender equality, Gender Equity, gender differences, gender difference across school systems, sdg 5
Mathematics education	Mathematics education, Mathematics Education
Sustainable development goals	sdg, sdgs, sustainable development goals (sdgs)
Education for sustainable development	esd, education for sustainable development (esd), education for sustainable development (esd truncated)
STEM education	STEM education, stem
Quality education	sdg 4 (quality education), sdg4
Primary education	primary school, primary schools, primary education
Teacher education	teacher training, teacher professional development
Bibliometric analysis	bibliometric, bibliometrics, systematic literature review
Critical mathematics education	critical mathematics education within the sociopol
Ethnomathematics	ethonomathematics

Bibliometric Network Analysis and Visualization

Network analysis was performed using VOSviewer version 1.6.20 on two main domains: (a) co-authorship to map research collaboration, and (b) keyword co-occurrence to identify thematic clusters, following the guidelines outlined in the software manual (Eck & Waltman, 2023). Co-authorship analysis, grounded in the theoretical framework of social network analysis (Wasserman & Faust, 1994), enables the identification of collaboration patterns, central actors, and network structures within a research community. The analysis parameters applied in VOSviewer were as follows: counting method = Full Counting; author threshold = minimum of 2 documents; keyword threshold = minimum of 4 occurrences. The analysis focused on the largest connected component of each network. The results were visualized in three forms: Network Map, Overlay Map to identify temporal trends, and Density Map to illustrate the concentration of research topics. To improve visual readability, labels are displayed only for the top 20 items based on total link strength (for keywords) or number of documents (for authors) in all VOSviewer visualizations. As a result, peripheral items with lower link strength—potentially representing emerging or niche topics—are not visible in the figures, though they remain part of the quantitative analysis (e.g., occurrence counts, link strength calculations). This display optimization prioritizes core thematic structures while potentially underrepresenting the full diversity of the research landscape. Cluster coloring is performed automatically using the VOSviewer's built-in VOS clustering algorithm, while node size represents the corresponding quantitative metric (number of documents for authors and number of occurrences for keywords) (Eck & Waltman, 2023).

RESULTS AND DISCUSSION

Dataset Overview and Growth Trend

An initial search via Google Scholar using Publish or Perish yielded 200 article metadata. After undergoing a deduplication process and rigorous screening based on inclusion/exclusion criteria, 100 final articles that met the requirements were analyzed (n = 100). From this final dataset, the total cumulative citations recorded were 2,766 citations for the 2015–2025 publication period, resulting in an average of 27.66 citations per article. The corpus exhibited an h-index of 26 and a g-index of 45 (Hirsch, 2005), indicating substantial scholarly impact within the field (Egghe, 2006). Annual citation rates averaged 276.6 citations per year. The distribution of publication years (presented in Table 4) shows a trend of growth in research from year to year.

Table 4. Publication time distribution

Year	Number of Publications	Notes
2015	1	Early stage of research intersection; foundational studies.
2016	2	Slow growth; initial exploratory works.
2017	3	Gradual increase; thematic consolidation begins.
2018	8	Noticeable rise; alignment with SDG agenda gains traction.
2019	5	Slight dip; reflective of global academic shifts.
2020	12	Significant growth; post-pandemic emphasis on sustainability and equity.
2021	14	Steady increase; technology and gender integration in focus.
2022	12	Consolidation phase; methodological diversification.
2023	15	Continued growth; emergence of systematic and bibliometric reviews.
2024	42	Peak publication year; reflects heightened academic and policy priority.
2025	26	Partial data (to Dec 2025); indicates sustained high interest.

Citation Landscape and Influential Works

The citation analysis reveals the most impactful works in the field. Table 5 presents the top-15 most cited articles, which collectively received 1,558 citations (56.3% of total citations). The journal Sustainability dominates this list with 7 out of 15 articles, indicating its central role in publishing research at the intersection of mathematics education and sustainable development. This prominence aligns with the journal's extensive publication record on sustainability-related topics, including gender equality in STEM education (Jeong & González-Gómez, 2024; Sharif et al., 2024)

Table 5. Top-15 most cited articles on mathematics education, gender, and sustainable development (2015-2025)

