Augmented Reality in Mathematics Education: A Bibliometric Analysis of Research Trends, Pedagogical Transformations, and Future Directions

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ABSTRACT

This study provides a comprehensive bibliometric analysis of research on Augmented Reality (AR) in mathematics education, aiming to map publication trends, research hotspots, collaboration patterns, and emerging themes from 2002 to 2026. Using the Scopus database as the primary source, the study followed PRISMA guidelines for data selection and obtained a final dataset of 209 documents authored by 641 researchers from 136 indexed sources. Descriptive analysis reveals a significant annual growth in publications, with a sharp increase beginning in 2019, indicating AR's rising prominence as a transformative tool in mathematics learning. VOSviewer and RStudio were used to analyze keyword co-occurrence, thematic clusters, and evolution of research topics. The results identify three major clusters: (1) AR and virtual environments for enhancing spatial ability and geometry understanding, (2) AR integration in STEM and mathematics learning including motivation, ethnomathematics, and special needs contexts, and (3) emerging intersections with game-based learning, artificial intelligence, and mobile technologies. Overlay visualization highlights emerging topics such as embodied learning, spatial skills development, ethnomathematics, and dyscalculia support, reflecting a shift toward more human-centered and inclusive pedagogical applications of AR. The study concludes that AR serves not only as a visualization tool but also as a pedagogical ecosystem capable of fostering conceptual understanding, engagement, and personalized learning experiences. These findings offer valuable insights for educators, researchers, and policymakers in shaping future research directions and integrating AR effectively into mathematics education in alignment with 21st-century learning demands.

KEYWORDS: Augmented Reality; Mathematics Education; Bibliometric Analysis; Spatial Skills; Embodied Learning.

1. INTRODUCTION

The development of digital technology has brought significant changes to various aspects of life, including education (Aleksieva, 2025). This digital transformation requires educational institutions to ensure that learning processes align with the needs of the 21st century, where critical thinking, problem-solving, and technological literacy are key competencies for learners (Nazyrova et al., 2025). In this context, the use of immersive technologies such as Augmented Reality (AR) has gained widespread attention due to its ability to integrate virtual objects into real environments in real time, thereby creating more interactive and meaningful learning experiences (Xiao et al., 2020).

Mathematics education is one of the fields that greatly benefits from the presence of AR. Mathematics, as an abstract discipline filled with symbols, often creates difficulties for students in understanding concepts, particularly those related to space, shapes, structures, and relationships between objects (Walkington et al., 2025). AR acts as a pedagogical mediator that bridges the gap between abstract representations and concrete visualization by presenting 2D and 3D objects that can be directly manipulated (Bertrand et al., 2024). This not only supports conceptual understanding but also enhances students' visual–spatial abilities (Elsayed & Al-

Najrani, 2021; Ozcakir et al., 2021; Zapata et al., 2024). Beyond its impact on learning processes, the integration of AR aligns with global agendas on digital literacy and future-ready education (Iqbal et al., 2022; Montero Izquierdo et al., 2025; Walkington et al., 2024; Zekeik et al., 2025). The use of AR introduces students to cutting-edge technologies that will become widely utilized in future industries such as creative media, engineering, healthcare, and science (Poçan et al., 2023; Walkington et al., 2024). Thus, AR functions not only as a learning tool but also as a medium to strengthen students' preparedness for rapid technological change.

Although research on AR in education continues to grow, there is considerable variation in terms of focus, methodological approaches, educational contexts, and the technologies used. These studies range from experiments on AR's effect on learning outcomes, development of AR applications for specific topics, to investigations of teacher and student perceptions (Bagossi et al., 2022; Cai et al., 2019; Cascales-Martínez et al., 2017; Pujiastuti et al., 2025). However, this rapid growth in publications has not been systematically mapped, making it difficult for researchers and practitioners to understand the current state of the field, research gaps, and future directions. At the same time, there is a need to identify patterns of scientific collaboration, keyword mapping, dominant research themes, and the evolution of topics over time. Such information is essential for understanding how the global academic community discusses the use of AR in mathematics learning, as well as how it contributes to curriculum innovation, pedagogical transformation, and teacher professional development across diverse educational contexts. Without comprehensive mapping, stakeholders may struggle to determine appropriate research strategies aligned with contemporary educational needs.

