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Trend, challenges, and determinants of technology integration in geometry problems-solving: A sequential explanatory analysis

Della Maulidiya[1*], Mela Aziza[2]
[1]Department of Mathematics Education, Faculty of Teacher Training and Education, Universitas Bengkulu, Bengkulu, Indonesia
[2]School of Mathematics, The University of Edinburgh, Scotland, United Kingdom

*Corresponding author: della.maulidiya@unib.ac.id

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ABSTRACT

This study explores trends, challenges, and success factors in integrating technology to enhance students' conceptual understanding and problem-solving skills in geometry. Using a sequential explanatory design, a quantitative analysis based on text mining and bibliometric methods was conducted on 197 articles from the ERIC database, followed by thematic analysis. The results indicate an annual publication growth of 32.26%, with key success factors including teacher competence, students' mathematical literacy, pedagogy-technology integration, and evaluation of instructional effectiveness. The COVID-19 pandemic accelerated the transformation of technology from an auxiliary tool to a core element of active learning. However, limited access and technological adaptation to complex problems remain significant obstacles. This study recommends teacher training, exploration of technology in teaching, and the development of innovative strategies and accessible technological tools. The implications of this study provide strategic guidance for policymakers, educators, and developers to optimize the use of technology in geometry education more innovatively and inclusively.

Tren, tantangan, dan faktor penentu integrasi teknologi dalam pemecahan masalah geometri: Analisis sequential explanatory

Kata Kunci:

perangkat lunak dinamis, teknologi pendidikan, pemecahan masalah geometri, pembelajaran yang didukung teknologi, penambangan teks

ABSTRAK

Penelitian ini bertujuan mengeksplorasi tren, tantangan, dan faktor keberhasilan dalam integrasi teknologi untuk meningkatkan pemahaman konseptual dan keterampilan pemecahan masalah geometri siswa. Menggunakan desain sequential explanatory, *dilakukan analisis kuantitatif berbasis penambangan teks dan bibliometrik terhadap 197 artikel dari basis data ERIC, yang dilanjutkan dengan analisis tematik. Hasil menunjukkan pertumbuhan tahunan publikasi sebesar 32,26%, dengan faktor keberhasilan utama meliputi kompetensi guru, literasi matematis siswa, integrasi pedagogi-teknologi, dan evaluasi efektivitas pembelajaran. Pandemi COVID-19 mempercepat transformasi teknologi dari alat tambahan menjadi elemen inti pembelajaran aktif, meskipun tantangan seperti akses terbatas dan adaptasi teknologi pada masalah kompleks masih menjadi hambatan signifikan. Penelitian ini merekomendasikan pelatihan guru, eksplorasi teknologi dalam pengajaran, serta pengembangan strategi inovatif dan perangkat teknologi yang mudah diakses. Implikasi dari penelitian ini menawarkan panduan strategis bagi pembuat kebijakan, pendidik, dan pengembang untuk* *mengoptimalkan pemanfaatan teknologi dalam pendidikan geometri yang lebih inovatif dan inklusif.*

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Contribution to the literature:

This research contributes to:

- Identifying key trends and challenges associated with technology-enhanced problem-solving in geometry.
- Combining bibliometric analysis, text mining, and thematic analysis to provide a comprehensive overview.
- Offering practical recommendations and actionable advice for educators and developers.
- Encouraging technology integration as a fundamental component of active learning in geometry education, aligned with constructivist principles that emphasize exploration and knowledge construction.

1. INTRODUCTION

Geometry problem-solving is a cornerstone of mathematics education, cultivating critical thinking, spatial reasoning, and problem-solving abilities essential for students' cognitive development. Geometry is unique in mathematics for its extensive applications, from visual presentations and computer animation to virtual reality [1]. With the growing role of technology in education, particularly during the COVID-19 pandemic, technology-enhanced learning environments have shown promise in increasing student engagement and fostering critical thinking and problem-solving skills [2], [3]. Technology enables innovative teaching methods like simulations and animations, promoting interactive learning environments and active student participation in exploring geometric principles [1]. Solving technological problems inherently involves a creative process, aligning with technology integration in enhancing problem-solving skills in geometry education [4], [5]. In recent years, technology integration in geometry education can potentially enhance students' engagement with mathematical concepts, promoting cognitive development and preparing them for future demands in a technology-driven world.

Additionally, technology boosts students' and teachers’ motivation and engagement in geometry learning while supporting their visualization skills and spatial abilities, which are essential for mastering geometric principles [1], [6]. For instance, GeoGebra, a popular dynamic geometry software (DGS), integrates algebra and geometry concepts, aiding in mathematical discovery and enhancing students' creative thinking through interactive 3D visualizations [7], [8]. The student's intentions to use DGS are significantly influenced by perceived usefulness, ease of use, attitude, and mathematics value [9]. Previous studies also have identified the potential of DGS in geometry learning [1], [2], [4], [9]. However, teaching geometry problem-solving effectively can be challenging despite its broad applications.

Previous research in the Philippines has identified key factors influencing teachers' intention to use GeoGebra in mathematics instruction, including perceived usefulness, perceived ease of use, attitude toward usage, behavioral intention, subjective norms, and facilitating conditions [6]. These factors have been found to significantly impact teachers' willingness to adopt GeoGebra as a teaching tool. Conversely, students often struggle to acquire general and specific problem-solving strategies [10]. GeoGebra, a popular DGS known for its visualization features and free accessibility, faces challenges in integration due to factors like user confidence, student-to-teacher ratios, and the complexity of certain commands [7]. Furthermore, effective implementation of GeoGebra requires careful alignment with the material's specific characteristics, teaching approaches, and desired competency outcomes [8]. Research on how DGS and other educational technologies can be systematically integrated to optimize their impact on student learning outcomes is limited despite its potential to enhance higher-order thinking skills and spatial abilities. A comprehensive understanding of the factors and challenges faced in implementing technology-enhanced problem-solving activities is also lacking.

Big data enables in-depth analysis of scholarly publications using article metadata, which can be accessed for free, including titles, abstracts, keywords, author identities, and journal names. Bibliometric research is a quantitative method that utilizes this metadata to analyze scholarly publications within a specific field [11]. The researcher conducts bibliometric analysis to identify trends and relationships, map scientific knowledge, uncover potential research opportunities, and provide an overarching field view [11], [12]. Bibliometric analysis has been widely used by educational researchers, for instance, GeoGebra applications in Indonesia [8], ethnomathematics [13], and the impact of learning media on character values [14]. Most studies only focus on research trends, but bibliometric analysis holds potential for theoretical development [11], for example, to identify milestones in smart learning environments evolution [12]. Therefore, this technique could create opportunities for future exploration of the development and changes in educational technology.

This study employs a mixed methods approach, including bibliometric analysis, text mining, and thematic analysis, to analyze the literature on technology-enhanced problem-solving in geometry. The analysis aims to identify key factors influencing technology-supported problem-solving, identify research gaps, and provide recommendations. This research is crucial for educators, researchers, educational technology developers, and policymakers to improve mathematical instruction and student outcomes in geometry. The study aims to provide a foundational analysis for future advancements in this field. The research questions (RQs) are as follows.

RQ1: What are the dominant research trends in technology-enhanced geometry problem-solving over time?

RQ2: What are the critical factors for implementing technology in geometry problem-solving education?

RQ3: What are the challenges in applying technology to geometry problem-solving in educational settings?