Rank	Authors	Title	Year	Source	Cites	DOI	Indexing
1	Szabo et al.	Examples of problem-solving strategies in mathematics education supporting the sustainability of 21st-century skills	2020	Sustainability	445	10.3390/su122310113	Scopus Q1
2	Lopez-Inesta et al.	Towards breaking the gender gap in Science, Technology, Engineering and Mathematics	2020	IEEE Transactions on Education	196	10.1109/TE.2020.2987744	Scopus Q1
3	Roos, H.	Inclusion in mathematics education: An ideology, a way of teaching, or both?	2018	Educational Studies in Mathematics	176	10.1007/s10649-018-9854-z	Scopus Q1
4	Schukajlow et al.	Emotions and motivation in mathematics education: Where we are today and where we need to go	2024	ZDM–Mathematics Education	137	10.1007/s11858-022-01463-2	Scopus Q1
5	Mukuka et al.	Students' experiences with remote learning during the COVID-19 school closure: implications for mathematics education	2021	Heliyon	135	10.1016/j.heliyon.2021.e07523	Scopus Q1
6	Rico et al.	Integrating mathematics and science teaching in the context of education for sustainable development: Design and pilot implementation of a teaching-learning sequence	2021	Sustainability	69	10.3390/su13084500	Scopus Q1
7	Hwang et al.	Exploring research trends of technology use in mathematics	2023	Education and Information Technologies	60	10.1007/s10639-	Scopus Q1

Rank	Authors	Title	Year	Source	Cites	DOI	Indexing
		education: A scoping review using topic modeling				023-11603-0	
8	Lafuente-Lechuga et al.	Mathematics applied to the economy and sustainable development goals: A necessary relationship of dependence	2020	Education Sciences	57	10.3390/educsci10110339	Scopus Q2
9	Li, H. C., & Tsai, T. L.	Education for sustainable development in mathematics education: What could it look like?	2022	International Journal of Mathematical Education in Science and Technology	52	10.1080/002073 9X.2021.1941361	Scopus Q2
10	Sakaria et al.	Examining the optimal choice of SEM statistical software packages for sustainable mathematics education: A systematic review	2023	Sustainability	51	10.3390/su15043209	Scopus Q1
11	Geiger et al.	The connections between citizenship education and mathematics education	2023	ZDM–Mathematics Education	50	10.1007/s11858-023-01521-3	Scopus Q1
12	Kabuye Batiibwe, M. S.	The role of ethnomathematics in mathematics education: A literature review	2024	Journal of Mathematics Education	50	10.1177/2752726324130400	Scopus Q3
13	Pilotti, M. A. E.	What lies beneath sustainable education? Predicting and tackling gender differences in STEM academic success	2021	Sustainability	47	10.3390/su13041671	Scopus Q1
14	Johnson et al.	Using Bayesian networks to provide educational implications: Mobile learning and ethnomathematics to improve sustainability in mathematics education	2022	Sustainability	45	10.3390/su14105897	Scopus Q1
15	Vásquez et al.	Integrating sustainability in mathematics education and	2023	Eurasia Journal of Mathematics, Science and	43	10.29333/ejmste/13809	Scopus Q2

Rank	Authors	Title	Year	Source	Cites	DOI	Indexing
		statistics education: A systematic review		Technology Education			

The dominance of Sustainability journal (7 out of 15 articles) confirms its role as a primary outlet for research at the intersection of mathematics education and sustainable development. Notably, seven of the top-15 articles were published between 2023 and 2025, indicating rapid growth of interest in this field. The presence of multiple articles (Alsina & Vásquez, 2025; Vásquez et al., 2023) aligns with the co-authorship network findings that position Alsina as a central figure in this research community. Furthermore, articles addressing gender issues are well-represented (Kelly et al., 2018; Pilotti, 2021), confirming that gender equality (SDG 5) is a central theme alongside sustainability.

To map the research collaboration landscape, a co-authorship analysis was performed using VOSviewer (Eck & Waltman, 2023). Author metadata extracted from the RIS files of the final dataset (n=100) revealed a total of 229 distinct researchers. The co-authorship network analysis (unit of analysis = authors) showed that the majority of these researchers do not form a single, interconnected network.

To identify meaningful collaboration patterns, a minimum threshold of two documents per author was applied. This reduced the set to nine authors who met the productivity criterion. Of these nine, five authors—Vásquez, C., Seckel, M. J., Alsina, Á., Méndez-Alonso, D., and Prieto-Saborit, J. A. —formed the largest set of connected items (i.e., the main component of the collaboration network). The remaining four authors (Ismailova, Z.; Li, H. C.; Roux, K. le; and Xiong, B.), while meeting the productivity threshold, existed as isolated nodes with no co-authorship links to others in this thresholded network and were therefore excluded from the network visualization. The resulting network (Figure 2) confirms the central role of Alsina & Vásquez (2025) and Vásquez et al. (2023), who was identified as a hub in the broader intellectual structure of the field based on citation and co-authorship patterns (Newman, 2004).

Co-authorship Collaboration

The collaboration network visualization (Figure 2) reveals that Alsina, Á. is one of the most central figures, with four documents and a total link strength of five. Vásquez, C. also demonstrates strong centrality with three documents and a total link strength of five, while Seckel, M. J. has two documents and a total link strength of four. Two additional researchers, Méndez-Alonso, D. and Prieto-Saborit, J. A., are also part of this connected component, each with two documents and a total link strength of two, indicating secondary but meaningful connections to the core group.