One appropriate method to address this need is bibliometric analysis (Boutracheh et al., 2023; Gureev & Mazov, 2015; Salemi & Koosha, 2013). Bibliometrics offers a quantitative approach for mapping the structure, evolution, and developmental directions of a scientific field through the analysis of academic publications (Bornmann & Marx, 2018; Hook, 2020; Liu et al., 2022). Using techniques such as co-citation analysis, co-authorship analysis, and keyword co-occurrence, researchers can identify patterns of relationships among scholars, research trends, and emerging themes (Leydesdorff et al., 2016; Thompson & Walker, 2015). This method enables a comprehensive synthesis of hundreds or even thousands of articles efficiently and objectively (Gheno, 2021). Several previous bibliometric studies have examined educational technology, but research that specifically maps the use of AR in mathematics education remains limited. Most studies focus on STEM education in general or on AR without specifying its application in mathematics (Adnan et al., 2024). Therefore, this study aims to fill this gap by providing a comprehensive mapping of AR research in mathematics education over the past several decades.

Based on this background, this study aims to analyze global publication trends on the use of AR in mathematics learning, identify collaboration patterns among authors and countries, map major research themes and emerging topics, and determine future research directions. The findings of this study are expected to contribute to the development of theory, practice, and educational policy, particularly in utilizing AR as part of innovative and future-oriented teaching and curriculum practices..

2. METHOD

This study applied a bibliometric analysis approach to systematically map the development of educational technology research in higher education. The study procedure followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines developed by (Moher et al., 2009), which provide a structured framework to ensure transparency and reproducibility in the article selection process. The data were retrieved from the Scopus database. The search strategy was developed using predefined keywords related to augmented reality in mathematics education. The detailed search string is presented in Figure 1. The complete selection process, from identification to inclusion stages, is also illustrated in Figure 1 following the PRISMA flow diagram. During the screening stage, the study excluded non-article document types, review papers, book chapters, and other non-research article documents. Additionally, the study limited the publication period (2002–2026) to capture the latest developments and trends in augmented reality within mathematics education. In the eligibility stage, only articles published in English were included. This criterion was applied because the visualization tools used in this study perform optimally on English-language metadata and keywords, thereby yielding more accurate mapping and clustering results. After applying all screening and eligibility criteria, the final dataset obtained at the inclusion stage was used for further bibliometric analysis