These RQs provide a framework for investigating the potential benefits and challenges of integrating technology into geometry problem-solving instruction.

2. METHOD

This study utilized a sequential explanatory mixed-method approach, combining quantitative and qualitative analyses to investigate a phenomenon [15]. It began with bibliometric analysis and text mining to identify statistical patterns in academic literature. Bibliometric research extends beyond performance metrics and science mapping by identifying literature gaps, addressing social biases, and informing theory development and practical applications in institutional policies and decision-making [11]. Text mining is a technique that organizes and filters information, uncovers hidden patterns, and provides a comprehensive understanding of broader contexts and application themes, enhancing bibliometric analysis by providing deeper insights into research field structure and dynamics [3], [15]. The quantitative findings, highlighting research trends, were further refined through thematic analysis to examine the context and underlying meaning of identified topics and themes within the analyzed articles. These approaches comprehensively comprehend the themes and challenges linked to geometry-based problem-solving technology. After receiving athics approval, the research was conducted.

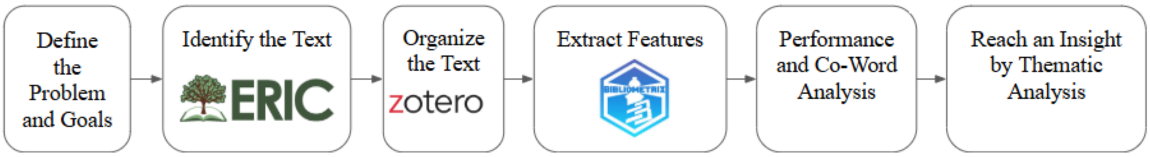

Figure 1. Research Flowchart

3.1 Define the Problem and Goals

The research process starts with defining a specific problem and setting measurable goals to ensure relevant and focused analysis, guiding the selection of appropriate data and methods. It's crucial to define the goals of a bibliometric study before choosing how to analyze the data [11], [12], [16]. A bibliometric study aims to review the performance and science of a research field, focusing on the prolific research constituents like authors, institutions, countries, and journals and the bibliometric structure encapsulating the intellectual structure [12], [16].

3.2 Text Identification and Organization

The research problem and goals are defined, followed by using ERIC and locating and organizing relevant textual data. ERIC is a valuable tool for educational research due to its comprehensiveness, quality assurance, accessibility, search functionality, and broad coverage. Researchers can explore the literature to identify relevant search terms [12], [16]. The 'Identify the Text' stage involves collecting research articles from the ERIC using predetermined keywords and selection criteria (Table 1).

Table 1. The Sample of Table Format

Stage	Criteria	Total Articles
Initial	Geometry AND problem	3,133
1st selection	Inclusion of descriptor: computer software	259
2nd selection	Inclusion of publication type: journal articles	200
3rd selection	Exclusion: remove secondary articles (1 article) or irrelevant abstracts (2 articles)	197

Table 1 outlines the article selection process. The search began with the keywords "geometry" and "problem." To refine the scope, the search criteria were narrowed by incorporating the term "computer software," specifically focusing on articles discussing software use in geometry. The search was limited to journal articles, yielding 200 articles. After excluding irrelevant and secondary papers, the final dataset was 197, and metadata was exported in bib format, which is a PubMed Bibliographic Citation Info file.

3.3 Organize the Text

The process involves systematically collecting and organizing relevant texts into a corpus (a collection of documents), a structured foundation for subsequent text-mining analyses [17]. Zotero is used in the 'Organize the Text' stage to organize articles into a comprehensive corpus, enabling efficient retrieval and analysis. Researchers can categorize texts based on criteria like author, publication date, abstract, keywords, and source name, improving data quality and exporting metadata in Bib Tex format.

3.4 Extract Feature

Extracting key terms, phrases, and concepts from textual data is crucial for obtaining meaningful insights into the research question [17]. Biblioshiny, an R package for bibliometric analysis, was used in this study to extract features from a corpus, offering various text mining and visualization functions [12]. The tool extracted metadata from articles, including titles, authors, publication years, journals, and Keywords Plus, standardized descriptors by ERIC for precise content classification.

3.5 Text Analysis: Performance and Co-Word Analysis

The text analysis stage in this study utilizes both performance and co-word analysis to address the research questions related to research trends, influential factors, and challenges in technology-enhanced geometry problem-solving. Performance analysis is a fundamental aspect of bibliometric studies, providing insights into the contributions of various research entities within a specific field [18]. Meanwhile, co-word analysis focuses on words instead of publications to examine the actual content by analyzing the co-occurrence of words [18]. The co-word analysis examines frequent co-occurrences of terms in Keywords Plus, titles, and abstracts, revealing challenges educators face in implementing geometry problem-solving technology. The n-grams method, including unigrams, bigrams, and trigrams, provides deeper insights into patterns and relationships.

Table 2 summarizes the relationship between each research question and the corresponding analysis method, ensuring a clear and logical alignment between the research objectives and the analytic approaches, thereby facilitating a comprehensive understanding of the study's methodological framework.

Table 2. The Relationship between Research Questions and Analysis

RQs	Performance analysis			Co-Words analysis	
	Annual scientific production	Three-Field Plot	Trend Topics	Most Frequent Words	Correspondence Analysis
RQ1	√	√	√	-	-
RQ2	-	-	√	√	√
RQ3	-	-	√	√	√

Table 2 outlines the different types of analysis needed for different research questions. RQ1 can be addressed using performance analysis, such as annual scientific publication graphs, a three-field plot, and trend analysis. It helps visualize connections between publication year, citation count, and research field and identify trends over time. RQ2 and RQ3 can be addressed using co-word analysis, identifying key themes and relationships within the dataset. Correspondence analysis was used to identify clusters of interrelated keywords and represent underlying themes. These approaches provide a comprehensive understanding of the research landscape. Additionally, combining these methods ensures that both quantitative trends and qualitative insights are captured. This integration enables researchers to derive actionable conclusions and formulate strategies for future studies.

3.6 Reaching Insights and Recommendations by Thematic Analysis

The text mining process concludes with analyzing results to produce conclusions or suggestions. Researchers analyze feature extraction and analysis outcomes to derive significant insights, which can inform decision-making, develop new theories, or guide future research. Thematic analysis helps understand technology-enhanced geometry problem-solving evolution, highlighting growth areas and gaps that require further exploration.

3. RESULTS AND DISCUSSION

The following sections will address the research questions by exploring the trends, factors, and challenges in implementing technology-enhanced geometry problem-solving. Additionally, the analysis will highlight the interplay between pedagogical strategies and technological tools in fostering student engagement. Practical recommendations for overcoming barriers and optimizing implementation will also be discussed.

3.1 Dominant Research Trends in Technology-Enhanced Geometry Problem-Solving Over Time

The analysis of annual scientific production shows a clear upward trend in scholarly publications on technology-enhanced geometry problem-solving, indicating growing academic interest. Figure 2 illustrates this significant increase over time, with an annual growth rate of 32.26% from 1996 to 2024. This rise reflects a heightened focus on using technology to transform geometry education within the academic community. This trend also highlights the increasing recognition of technology's potential to address persistent challenges in geometry learning. Moreover, it underscores the urgent need for further research to maximize the effectiveness and accessibility of these technological interventions.