The purple cluster in Figure 2 represents this core network of five interconnected researchers. Within this structure, Alsina, Á. and Vásquez, C. function as primary hubs, with Vásquez, C. showing the most extensive connections (linking to Alsina, Seckel, Méndez-Alonso, and Prieto-Saborit). Seckel, M. J. also serves as an important bridge, connecting to Alsina, Vásquez, Méndez-Alonso, and Prieto-Saborit. This pattern reveals a collaborative core where Vásquez and Seckel act as brokers connecting Alsina with the Méndez-Alonso-Prieto-Saborit dyad.

The total link strength within this component is 18 (Alsina=5, Vásquez=5, Seckel=4, Méndez-Alonso=2, Prieto-Saborit=2). Alsina, Á. contributes 28% (5/18) of the total connections, while Vásquez, C. also contributes 28% (5/18), indicating shared centrality rather than a single dominant hub. The remaining four authors (Ismailova, Z.; Li, H. C.; Roux, K. le; and Xiong, B.), despite meeting the productivity threshold, remain unconnected to this main cluster with a link strength of zero. These findings underscore the fragmented nature of global research collaboration at the intersection of mathematics education, gender, and sustainable development. Intensive and productive collaboration appears concentrated within a small core group of five researchers, while broader connectivity across the field remains limited.

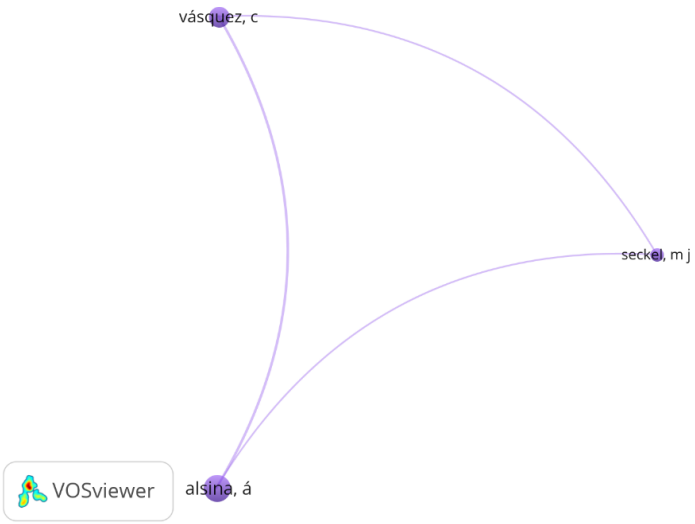


Figure 2. Visualization of the Author Collaboration Network

The Overlay Visualization (Figure 3) reveals the temporal trends in author collaborations. Using a color gradient where bright yellow denotes publications from 2024, it is evident that the collaborative relationships among the five connected authors (Alsina, Vásquez, Seckel, Méndez-Alonso, and Prieto-Saborit) all appear in bright yellow. This indicates that their research collaboration is recent and active, concentrated in the 2023--2024 period. In contrast, the isolated nodes (Ismailova, Z.; Li, H. C.; Roux, K. le; and Xiong, B.) appear in darker colors (blue to green), suggesting that their contributions, while meeting the productivity threshold, are either older or not part of the recent collaborative wave centered around the Alsina-Vásquez-Seckel network.