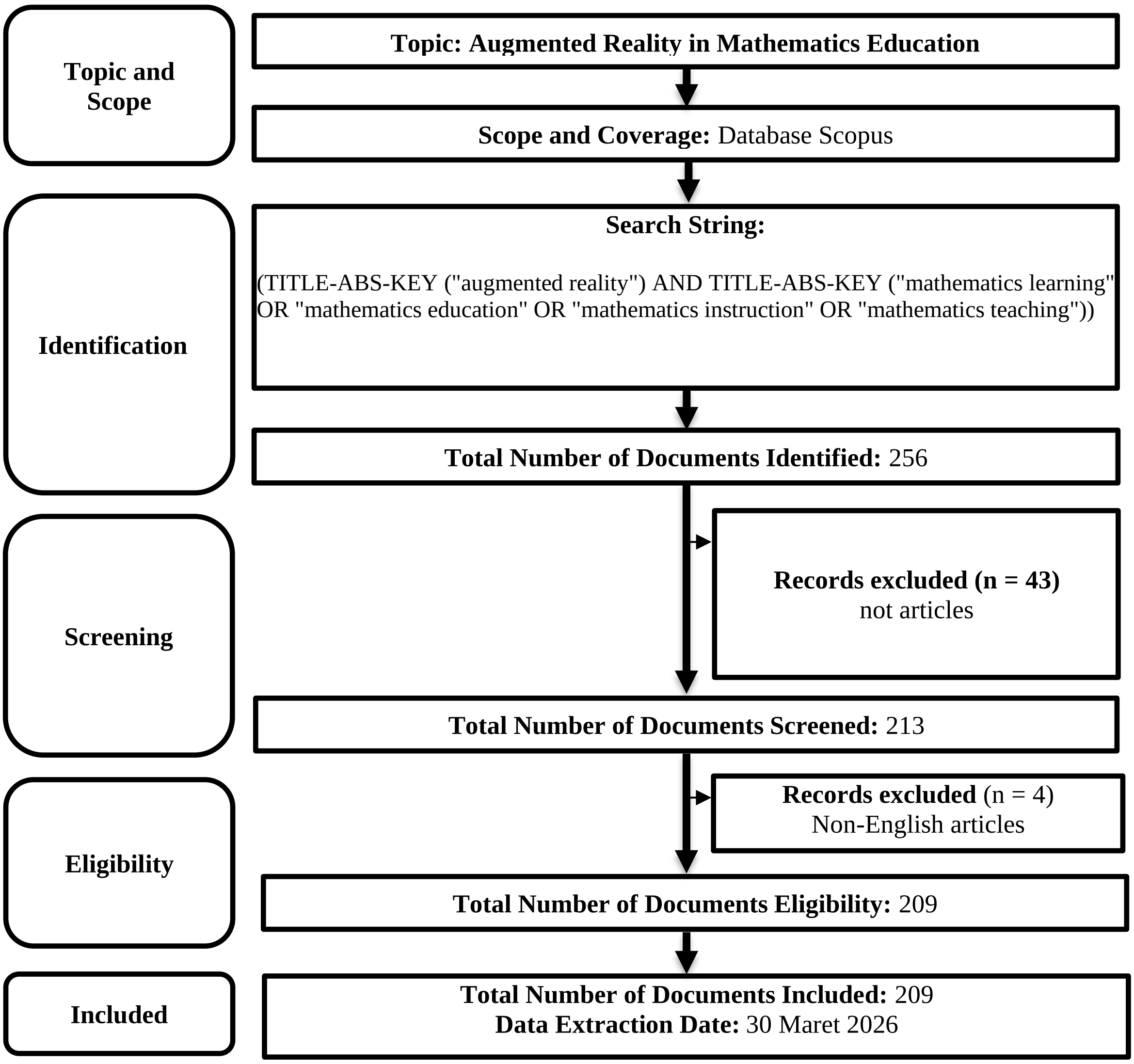


Figure 1. Data Collection Process

The final dataset consisted of 209 documents, retrieved from 136 indexed sources. A total of 641 authors contributed to these publications, indicating a highly collaborative research landscape, with an average of 3,62 co-authors per document. The dataset showed an annual growth rate of 3,59. In addition, the dataset contained 474 author keywords and 16625 cited references, reflecting a broad and diverse research knowledge base. The average document age was 4.18 years, indicating relatively recent scholarly contributions, while the average citation per document was 15.8, demonstrating moderate scholarly impact across the dataset. A visual summary of these main dataset characteristics is presented in Figure 2. These descriptive statistics provide an overview of the dataset characteristics and ensure transparency in the bibliometric analysis process.

Figure 2. Main Dataset Informations

The dataset size can be considered robust for bibliometric mapping. With more than 200 documents, over 10,000 references, and a large number of authors and keywords, the dataset provides strong statistical power for network visualization, trend detection, collaboration analysis, and knowledge structure mapping, while minimizing bias associated with smaller datasets. The 25-year time span offers an optimal balance between recency and analytical stability, ensuring sufficient data volume for robust bibliometric analysis while maintaining relevance to contemporary technological developments, thus enabling the findings to accurately represent current and future research directions.

The data analysis process was conducted using two main tools. First, keyword development and trend analysis were performed using RStudio to identify the evolution and frequency patterns of research topics over time. Second, network mapping and visualization analysis were conducted using VOSviewer to generate co-occurrence networks, research clusters, and thematic structures within the field of augmented reality in mathematics education.