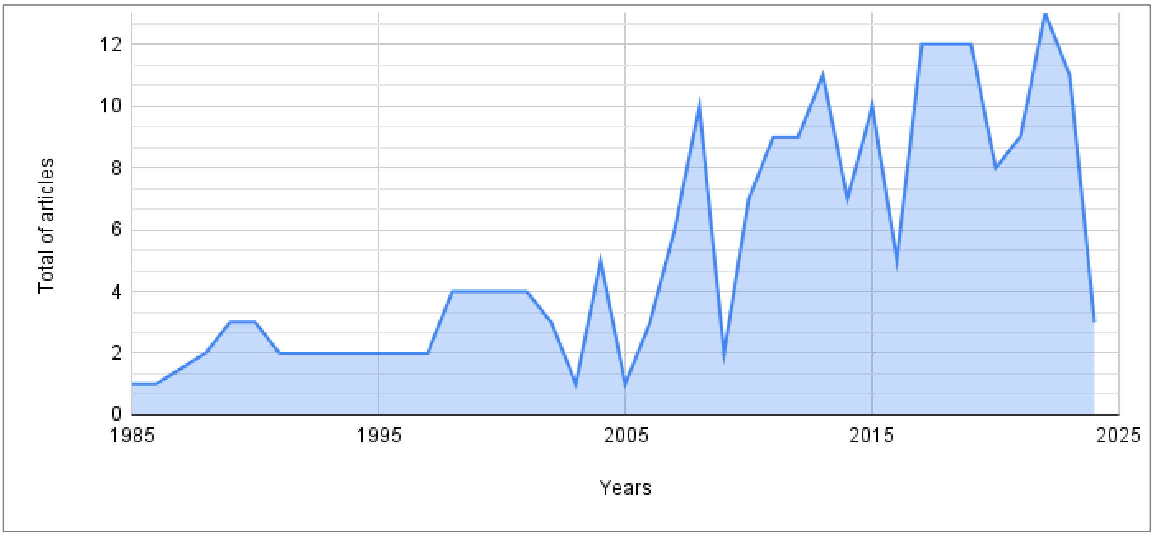

Figure 2. Annual Publications for Technology-Enhanced Problem-solving in Geometry (1985 - 2024)

The consistent increase in publications (Figure 2) indicates that technology's role in enhancing geometry problem-solving is a rapidly expanding field fuelled by educational technology advancements and institutions' evolving needs. Research output has steadily risen, with fluctuations linked to various factors. Notably, there was a sharp increase in publications after 2020, coinciding with the shift to remote and hybrid learning during the COVID-19 pandemic, accelerating the use of digital tools in education. This period emphasized technology's role in creating interactive and visual learning experiences, especially through platforms like GeoGebra and Desmos. These tools have not only facilitated concept visualization but also supported collaborative problem-solving among students. The trend highlights the necessity of continued innovation to address diverse learning environments and educational challenges.

The Three-Field Plot diagram (Figure 3) shows the relationships between journals, keywords, and authors, revealing research trends and key contributors. It underscores the evolving focus areas in the field.

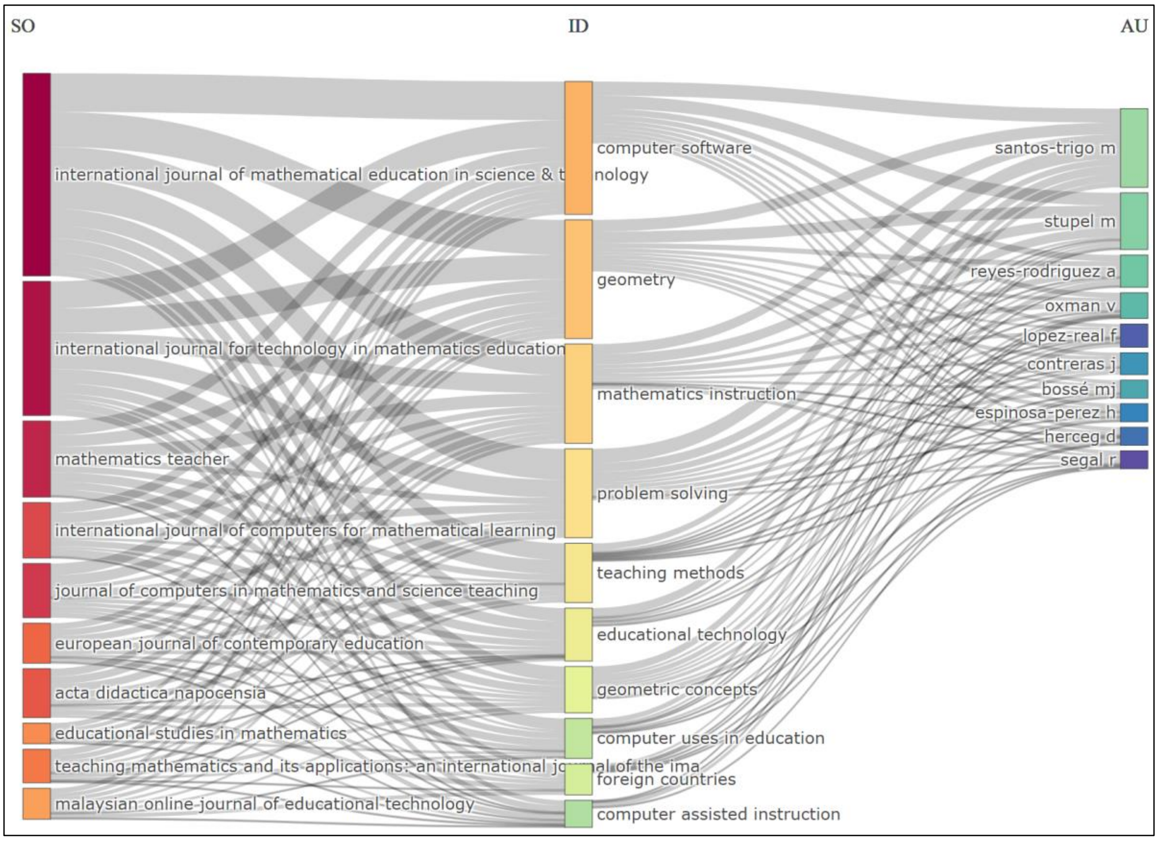

Figure 3. Three-field Plot Diagram for Sources (SO), Keywords Plus (ID), and Authors (AU)

Figure 3 shows the International Journal of Mathematical Education in Science and Technology (IJMEST) and the International Journal for Technology in Mathematics Education (IJTME) as primary sources in this field. Since 2014, IJMEST has been ranked in Q2 on ScimagoJR, while IJTME has been ranked in Q3 since 2013, both within the field of education. From 2000 to 2024, the IJMEST published 30 articles on this topic, with a significant rise in publications, especially post-2010, examining the use of dynamic geometry tools, like GeoGebra, for interactive learning. The IJTME contributed 21 related articles from 2006 to 2023. Key descriptors such as “computer software,” “geometry,” and “mathematics instruction” indicate a thematic focus on technology-enhanced geometry learning. Both journals emphasize technology integration, problem-solving, teacher education, and fostering students' mathematical understanding. This underscores their pivotal role in advancing research and practices in integrating technology to support innovative approaches in geometry education.