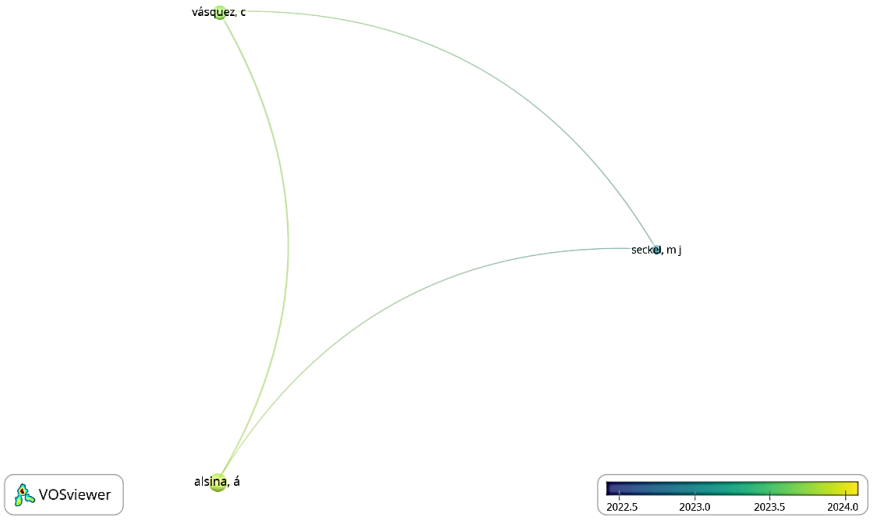


Figure 3. Visualization of Author Collaboration Overlay

The Density Visualization (Figure 4) highlights the concentration of scholarly output, showing Alsina, Á. and Vásquez, C. as bright yellow hotspots, while Seckel, M. J., Méndez-Alonso, D., and Prieto-Saborit, J. A. appear in green areas with moderate density. This visualization confirms that Alsina and Vásquez are the most productive central figures driving the latest collaboration network in this field. The absence of any other significant yellow hotspots in the density map reinforces the finding that research collaboration in this interdisciplinary space is highly centralized around a small core group of five researchers, rather than distributed across multiple research groups or geographic regions.

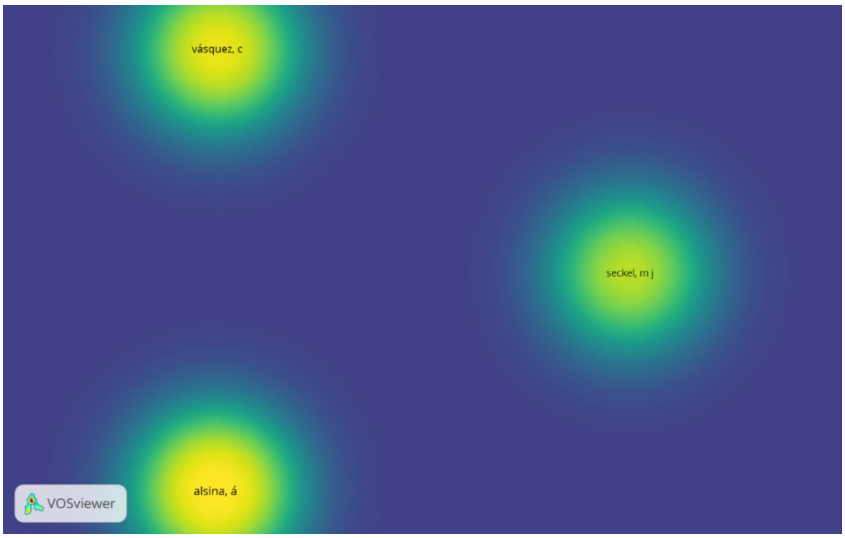


Figure 4. Visualization of Author Collaboration Density

Keyword co-occurrence & Clusters

In this section, 22 keywords that met the selection criteria (minimum occurrence threshold of four times) were analyzed using three VOSviewer visualizations. These 22 terms, drawn from a total of 345 items, were classified into three main thematic clusters.

Cluster 1 (Green, 10 items) focuses on digital innovation and pedagogy, covering topics such as artificial intelligence (AI), ICT, teacher training, SDG 4, and ethnomathematics. Cluster 2 (Red, 8 items) emphasizes the development of sustainability competencies through critical thinking, 21st-century skills, and education for sustainable development (ESD). Cluster 3 (Purple, 4 items) addresses fundamental issues related to gender equality and STEM within the framework of sustainable development.

The density visualization reveals a high concentration on the core terms "mathematics education" (31 occurrences, total link strength 59) and "sustainability" (13 occurrences, total link strength 41). This confirms the saturation of research on these two topics and their centrality in the intellectual structure of the field.