3. RESULTS AND DISCUSSION

In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Results can be presented in figures, graphs, tables and others that make the reader understand easily. The discussion can be made in several sub-sections.

Publication Trends

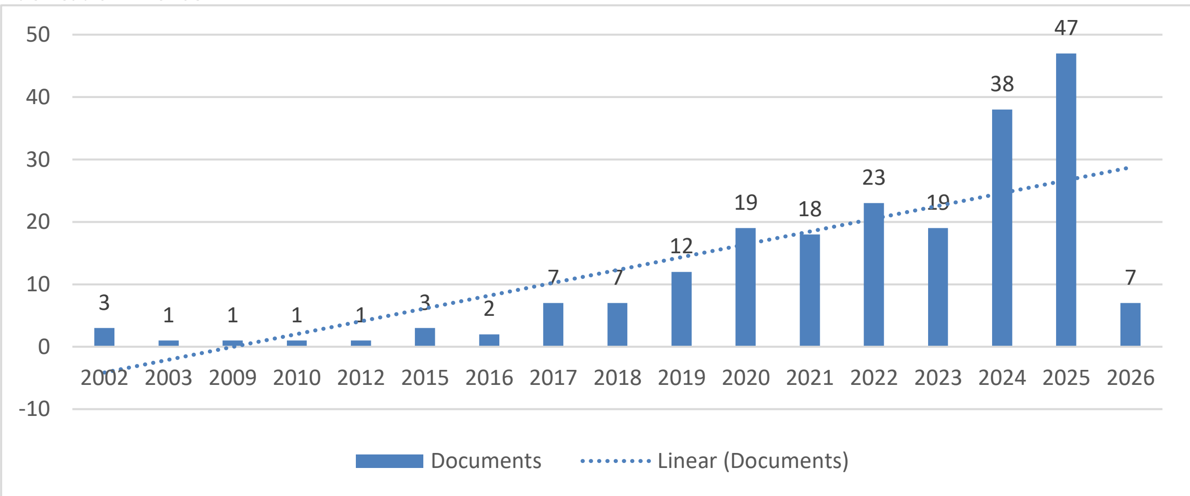


Figure 3. Publication Trends

Figure 3 illustrates the publication trends related to Augmented Reality (AR) in mathematics education from 2002 to 2026. Overall, the number of publications has increased significantly over the past two decades. In the early period (2002–2012), research was still very limited, with only one to three documents published per year, indicating that the use of AR in the context of mathematics education was still in an exploratory stage and had not yet become a mainstream research topic. A noticeable increase began after 2015, marked by the rise in publications reaching seven documents in both 2017 and 2018. This phase reflects the growing interest in AR as mobile devices, educational applications, and 3D technologies became increasingly accessible. Publication growth intensified sharply from 2019 onward, with a consistent upward trend through 2025. Between 2019 and 2021, the number of studies ranged from 12 to 19 documents per year, representing a period of accelerated and more intensive research activity. The most substantial increase occurred in 2024 and 2025, with 38 and 47 publications respectively, indicating that AR research in mathematics education has entered a maturity phase and has become a highly prominent topic within the global academic community. This surge can also be associated with the rising demand for technology-supported learning in the post-pandemic era, as educational institutions increasingly integrated interactive technologies to enhance the understanding of abstract mathematical concepts.

The linear trend line on the graph confirms a strong long-term upward trajectory, suggesting that this field holds promising prospects for continued growth. Although the data for 2026 still shows a preliminary figure (7 publications), this value likely does not represent the full-year total, as most scientific databases are updated toward the end of the year. Overall, this pattern indicates that research on AR in mathematics education continues to grow rapidly, driven by technological innovation, increased pedagogical interest in immersive learning, and the need for instructional strategies that support visualization and comprehension of complex mathematical concepts.