The Three-Field Plot shows that research in this area has a strong foundation with support from leading journals and influential authors. It implies that to contribute significantly to this field, new researchers need to understand the main focus of the topic, follow the developments published in these journals, and perhaps collaborate with established researchers. Authors such as Manuel Santos-Trigo and Moshe Stupel are noted for their significant contributions to educational technology research in geometry. Table 3 shows articles written by two top authors published in the two top journals. These findings highlight the importance of identifying influential works as a starting point for advancing research. Establishing connections with these academic networks could accelerate the impact of future studies.

Table 3. The example of articles written by top authors published in the two top journals

Years	Titles and References	Cited By	Journals
2008	Connecting dynamic representations of simple mathematical objects with constructing and exploring conic sections. [19]	8	IJMEST
2013	A special application of absolute value techniques in authentic problem-solving. [20]	7	IJMEST
2016	Digital technology is used to find multiple paths to solve and extend an equilateral triangle task. [21]	30	IJMEST
2017	On teaching extrema triangle problems using dynamic investigation. [22]	5	IJMEST
2018	The effectiveness of the 'what if not ' strategy coupled with DGS in an inquiry-based geometry classroom.[23]	13	IJMEST
2018	Various solution methods, accompanied by dynamic investigation, for the same problem as a means for enriching the mathematical toolbox. [24]	3	IJMEST
2019	An Interesting Dynamic Investigation of a Sangaku Problem, and What Else Can Be Asked, as a Research Activity. [25]	1	IJTME
2022	Complementary Euclidean Geometry and Trigonometry in Solving Tasks. [26]	0	IJTME
2022	Revisiting Geometrical Preservation Properties Using Proof Without Words and Interactive Technology. [27]	0	IJTME
2023	Using Technology and Proofs Without Words in Teaching Mathematical Reasoning to Pre-Service and In-Service Geometry Teachers. [28]	0	IJTME
2024	The problem and geometric application of infinite sequences formed from three given numbers by calculating their pairwise means. [29]	0	IJMEST

Table 3 articles highlights an investigative approach to geometry learning using technology to explore concepts actively. DGS is used to visualize, explore, and solve geometry problems, integrating various concepts. This method enriches the learning experience and fosters deeper conceptual understanding. However, further research is needed to understand how technology can be effectively used in different learning contexts. Additionally, it is essential to evaluate the long-term impact of such technological integration on students' problem-solving abilities. Collaborative efforts between educators and researchers can provide more comprehensive insights into optimizing technology for diverse educational settings.

This study uses trend topic diagrams (Figure 4) to explore research topics temporally. Based on Keywords Plus, the diagrams display the temporal development of various terms frequently used in research related to technology in geometry problem-solving. The parameters established in this study include a minimum word frequency of 5 and several words per year set at 3. These parameters ensure the identification of significant trends while reducing the influence of less relevant terms. The resulting diagrams provide a clear visualization of how key topics have evolved over time, reflecting shifts in research focus.

Technology integration in geometry learning began as early as the 1980s (Figure 4). Initially, technology applications focused on helping students visualize abstract geometry concepts and facilitate independent exploration, as evidenced by terms such as "computer graphics" and "computer-oriented programs." The consistent research efforts since the 1980s underscore the academic community’s dedication to understanding how technology can enhance geometry education effectively. These advancements have not only shaped the way geometry is taught but also transformed how students engage with the subject. As technology continues to evolve, its potential to address more complex educational challenges in geometry remains a promising area for future exploration.

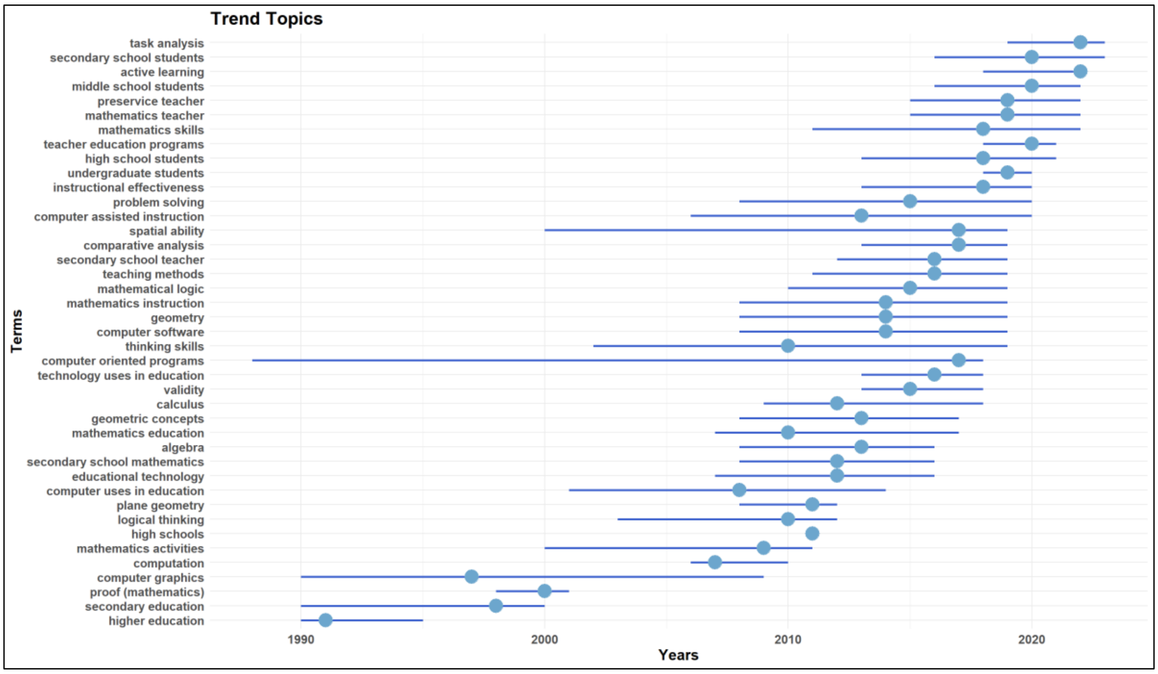

Figure 4. Trend Topics Based on Keywords Plus

The Trend Topics analysis reflects the evolution of research focus, with the early 2000s marking foundational innovations in technology-driven learning. Figure 4 shows that terms like "computer software," "problem-solving," "geometry," and "educational technology" gained significant attention starting in the early 2000s, peaking in 2012. From 2010 to 2020, terms such as "geometry," "mathematics instruction," and "geometric concepts" demonstrated notable growth, indicating that technology not only assists in teaching geometry but also enhances students' problem-solving skills through visualization and manipulation of geometric objects.

Numerous researchers explored how technology could support and transform educational practices during this period, particularly in fostering interactive and student-centered learning environments. Santos-Trogo et al. explored how dynamic software aids students in constructing geometric configurations, enabling them to reconstruct and examine mathematical relationships, formulate questions, make conjectures, present arguments, and communicate results [19]. By 2010, research expanded to broader instructional strategies, integrating technology as both a teaching aid and a tool for developing problem-solving skills. Overall, these articles published between 2000 and 2011 collectively indicate a shift from visualization and exploration toward problem-solving and proof construction. This transition is supported by advancements in dynamic software and sustained efforts to prepare teachers to integrate these tools effectively into the classroom.