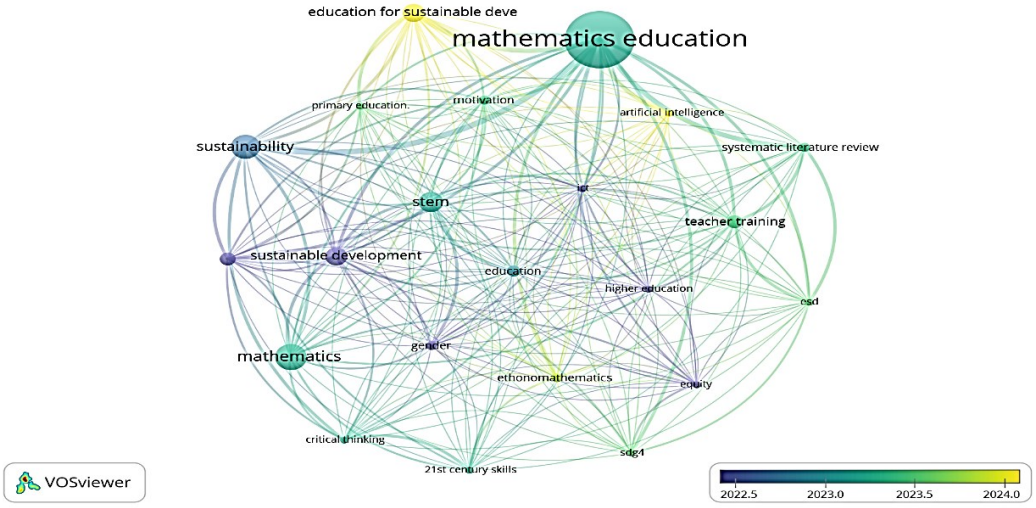


Figure 5. Keyword Overlay Visualization

Furthermore, the Overlay visualization (Figure 5) reveals a distinct temporal shift in research focus within mathematics education. Early topics, depicted in dark blue and purple (corresponding to the 2022 period), are dominated by foundational concepts and structural social issues such as sustainable development and gender. In contrast, the most recent items, shown in bright yellow (2024 period), demonstrate an intense focus on the integration of

technology and global competencies, including artificial intelligence (AI), ICT, critical thinking, and 21st-century skills. This shift indicates that research priorities have moved toward positioning mathematics education as a driver of practical solutions to future challenges, aligning closely with the targets of SDG 4 (Quality Education) and SDG 5 (Gender Equality). However, these findings also confirm the persistence of research fragmentation: despite the simultaneous presence of both themes in the literature, the connectivity between gender issues and digital technology integration (AI/ICT) remains weak in the current intellectual landscape, as they appear in distinct temporal and thematic clusters.

The Density Visualization (Figure 6) from the keyword co-occurrence analysis presents a highly informative thematic map of the research structure and focus in this field. The map clearly shows that the core of all reviewed literature is dominated by the topics of mathematics education (31 occurrences, total link strength 59) and mathematics (14 occurrences, total link strength 34), where the bright yellow areas indicate the most concentrated discussions and strongest connectivity. These findings confirm that academic discourse remains firmly rooted in the disciplinary, pedagogical, and curricular aspects of mathematics teaching.

However, the most significant development is the expansion of focus toward global issues. The emergence of high-density clusters around the keywords sustainability (13 occurrences, total link strength 41) and sustainable development (10 occurrences, total link strength 34) demonstrates that the research community is now actively integrating the role of mathematics in addressing social and environmental challenges. This shift is not merely theoretical but is also evident in the emphasis on developing relevant competencies, such as critical thinking (4 occurrences, total link strength 29) and 21st-century skills (4 occurrences, total link strength 26). Thus, the goal of mathematics education today extends beyond content mastery to equipping students with analytical skills to contribute to solving global problems.

Alongside these emerging trends, the research maintains consistent attention to structural and policy issues. Gender equality (5 occurrences, total link strength 26) remains an important theme, alongside STEM (11 occurrences, total link strength 33), reflecting ongoing efforts to address access and participation gaps. In terms of policy alignment, the inclusion of the keyword SDG 4 (4 occurrences, total link strength 26) underscores researchers' efforts to connect their findings with the Sustainable Development Goals framework. Meanwhile, newly emerging topics such as artificial intelligence (4 occurrences, total link strength 24) and ICT (4 occurrences, total link strength 23) remain on the periphery with lower density. This indicates that while the potential of these technologies is increasingly recognized, their full integration into mathematics pedagogy is still in its early stages and represents a significant opportunity for future research.