Table 1. Cite Trends

Author (year)	Research Focus	Source	Citations
(Kaufmann & Schmalstieg, 2003)	Mathematics and geometry education with collaborative augmented reality	Computers and Graphics Pergamon	393
(Demitriadou et al., 2020)	Comparative evaluation of virtual and augmented reality for teaching mathematics in primary education	Education and Information Technologies	163
(Cai et al., 2019)	Tablet-based AR technology: Impacts on students' conceptions and approaches to learning mathematics according to their self-efficacy	British Journal of Educational Technology	124
(Cai et al., 2020)	Probability learning in mathematics using augmented reality: impact on student's learning gains and attitudes	Interactive Learning Environments	114

The citation trend analysis shows that the article by Kaufmann & Schmalstieg (2003) is the most frequently cited publication in the field of augmented reality (AR) for mathematics education, with a total of 393 citations. The high citation count is due to its highly fundamental contribution through the development of Construct3D, an AR-based learning environment designed to support collaborative learning of three-dimensional geometry. This innovative approach allows students and teachers to interact intuitively with geometric objects in a virtual 3D space, thereby facilitating the development of spatial abilities and understanding of complex geometric concepts. In addition, its flexibility in device usage and its potential for integration across various learning contexts make this article a theoretical and methodological foundation for many subsequent AR studies, making it one of the most widely referenced works in the field.

Several other influential publications also demonstrate high citation levels and reflect the latest directions in AR research within mathematics education. The article by Demitriadou et al. (2020), with 163 citations, provides an important contribution through a comparative evaluation of virtual reality (VR) and AR in teaching mathematics at the primary school level. The study highlights the advantages of AR in enhancing student engagement and understanding of fundamental mathematical concepts while offering empirical evidence that strengthens claims regarding the effectiveness of AR in early education. Meanwhile, the article by Cai et al.

(2019), which has received 124 citations, focuses on the use of tablet-based AR technology to analyze how students' perceptions, learning approaches, and self-efficacy influence mathematics learning. Their findings broaden the perspective that the success of AR-based learning does not rely solely on the technology itself but is also shaped by psychological and metacognitive factors. The fourth article, Cai et al. (2020), with 114 citations, examines the use of AR in probability learning and shows that AR integration can enhance students' understanding of probability concepts while fostering more positive learning attitudes. Overall, these citation trends indicate that AR research in mathematics education is developing in two major directions: first, the design and refinement of AR systems capable of visualizing geometric concepts in realistic and interactive ways; and second, the evaluation of AR's impact on cognitive, affective, and pedagogical aspects of mathematics learning. The most highly cited articles affirm that AR functions not only as a visualization tool but also as a pedagogical medium capable of transforming learning approaches more profoundly. These findings suggest that future research will likely continue toward more personalized, collaborative, and data-driven AR integration to enhance the effectiveness of mathematics learning across educational levels.

Distribution of publications

The country collaboration map for research related to augmented reality in mathematics education shown in Figure 4 illustrates that Indonesia is the largest contributor in terms of publication volume, as indicated by the dominant size of its node and its strong connectivity with other countries such as Malaysia, China, Japan, and Austria. This suggests that in recent years, Indonesia has become one of the leading centers of AR research productivity in the field of education, driven by increasing attention to instructional innovation and the adoption of immersive technologies across various educational institutions. In addition, the Southeast Asian cluster—comprising Indonesia, Malaysia, Thailand, and parts of China—demonstrates a strong collaborative network, indicating active knowledge exchange and joint research efforts within the region. On the other hand, the United States appears as a global hub of collaboration, with extensive connections to countries such as the United Kingdom, Germany, Switzerland, and Italy. The relatively large node representing the United States shows that it remains an important actor in methodological and theoretical contributions, even though its publication volume has not surpassed that of Indonesia in recent years. European countries such as Germany, Switzerland, Israel, and Italy appear to form a smaller yet solid network, reflecting the strength of laboratory-based studies and modern pedagogical approaches that characterize educational technology research in the region.

Figure 4. Distribution of publications

This distribution indicates that AR research in mathematics education is developing through two major centers: Asia—particularly Indonesia and Malaysia—as drivers of publication productivity; and the United States and Europe as hubs for theoretical integration, global collaboration, and technological development. The map also reflects that AR in mathematics education has become an international research phenomenon involving countries across multiple continents, signifying the high global relevance of immersive technologies in transforming mathematics learning.