Post-2012 trends emphasize "active learning" and "spatial ability," aligning with modern pedagogical approaches prioritizing student engagement and interactive environments. The emergence of these terms reflects a growing interest in how technology supports interactive learning and enhances spatial reasoning, both essential components of activity-based learning approaches. For example, students can effectively study authentic problems by using educational technology tools like GeoGebra to conduct virtual experiments that allow them to analyze inductively and generate hypotheses, which they can subsequently prove deductively using theoretical mathematical tools [20], [22], [25]. Cekmez and Guler [4] explored how students' problem-solving skills can be developed using DGS as heuristic tools to investigate non-routine geometry problems. The results also showed that DGS within an active learning framework improved students' problem-posing skills through problem-posing tests, open-ended questions, and student diaries over time, with students showing positive views about the process [30]. It reflects an increasing recognition of technology's role in fostering dynamic learning experiences.

Finally, researchers are exploring the intersection of technology with cognitive processes, such as logical reasoning and the validation of learning outcomes, indicating a deeper understanding of technology as a critical tool for enhancing mathematical thinking and conceptual understanding in geometry. Terms like "mathematical logic" and "validity" indicate a growing focus on testing the effectiveness of technology-based learning methods. Teachers can assign DGS-assisted mathematics activities to build complex dynamic models so that students practice mathematical thinking by discussing different paths to solutions and producing innovative mathematical outcomes [21], [29]. The open-ended geometrical problems can be taught using proofs without words and GeoGebra applets, suitable for all levels of mathematics education, highlighting the potential of these tools in teaching and learning [27], [28]. Another example is the windmill-related problems in geometry, algebra, and elementary number theory, which students solve using the Logo program, including turtle graphics, to create a mathematical model that explores rotational symmetry and connects seemingly unrelated problems [31]. The shift highlights the integration of technology with mathematical reasoning, using it as a medium to understand geometric concepts.

The discussion reveals that research trends in technology-enhanced geometry problem-solving have evolved from foundational explorations of software integration to more complex investigations into active learning and cognitive development. It reflects the broader shift in educational research towards leveraging technology to enhance learning outcomes and engage students and teachers in more meaningful and interactive ways. Key themes and shifts are visualized in Figure 5.

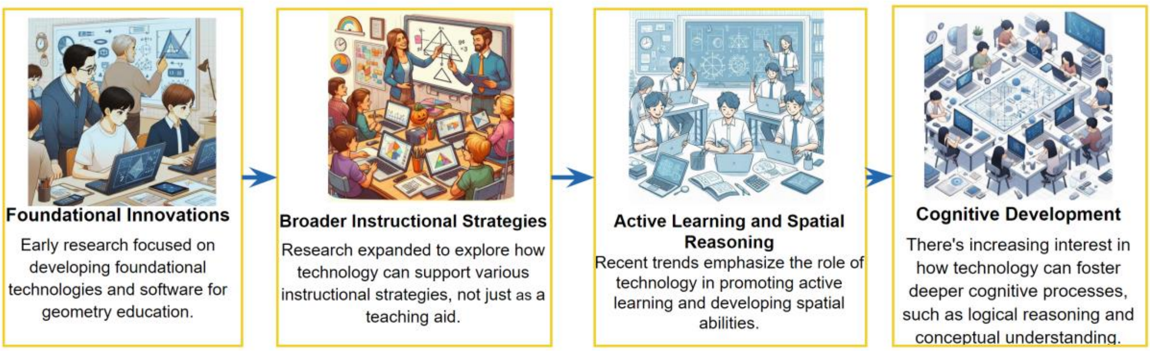

Figure 5. Key Themes and Shifts of Research Trends in Technology-enhanced Geometry Problem-solving (Pictures Generated by Microsoft Bing Image Creator in August 2024)

Terms like "secondary school students" and "higher education" consistently appeared, showing that technology is applied across various educational levels. A study investigated the impact of GeoGebra on students' mathematics attitudes, specifically persistence, rigor, and autonomy, and showed that using GeoGebra in middle grades can improve these attitudes by leveraging initial positive attitudes toward mathematics [32]. Research in higher education focuses on improving the competencies of mathematics teachers to improve the quality of education and prepare them for the development of curriculum, technology, and teaching methods, as done by Shahbari and Stupel [26], Segal et al. [23], and Stupel et al. [28].

The diagram in Figure 5 shows the evolution of research in technology-enhanced geometry education. Initially, it focused on developing basic tools, but now it explores how technology can support diverse instructional strategies and improve learning. Recent trends emphasize technology's role in promoting active engagement, spatial reasoning, and higher-order thinking skills. Future research will explore how technology can enhance problem-solving capabilities and deeper understanding in geometry education.

3.2 Factors influencing the successful application of technology to enhance geometry problem-solving outcomes

Several critical factors influence the successful application of technology to enhance geometry problem-solving outcomes, as identified through the analysis of most frequent words and factorial analysis. This study compares word clouds obtained from word frequencies in Keyword Plus, titles, and abstracts. Extraction of keywords plus, titles, and abstracts produces a list of terms that are then used to obtain factors that determine the application of technology in solving geometry problems in learning. Table 4 summarizes the extraction results from keywords plus titles and abstracts.

Table 4. Frequencies of Terms Extracted from Keywords Plus, Titles, and Abstracts

Keywords Plus	**Titles**		**Abstracts**	
	Bigrams	**Trigrams**	**Bigrams**	**Trigrams**
387	545	214	4,032	1,800

The following graph (Figure 6) shows the frequency distribution of keywords plus meets the Luhn distribution theory [33], [34].

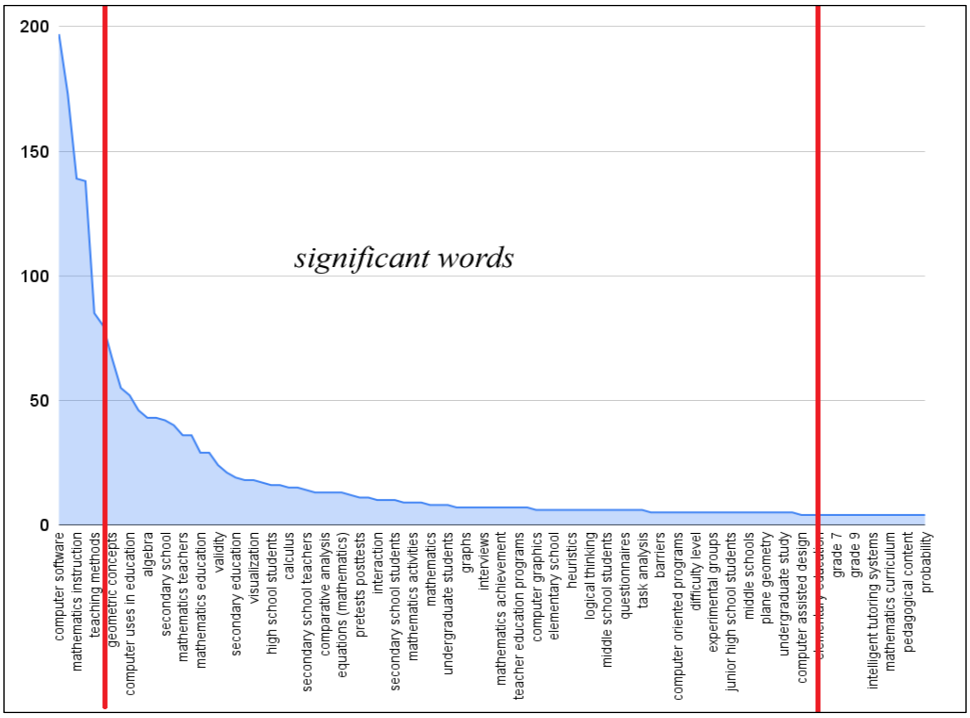

Figure 6. Luhn Distribution for the Glossary of Terms in Keywords Plus

The words at the extremes (higher cut-off on the right and lower cut-off on the left) were excluded to obtain reliable analytical results. Only significant words are examined further since they provide the most relevant information and add value to the analysis [33]. Focusing on these essential terms allows researchers to better understand the data's prevailing trends, topics, and research interests, resulting in more robust and actionable conclusions. The words in the cut-off category will be compiled into a list of stop words for future processing.