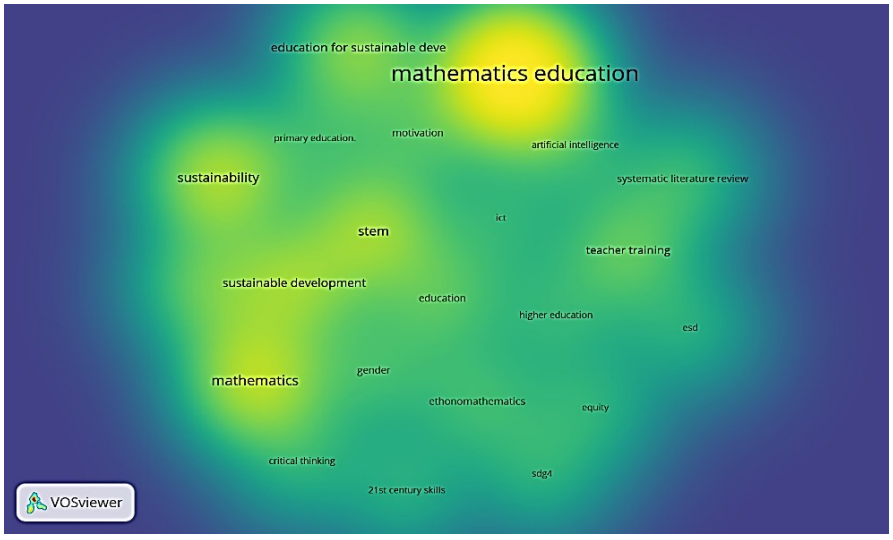


Figure 6. Keyword Density Visualization

The bibliometric mapping of 100 selected articles reveals that research integrating mathematics education, gender equality, and sustainable development (SDGs) is undergoing dynamic evolution but remains fragmented. The pattern of keyword connectivity across three main clusters indicates that the global literature is in a transitional stage, moving from foundational issues such as gender equality and STEM (Cluster 3) toward digital innovation approaches, including Artificial Intelligence (AI) and ICT (Cluster 1). This fragmentation is evident in the weak relational ties between the gender cluster and the digital technology cluster, confirming Skovsmose (2023) argument that contemporary mathematics education has not yet fully bridged the instrumental-technological orientation with the social transformation agenda in an integrative manner. Thus, these bibliometric findings reveal a significant epistemic gap, particularly in the lack of integration between advanced digital technology, ethnomathematics, and the sustainability agenda within a single, comprehensive pedagogical framework.

Table 6 summarizes the thematic clusters identified through keyword co-occurrence analysis,presenting the main keywords in each cluster along with their occurrence and total link strength. This table provides a quantitative overview before a more detailed cluster-by-cluster discussion.

Table 6. Thematic Clusters Identified from Keyword Co-occurence

Cluster	Theme	Top Keywords (Occurrence; TLS)	Representative Papers	Main Interpretation
Cluster 1 (Green)	Digital Innovation and Pedagogical Practices	mathematics education (31; 59), teacher training (6; 28), SDG 4 (4; 26), AI (4; 24), ICT (4; 23), ethnomathematics (5; 21)	Hwang et al., (2023); Son, (2024)	This cluster reflects studies emphasizing the use of digital technologies and innovative pedagogical approaches in mathematics education. Although AI and ICT appear as emerging topics, their relatively low link strength with sustainability- and equity-related keywords indicates that digital innovation is still predominantly framed in an instrumental and technical manner.
Cluster 2 (Red)	Sustainability Competencies and Cognitive Skills	sustainability (13; 41), ESD (10; 32), critical thinking (4; 29), 21st-century skills (4; 26), primary education (5; 24), motivation (4; 22)	Lina & Johar, (2025); Vásquez et al., (2023)	This cluster highlights the role of mathematics education in fostering sustainability-oriented competencies. Strong interconnections between ESD, sustainability, and higher-order cognitive skills suggest a growing emphasis on holistic learning outcomes aligned with Sustainable Development Goal 4 (Quality Education).
Cluster 3 (Purple)	Gender Equality and STEM Foundations	sustainable development (10; 34), STEM (11; 33), gender (5; 26), gender equality (4; 19)	Cheryan et al., (2017); Hyde, (2014)	This cluster focuses on equity-related issues, particularly gender equality within STEM-oriented mathematics education. Despite its relevance to SDG 5, the cluster shows

Cluster	Theme	Top Keywords (Occurrence; TLS)	Representative Papers	Main Interpretation
				limited connectivity with digital innovation keywords, indicating a persistent thematic separation between gender-focused research and technology-enhanced learning.

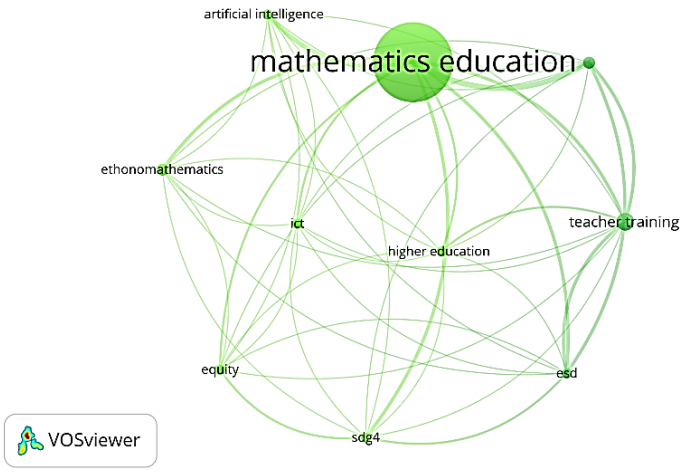


Figure 7. Visualization of Cluster 1 Keywords

The first cluster (Cluster 1 - Green, Figure 7) comprises 10 items, with the keywords mathematics education, artificial intelligence (AI), ICT, teacher training, and SDG 4 dominating the research network. Although mathematics education serves as the central node with 31 occurrences and a total link strength of 59, the research focus in this cluster remains predominantly technical-instrumental in nature. Studies in this cluster largely discuss the use of digital technology in isolation, without deeply integrating it with local cultural issues such as ethnomathematics or with broader sustainable development goals. This lack of integration between advances in digital technology, pedagogy, and the sustainability agenda reveals a conceptual fragmentation that presents a clear gap for future research. This finding aligns with Son (2024), who confirms that mathematics education research has not yet fully integrated the potential of digital technology into learning for sustainability in an integrative and holistic manner.