Research Focus

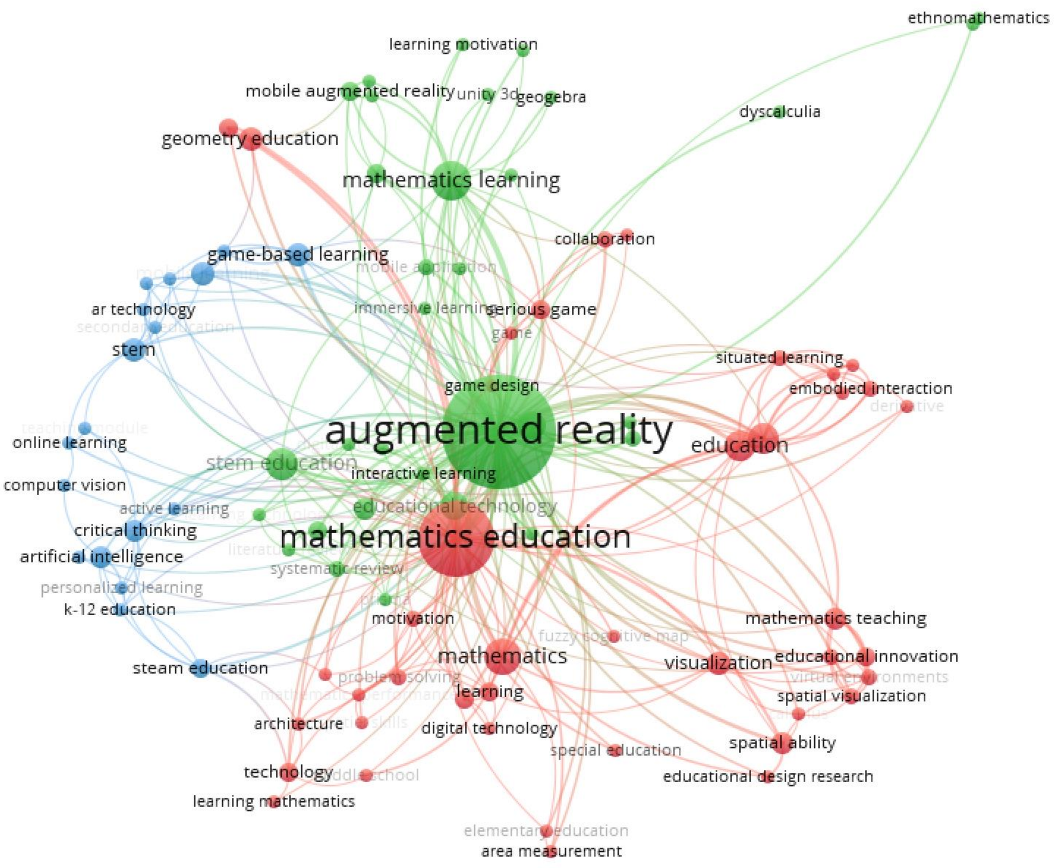


Figure 5. Network Visualization

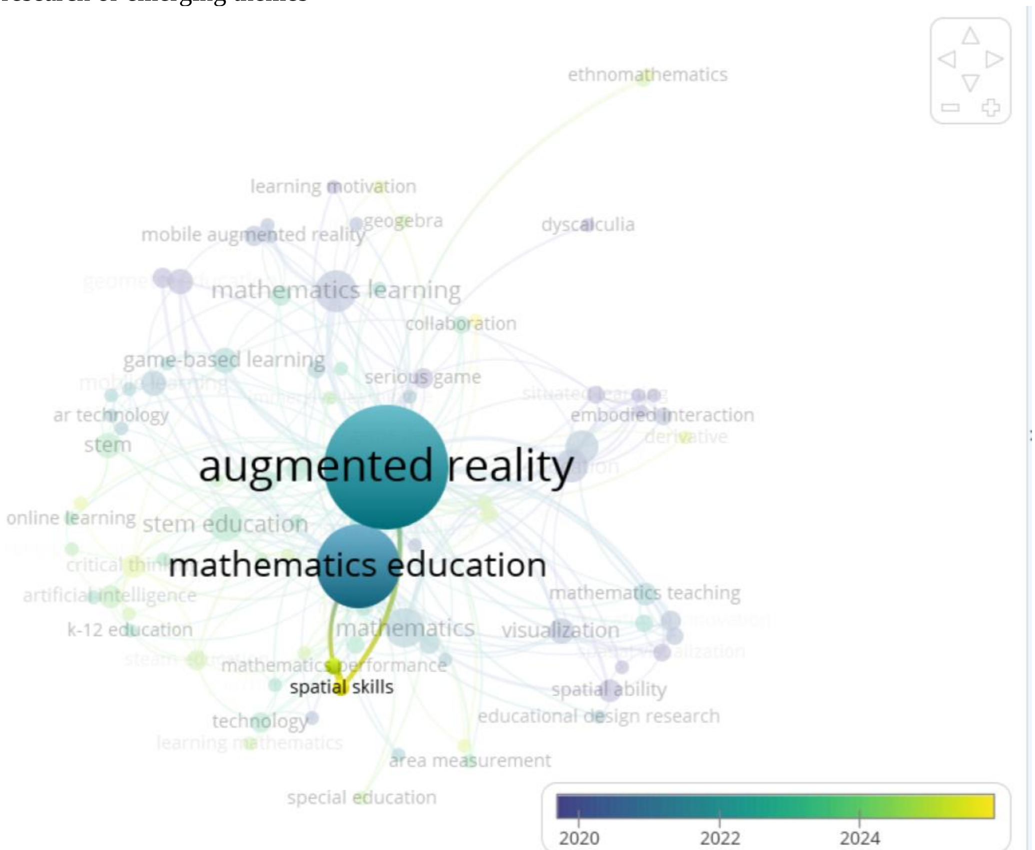
The keyword mapping of research on augmented reality in mathematics education in Figure 5 reveals three major clusters that represent the evolving focus of studies over the past two decades. The first cluster, shown in red, centers on the themes of mathematics education, virtual reality, and spatial ability. This cluster reflects research focusing on how immersive technologies such as AR and VR are used to enhance students' understanding of geometric concepts, mathematical visualization, and spatial abilities. Many studies within this cluster emphasize that the ability to mentally visualize abstract objects in three-dimensional space is one of the main challenges in mathematics learning, making AR a highly relevant pedagogical solution.

The second cluster, shown in green, is the largest and most dominant, centered on the keywords augmented reality, mathematics learning, STEM, and geometry education. This cluster highlights the direct integration of AR into mathematics learning, including its use to teach concepts such as geometry, algebra, and probability, as well as its incorporation into STEM education. The presence of keywords such as ethnomathematics, learning motivation, and dyscalculia indicates that AR research is also expanding toward culturally responsive pedagogies, support for students with special needs, and the enhancement of learning motivation. The appearance of keywords such as collaboration and situated learning aligns with previous studies (Bagossi et al., 2022; Dimas et al., 2025; Walkington et al., 2024), reinforcing the idea that AR functions not only as a visualization tool but also as an interactive learning space that enables students to collaborate and learn in context.

The third cluster, shown in blue, focuses on themes such as game-based learning, artificial intelligence (AI), critical thinking, mobile learning, and online learning. This cluster represents the latest direction in AR research, particularly the integration of AR with intelligent technologies and educational game design to enhance students' learning experiences. Keywords such as AI, computer vision, and personalized learning suggest a growing shift toward the development of adaptive AR-based learning systems. Meanwhile, the emergence of game design, serious games, and mobile augmented reality highlights the increasing trend toward game-based and mobile approaches, particularly for improving student engagement and critical thinking in mathematical problem solving.

Overall, the three clusters demonstrate that research on augmented reality in mathematics education is developing in a multidimensional manner: from enhancing spatial skills and visualization of mathematical concepts, to integrating AR into STEM and formal education, to combining AR with game technologies and artificial intelligence to create more adaptive, interactive, and meaningful learning experiences. These findings indicate that AR has evolved from a simple visualization aid into a comprehensive learning ecosystem with the potential to transform pedagogical approaches in future mathematics education.