The word cloud visualization (Figure 7) shows a strong relationship between the groups of words in Keywords Plus, Titles, and Abstracts. Cloud visualization highlights the dominant themes, focusing on geometry learning, technology integration, teacher and pre-service teacher roles, mathematical modeling, and problem-solving. Key terms include "geometry," "geometric," "geometers sketchpad," and "dynamic geometry." These terms highlight the importance of using dynamic geometry environments (DGE) or DGS like GeoGebra and Geometer's Sketchpad to teach geometric concepts effectively.

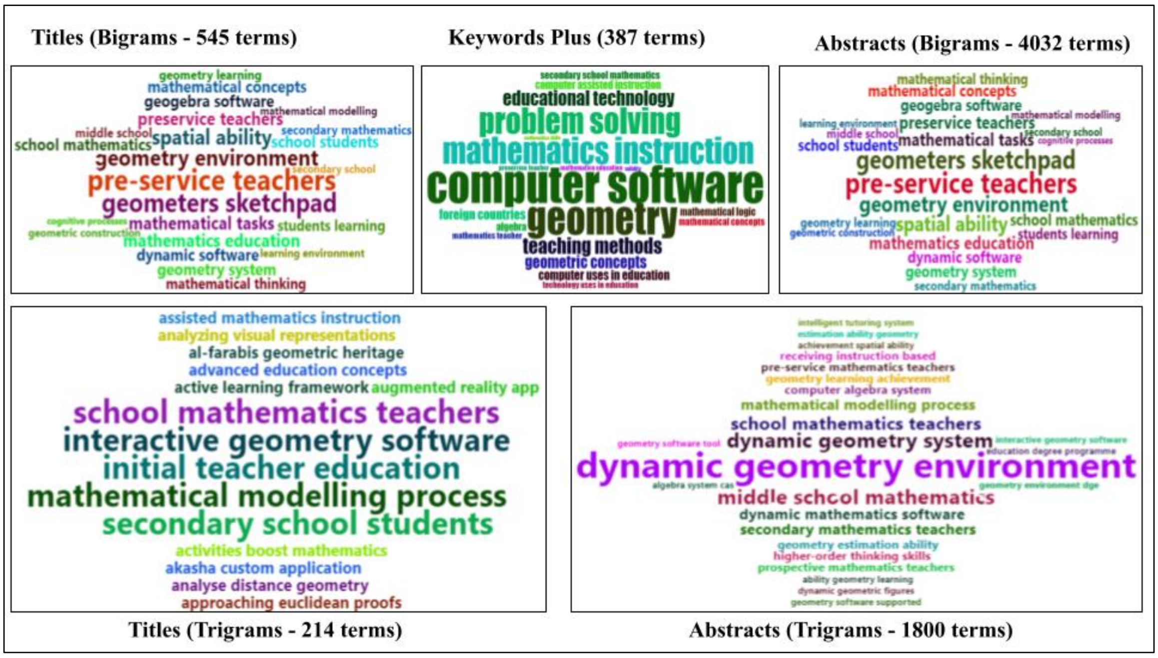

Figure 7. The Word Clouds of 50 Most Common Words for Keywords Plus, Titles, and Abstracts

The integration of technology in mathematics education is also highlighted, with terms like "computer software," "educational technology," "dynamic software," and "interactive geometry," highlighting how digital tools can enhance learning and support geometric visualization. The research also emphasizes the role of educators in mathematics learning, exploring how technology can be effectively integrated into teaching practices and equipping pre-service teachers with the necessary skills.

Mathematical modeling and problem-solving are key research areas, fostering students' ability to apply mathematics in real-world contexts. The visualization highlights the practical applications of geometry software in education, specifically emphasizing teacher and student roles. The prominence of "computer software," "problem-solving," and "mathematics instruction" highlights the broader interest in leveraging technology to support instructional methods and enhance problem-solving abilities in geometry.

This study also analyzes Keywords Plus into five clusters using the Correspondence Analysis (CA) method, producing a word map as shown in the figure. CA works by decomposing a contingency table (in this case, word frequencies) into several dimensions representing the maximum variation in the data. The primary output of CA is a factorial map that displays points (keywords or categories) in a compressed space. The distance between words on the map represents the association level; the closer two words are, the more frequently they appear together in the dataset.

In the CA visualization, the axes or dimensions depict the greatest data variance directions. In the factorial map (Figure 8), two dimensions are presented, Dim 1 and Dim 2. Dimension 1 accounts for the largest variance in the data, while Dimension 2 explains the second largest. Dim 1 accounts for 14.83% of the variance, and Dim 2 explains 10.14%. These two dimensions account for 24.97% of the total variance in the data. This indicates that roughly 25% of the relationships between words in Keywords Plus are captured by these two dimensions. This mapping is deemed sufficient for this research as it provides a general visualization and identifies key patterns in the relationships between keywords or concepts.