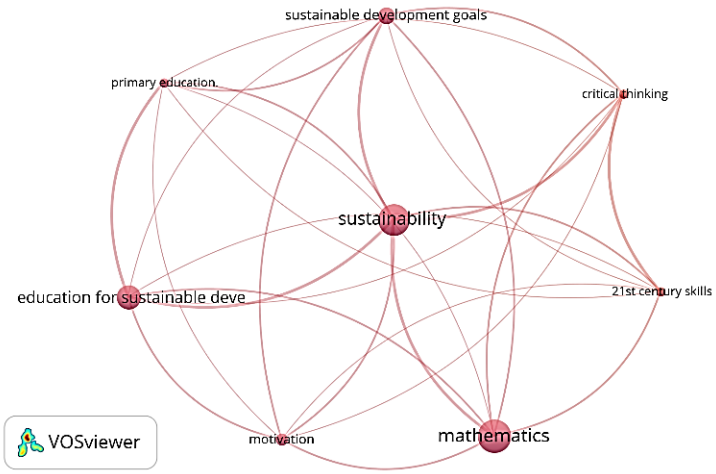


Figure 8. Visualization of Keywords in Cluster 2

The second cluster (Cluster 2 - Red, Figure 8) comprises eight items representing the theme "Integration of Cognitive Competencies and Education for Sustainability." The central focus of this cluster is the close relationship between sustainability (13 occurrences, total link strength 41) and education for sustainable development (10 occurrences, total link strength 32) with higher-order thinking skills such as critical thinking (4 occurrences, total link strength 29) and 21st-century skills (4 occurrences, total link strength 26). The co-occurrence of these keywords within a single cluster demonstrates that current research no longer views mathematics as an isolated discipline, but rather as a strategic vehicle for equipping students with the analytical skills needed to address global challenges. Additionally, the presence of the terms motivation and primary education indicates a research focus on strengthening students' intrinsic motivation from the primary level as a foundation for sustainability awareness. These findings reinforce the position of mathematics education as a key instrument in achieving SDG 4 (Quality Education), where mastery of mathematical content is holistically integrated with social and environmental responsibility.

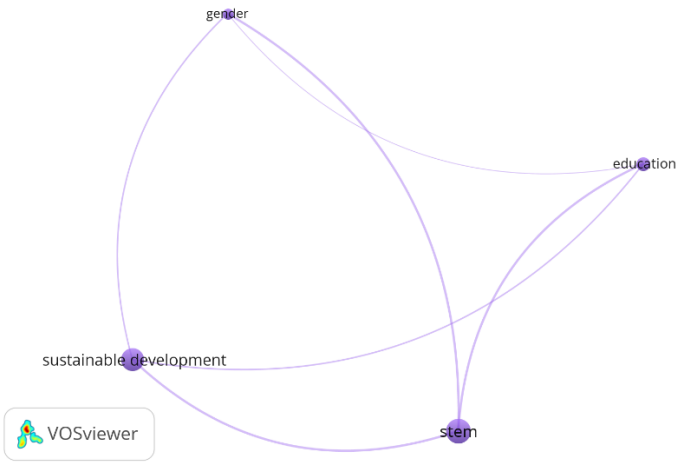


Figure 9. Visualization of Keywords in Cluster 3

The third cluster (Cluster 3 - Purple, Figure 9) consists of four items that specifically address the theme of "Gender Equality and Sustainable Development." The main focus of this cluster is the relationship between the keyword gender (five occurrences, total link strength 26) and STEM (11 occurrences, total link strength 33) within the framework of sustainable development.

Analysis of this cluster reveals that research discussions remain predominantly focused on comparisons of learning performance between male and female students an approach that tends to be superficial. As confirmed by the global literature, gender gaps in STEM fields are more deeply influenced by structural factors such as social norms, perceptions of ability, access to technology, and cultural expectations rather than by cognitive ability alone (Hyde, 2014). (Cheryan et al., 2017) further elaborate that gender disparities in STEM are perpetuated by masculine cultures, lack of role models, and ambient belonging—factors that mathematics education research must address beyond simple performance comparisons. Although this cluster holds a fundamental position within the SDG 5 (Gender Equality) agenda, its connectivity with digital technology issues such as artificial intelligence (Cluster 1) remains relatively weak. This finding confirms the persistent fragmentation in research efforts to integrate gender equality issues with current technological innovations in mathematics education.