Novelty research or emerging themes



Gambar 6. Overlay Visualization

The overlay visualization analysis in Figure 6 shows that research on augmented reality in mathematics education continues to evolve, with several emerging themes becoming increasingly prominent over the past five years. Keywords with brighter colors—such as spatial skills, embodied learning, situated learning, ethnomathematics, and dyscalculia—indicate topics that are relatively new and rapidly developing. One of the most notable novelties is the focus on spatial skills, which are now studied not only as a cognitive ability but also as a competence that can be significantly enhanced through immersive and interactive AR experiences. Recent studies show that AR can create rich 3D visual environments, making it an effective medium for strengthening students' spatial abilities in understanding geometry and complex mathematical representations.

Another emerging theme is embodied learning, a learning approach that connects physical movement and bodily interaction with the understanding of mathematical concepts. The presence of AR allows students to engage directly with virtual objects through movement, gestures, and physical manipulation, making the learning process not only mental but also sensorimotor. This aligns with the findings of Walkington et al. (2022), which highlight that embodied-focused learning can enhance the understanding of abstract concepts, especially in geometry and spatial reasoning. In addition, there is growing interest in ethnomathematics and dyscalculia, indicating an expansion of AR's impact and use into cultural contexts and special needs education. In the context of ethnomathematics, AR is beginning to be used to visually connect mathematical concepts with local cultural practices, making learning more contextual and meaningful. Meanwhile, the theme of dyscalculia suggests that AR is starting to be used as an intervention tool for students with mathematical learning difficulties, providing visual and interactive approaches that can help them understand basic concepts more effectively.

The emergence of these new themes confirms that the development of AR research is not only focused on technological innovation but also on broader pedagogical transformations, encompassing cultural contexts, special needs, bodily interaction, and the enhancement of specific cognitive competencies such as spatial ability. Thus, novelty in AR research reflects a direction that is increasingly human-centered and pedagogically grounded, opening significant opportunities for the development of more inclusive, adaptive, and immersive models of mathematics learning in the future.

Implications and Recommendations

The findings of this bibliometric study indicate that the use of Augmented Reality (AR) in mathematics education holds strategic potential to transform learning approaches from abstract to more concrete, interactive, and student-centered experiences. Various insights—ranging from the increasing focus on visual–spatial abilities, embodied learning, ethnomathematics, to support for students with special needs—suggest that AR is not only effective as a visualization tool but also as a pedagogical medium capable of strengthening conceptual understanding, enhancing motivation, and expanding access to inclusive and contextual mathematics learning. The findings on global collaboration patterns, keyword trends, and the evolution of recent research also provide a strong foundation for educators, curriculum developers, and policymakers to design more systematic and evidence-based AR implementation strategies that align with the demands of 21st-century digital literacy and the needs of future learning.

4. CONCLUSION

This study presents a comprehensive bibliometric mapping of the development of Augmented Reality (AR) in mathematics education over the past two decades, showing a highly significant growth in publications, particularly since 2019, along with the increasing adoption of immersive technologies in learning. Analyses of trends, country collaboration, and knowledge structures reveal that AR research has become increasingly diverse, covering improvements in spatial ability, integration within STEM learning, the development of culturally based pedagogical applications, and support for students with learning difficulties. The findings from the overlay visualization further highlight the emergence of new themes such as embodied learning, ethnomathematics, personalization, and AR-based interventions, reflecting a shift toward more human-centered and contextual research approaches. With a strong and robust dataset, this study not only illustrates the current landscape but also provides directions for future developments, indicating that AR will continue to play an essential role in mathematics learning innovation. Overall, this study reinforces that AR holds strategic potential for enhancing conceptual understanding, learning motivation, and equitable access to mathematics education, while opening substantial opportunities for the development of more interactive, adaptive, and relevant learning models to address the demands of 21st-century education.

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