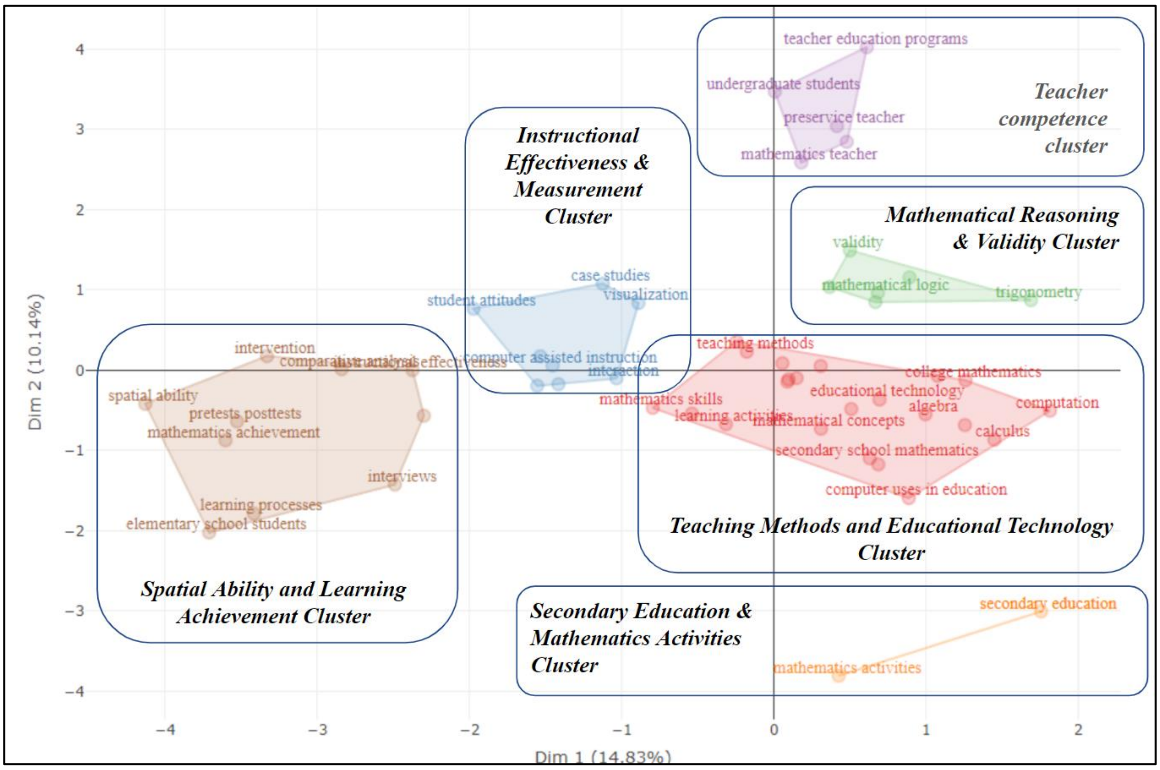

Figure 7. Factorial Map from Correspondence Analysis

The CA revealed six main clusters representing key factors and challenges in implementing technology for geometry problem-solving instruction. Each cluster reflects different aspects related to technology and the challenges encountered.

First, the Teacher Competence and Readiness Cluster (Purple) includes terms such as "teacher education programs," "undergraduate students," "pre-service teachers," and "mathematics teachers." This cluster focuses on teacher competence and education development, particularly how prepared teachers or pre-service teachers are to integrate technology into geometry instruction. Key factors in this cluster include teacher training and readiness and the role of teacher education programs in facilitating technology integration.

Second, the Mathematical Reasoning and Validity Cluster (Green) features terms like "validity," "mathematical logic," and "trigonometry." This cluster relates to logical reasoning and mathematical concepts such as trigonometry, indicating that deep mathematical reasoning and instructional validity are crucial in implementing technology for geometry problem-solving. A key challenge in this cluster is how technology can strengthen students' understanding of mathematical logic.

Third, the Spatial Ability and Learning Achievement Cluster (Brown) contains terms like "spatial ability," "pretests posttests," "mathematics achievement," and "learning processes." This cluster emphasizes spatial ability and student learning achievement in geometry problem-solving. Technology can aid in developing spatial abilities and supporting students' learning processes, but the challenge lies in ensuring that the technology truly enhances learning outcomes.

Fourth, the Teaching Methods and Educational Technology Cluster (Red) is associated with terms like "teaching methods," "educational technology," "algebra," "secondary school mathematics," and "computer uses in education." This cluster highlights the interaction between teaching methods and educational technology, particularly in secondary school mathematics. The main focus is how various technologies can effectively be integrated into teaching methods to enhance mathematical understanding. The primary challenge here is adapting technology to fit effective teaching methods.

Fifth, the Secondary Education and Mathematics Activities Cluster (Orange) includes terms like "secondary education" and "mathematics activities." This cluster identifies secondary education as a key area where technology is applied in mathematics instruction. The challenge here is ensuring that teachers and students at the secondary level have adequate access to technology and can utilize it to facilitate better mathematics learning outcomes.

Lastly, the Instructional Effectiveness and Measurement Cluster (Blue) includes terms such as "computer-assisted instruction," "visualization," "student attitudes," and "case studies." This cluster focuses on how technology-based instruction, such as computer-assisted instruction and visualization, impacts student attitudes and overall instructional effectiveness. The main challenge is measuring the impact of technology on student learning outcomes and ensuring that the technology used supports deeper understanding.

The six clusters identified through the analysis provide a comprehensive view of the critical factors influencing the successful integration of technology in geometry problem-solving education. The clusters reveal various aspects that contribute to the effectiveness of technology in enhancing students' understanding and performance in geometry. The process involves analyzing clusters to identify key themes and terms related to technology integration in geometry problem-solving instruction. These are then grouped based on their similarities and relationships, resulting in four key factors that can enhance the effectiveness of technology use in geometry instruction (Table 5).

Table 5. The Mapping Correspondence Analysis Cluster to Key Factors

Cluster's Label	Key Factors
Cluster 1. Teacher Competence and Readiness	Factor 1. Teacher Competence and Readiness
Cluster 2. Mathematical Reasoning and Validity	Factor 2. Mathematical Literacy
Cluster 3. Spatial Ability and Learning Achievement	
Cluster 4. Teaching Methods and Educational Technology	Factor 3. Integration of Pedagogy and Technology
Cluster 5. Secondary Education and Mathematics Activities	
Cluster 6. Instructional Effectiveness and Measurement	Factor 4. Evaluation of Effectiveness of Integration

Table 5 properly arranges the clusters and their relevant factors, representing the links discovered during the investigation. Thus, the analysis of the six clusters resulted in four key factors crucial for the effective implementation of technology in geometry instruction: teacher competence and readiness, mathematical literacy, integration of pedagogy and technology, and evaluation of the effectiveness of pedagogical and technological integration.

Teacher competence and readiness remain foundational, as educators are pivotal in facilitating technology-enhanced learning. Mathematics educators have consistently sought innovative approaches to teaching mathematics, focusing on improving student achievement and performance [1], [12]. They also should enhance students' abilities to apply, analyze, and synthesize material by reinforcing essential qualities, rules, and theorems learned in previous educational stages. To accomplish this, teachers must have a thorough understanding of mathematical ideas and the confidence to approach complex issues by solving mathematical assignments in investigation-based geometry utilizing DGS [23]. Therefore, investing in comprehensive professional development and training for teachers is essential to equip them with the necessary skills and confidence to effectively integrate technology into their teaching practices.

Equally important is the alignment of technology with mathematical reasoning and pedagogical methods, ensuring that the tools support and enhance students' cognitive development. The mathematical reasoning and validity cluster, along with the spatial ability and learning achievement cluster, combine to form the factor of mathematical literacy. The integration of dynamic software in mathematical education supports the development of logical reasoning and spatial abilities and enhances overall mathematical literacy [19]. Mathematical literacy involves the development of fundamental skills such as logical reasoning and spatial ability, which are essential for understanding and applying mathematical knowledge in real-world contexts.

Technology, particularly DGS, significantly enhances students' mathematical literacy by providing tools that help them better understand and engage with mathematical concepts. Dynamic technology for interactive learning, such as GeoGebra and Geometer's Sketchpad, is significant in supporting visualization and interactivity in geometry education. GeoGebra's constructiveness, ease of navigation, and interactivity enable new behaviors, such as flexible problem-solving, increased accuracy, and collaboration, resulting in students gaining independence from the teacher to deal with non-routine tasks [32]. The integration of DGS and augmented reality (AR) significantly enhances students' understanding of abstract and complex geometric concepts [1], [8]. The tools enable students to create dynamic geometric figures, improving their understanding and problem-solving skills and enhancing their application of mathematics in various situations.

The teaching methods and educational technology cluster and the secondary education and mathematics activities cluster contribute to integrating pedagogy and technology, emphasizing the importance of integrating teaching practices and technology in mathematics instruction. Both clusters highlight the crucial role of pedagogical approaches and technology in a successful learning environment [12]. Moreover, assessing the effectiveness of these technologies through student outcomes and their impact on mathematical abilities is essential to optimize their use in the classroom.