CONCLUSION

This bibliometric study provides an overview of research developments at the intersection of mathematics education, gender, and sustainable development during the 2015–2025 period. Based on the reported analysis of 100 selected journal articles, the findings

indicate increasing scholarly attention to this interdisciplinary field, particularly in recent years. The citation analysis reflects the visibility of publications addressing sustainability, mathematics education, and equity-related issues. However, the inconsistencies identified in the annual publication distribution require further verification before definitive conclusions regarding publication growth and peak productivity can be established.

The co-authorship analysis reveals that research collaboration remains concentrated within a relatively small network of interconnected scholars. Alsina and Vásquez emerge as prominent contributors, demonstrating comparable levels of total link strength within the largest connected component. This pattern suggests that although collaborative research has developed, broader connections among researchers remain limited within the analyzed dataset.

Keyword co-occurrence analysis identifies three major thematic clusters: (1) Digital Innovation and Pedagogy, emphasizing artificial intelligence, information and communication technology, and teacher development; (2) Sustainability Competencies, focusing on education for sustainable development, critical thinking, and 21st-century skills; and (3) Gender Equality and STEM Foundations, highlighting gender-related issues within mathematics and STEM education. The overlay visualization indicates growing attention to technology-enhanced learning and sustainability-related competencies. Nevertheless, relatively limited connectivity between digital innovation and gender-related keywords suggests that these research directions are not yet strongly integrated within the observed bibliometric network.

Overall, this study contributes to understanding the intellectual structure and thematic development of mathematics education research related to gender and sustainable development. Its principal contribution lies in identifying areas of thematic concentration, collaboration patterns, and potential opportunities for interdisciplinary investigation. As a descriptive bibliometric study, its findings should be interpreted as evidence of research patterns within the selected publications rather than as direct evidence of pedagogical effectiveness or causal relationships.

RECOMMENDATION

Based on the findings of this bibliometric study, several recommendations are proposed to strengthen future research on mathematics education, gender equality, and sustainable development.

First, future research should prioritize the development and empirical examination of integrative pedagogical frameworks that combine artificial intelligence, digital learning technologies, ethnomathematics, and education for sustainable development. Particular attention should be given to how these approaches can support contextualized mathematics learning while addressing sustainability competencies and equitable educational participation.

Second, researchers are encouraged to investigate gender-related issues beyond conventional comparisons of mathematical achievement between male and female students. Greater emphasis should be placed on structural and contextual factors, including access to digital technologies, sociocultural expectations, learning opportunities, and gender-responsive instructional practices. Such investigations may provide a more comprehensive understanding of educational equity within mathematics and STEM learning environments.

Third, stronger interdisciplinary and international research collaboration should be encouraged to expand scholarly connections beyond the relatively small groups identified in the co-authorship network. Collaborative research involving mathematics educators, sustainability researchers, educational technologists, and gender studies scholars could support the development of more comprehensive theoretical and methodological approaches.

Fourth, future studies should examine how sustainability competencies, including critical thinking, systems thinking, and responsible decision-making, can be meaningfully integrated into mathematics curricula and evaluated through appropriate learning assessments. Longitudinal and intervention-based research may be particularly valuable for examining

students' learning experiences and outcomes in relation to SDG 4 (Quality Education) and SDG 5 (Gender Equality).

Finally, subsequent bibliometric studies should consider integrating multiple academic databases, such as Scopus and Web of Science, alongside Google Scholar to improve bibliographic coverage and data reliability. Researchers should also strengthen metadata validation, keyword standardization, and transparent reporting of network analysis parameters. These methodological improvements would enhance reproducibility and support a more comprehensive understanding of emerging research directions in mathematics education, gender, and sustainable development.

ACKNOWLEDGMENTS

The author would like to express his highest appreciation to Universitas Muhammadiyah Prof. Dr. Hamka (UHAMKA), especially the Mathematics Education Study Program, for its institutional support and provision of facilities that enabled this research to be carried out successfully. The author would also like to thank colleagues and all parties who provided technical assistance, advice, and contributions in the process of data extraction using Publish or Perish to the stage of visualization analysis with VOSviewer. This collaborative support has been key to the success of mapping trends and intellectual networks on gender issues, sustainable development, and mathematics education presented in this article. The author hopes that the results of this study can make a real contribution to the development of a more inclusive and future-oriented mathematics education literature..

FUNDING INFORMATION

This research received no external funding.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Nabila Yasmin Muntaz			✓		✓		✓			✓				
Avhiesta Mahadryanie			✓		✓					✓				
Fitriana Rahmadhar			✓		✓					✓		✓		
Riki Amperadi			✓		✓		✓	✓	✓	✓				
Nur Moetya Harun			✓											
Auliya Zahra			✓											

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

ETHICAL APPROVAL

This study employed a bibliometric research design using publicly available bibliographic metadata retrieved from Google Scholar through Publish or Perish. As the research did not involve direct participation of human subjects, collection of personal or sensitive information, or experimental interventions, formal ethical approval was not required.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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