3.3 Challenges in Implementing Technology in Geometry Problem-Solving

The implementation of technology in geometry problem-solving faces several significant challenges. Effective technology integration faces challenges in teacher competence, mathematical literacy, pedagogy-technology integration, and instructional effectiveness evaluation. These factors require consistent effort and adaptation.

Teacher competence and readiness are critical issues, with many educators lacking the training to effectively incorporate technology into geometry instruction. This factor reveals a strong need for enhanced professional development programs to equip teachers with the skills to integrate technology into their daily teaching practices [35]. However, the limited use of digital technologies in the classroom may stem from insufficient and inadequate teacher training, leading to many educators being unprepared to effectively incorporate digital technology into the mathematics curriculum [1]. Additional training may be required for educators to effectively integrate technology into their teaching practices, potentially posing a barrier to successful implementation [36]. This lack of preparation can hinder the potential benefits of technology, ultimately affecting students' learning experiences and outcomes.

The success of technology integration also depends on the mathematical literacy of both teachers and students. A deep understanding of mathematical concepts is essential when using technology to solve complex geometry problems. Teachers must help students apply, analyze, and synthesize previously learned concepts, yet this requires educators who are confident in their mathematical knowledge and can guide students in using technology to strengthen their mathematical reasoning skills [37]. Furthermore, using technology to solve complex geometry issues presents difficulties since DGS has sophisticated features that teachers and students may find difficult to understand [4]. While technology is helpful for simpler tasks, its application in solving more intricate geometric problems can be challenging, slowing down the learning process. Therefore, some investigative tasks in geometry combined with another strategy could be given to pre-service mathematics teachers as part of an advanced course for integrating technological tools in the subject [22], [23], [29].

Integrating technology with effective teaching methods remains a core challenge. Another key barrier is limited access to technology and resources in some educational institutions, which hampers the ability of teachers and students to fully leverage technology in the classroom. Inadequate access to hardware and software resources in some schools or educational institutions poses a major obstacle [7]. Moreover, students' adaptation and acceptance of technology vary, with some students facing difficulties in using dynamic geometry software, necessitating more guidance and support to help them utilize these tools effectively [9].

Assessing the impact of technology on student learning in geometry is another complex challenge. The validity of technology-based learning methods is also a concern, as highlighted by the "Mathematical Reasoning and Validity" cluster, raising questions about whether these methods truly enhance deep geometry learning or serve merely as visual aids. The effectiveness and validity of technology-based learning methods for geometry need to be carefully studied [2]. Finally, the need for pedagogical shifts poses another challenge, as integrating technology often requires changes to traditional teaching methods, which some educators may resist [6]. Teachers and administrators need reliable ways to evaluate whether technology improves understanding and performance or if adjustments are needed. However, developing meaningful metrics and assessment methods for technology-enhanced learning requires further research and adaptation to ensure that technology integration genuinely supports instructional goals [38].

A complete strategy incorporating teacher training, in-depth mathematics understanding, and trustworthy evaluation criteria is required to increase the efficacy of technology-enhanced learning. Teacher competence, digital literacy, and a supportive learning environment are important for successful technology integration, as they emphasize the interplay between technology, pedagogy, and content knowledge [37]. Research indicates that technology-enhanced collaborative inquiry positively affects student learning outcomes, emphasizing the need for robust evaluation frameworks to measure these impacts [38]. Although teacher preparation and digital literacy are essential, it's also necessary to consider the possible obstacles to implementing these methods, such as educators' differing degrees of access to technology and resistance to change.

Evaluating the effects of technology-enhanced instruction requires a concerted effort. For example, assessing children's comprehension of geometric concepts through interviews and tests can be challenging due to their difficulty clearly expressing their thoughts [36]. These issues must be resolved for technology to be successfully incorporated into geometry education. A diagram illustrates the relationship between factors and their associated barriers (Figure 8).

Figure 8. Conceptual Framework of Technology-enhanced Problem Solving in Teaching and Learning Geometry

This study examines the significance of learning theories in technology-enhanced geometry education, particularly constructivism, which emphasizes active learning through hands-on experiences. As noted by Crompton et al., constructivist principles are embodied in DGS, enabling students to engage interactively with geometric concepts [39]. This interaction fosters a deeper understanding than traditional teaching methods, which might lead to superficial comprehension. Moreover, it highlights the potential of technology to bridge the gap between theoretical knowledge and practical application in geometry learning.

Additionally, integrating technological tools within the curriculum aligns with developmental theories proposed by Piaget and Vygotsky, which advocate for learner-centered approaches that enhance active participation and collaboration [40]. Technology facilitates communication and collaboration among students and educators, allowing for rapid knowledge and skill development. Research by Aslan et al. [36] further supports the assertion that integrating technology in geometry education can lead to more interactive and effective teaching practices, ultimately promoting problem-solving and critical-thinking skills. Integrating technology in geometry education, guided by relevant learning theories, presents promising opportunities for enhancing instructional practices and student comprehension.

The study has limitations due to its reliance on bibliometric and text-mining analysis, which may exclude relevant studies. It also lacks depth into contextual factors and cultural variations in technology integration within geometry education. The generalizability of the findings may be limited due to the diversity in educational systems and regional approaches. Future research could address these limitations through in-depth qualitative research or specific case studies. Conversely, thematic analysis is a structured method to describe the evolution of themes, factors, and challenges in geometry education. It helps educators, researchers, and policymakers understand the shift in technology-enhanced problem-solving. However, it may be constrained by the depth of literature, subjectivity, and lack of capture of nuanced trends. Thematic analysis may also introduce subjectivity, as themes are selected based on perceived patterns rather than quantitative metrics. Expanding this analysis with qualitative interviews or case studies could enhance the contextual understanding of these themes. Future research may delve further into how technology can be leveraged to improve problem-solving abilities and foster a deeper conceptual understanding of geometry. While this study focuses on technology in geometry education, the insights may have broader implications for technology integration across other areas of mathematics.

4. CONCLUSION

Overall, the successful integration of technology in geometry education requires a comprehensive approach that addresses technological factors and key pedagogical elements. The topic trend analysis reveals a shift in research focus—from viewing software as a teaching aid to recognizing it as an essential active learning component. Co-word analysis highlights four critical factors for effective technology integration in geometry problem-solving: teacher competence and readiness, mathematical literacy, the integration of pedagogy and technology, and the evaluation of instructional effectiveness. However, several barriers hinder this integration. Significant challenges include limited access to technological resources, inadequate teacher training, and the complexity of adapting technology to advanced geometry tasks.

Additionally, questions regarding the validity and impact of technology-based learning on deeper understanding persist, emphasizing the need for reliable evaluation methods. Addressing these barriers is essential to fully realize the potential of technology in enhancing geometry instruction. These findings provide valuable insights for educational technology developers, researchers, and educators aiming to optimize technology use in geometry education. The research implies several key actions: policymakers should support technology acquisition and teacher training; educators are encouraged to explore and experiment with technology tools; researchers must develop innovative strategies, evaluate their impact, and address challenges; and technology developers should focus on creating user-friendly and accessible tools.

AUTHOR CONTRIBUTION STATEMENT

DM contributed to formulating the research concept, collecting and analyzing data, integrating findings, drafting, and revising the manuscript. MA contributed to refining the research concept, conducting the literature review, analyzing data, drafting, and revising the manuscript. Both authors have read and approved the final version of the article.

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