Research Article

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Technological Tools Used in Mathematical Thinking at the University Level: A Systematic Review

Enny Román Castillo[1]
Johnny Antonio Marín León[1]
Edin Becerra Celiz[2]
Teresa Juliana Jara Alarcón[3]
Yessica Del Milagro Chunga More[4]

[1]Universidad César Vallejo, Lambayeque, Perú
[2]Universidad Nacional Autónoma de Chota, Cajamarca, Perú
[3]Universidad Nacional de Frontera, Piura, Perú
[4]Universidad Nacional de Jaén, Cajamarca, Perú

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Abstract

This systematic review analyzes the technological tools used in mathematical thinking at the university level, examining their impact and effectiveness in enhancing students' mathematical comprehension and problem-solving abilities. Through a comprehensive analysis of 125 scientific articles published between 2019 and 2024 and retrieved from the Scopus, SciELO, and Web of Science databases, the study identified key technological tools and their implications for mathematical education. The methodology followed PRISMA guidelines, incorporating bibliometric analysis via VOSviewer software to map collaboration networks and research trends. The results revealed five fundamental tools that transform mathematics teaching: MATLAB, GeoGebra, Mathematica, Python, and Khan Academy. The bibliometric analysis revealed a significant concentration of research in the United States and Europe, with growing contributions from Latin American countries. The findings indicate that effective technological tools combine three essential elements: mathematical visualization capability, interactivity, and immediate feedback. Furthermore, the study revealed a significant relationship between technological tool implementation and the development of higher-order thinking skills in university students. Geographic analysis revealed research gaps in underrepresented regions, suggesting the need for more inclusive studies. Key limitations include the rapid evolution of technological tools, which may affect the long-term applicability of findings, and the predominance of studies from well-resourced educational contexts, potentially limiting generalizability to resource-constrained settings. Future research should focus on investigating the effectiveness of these tools in diverse socioeconomic contexts, exploring emerging technologies such as artificial intelligence in mathematical education, and conducting longitudinal studies to assess their long-term impact on student learning outcomes. This review contributes to understanding how technological tools can be strategically integrated into university mathematics education, considering both pedagogical frameworks and technological infrastructure requirements.

Keywords: *Technological tools, Mathematical thinking, University education, Systematic review, Digital education*

1. Introduction

The current international landscape of higher education faces significant challenges in teaching mathematics, particularly in fostering an understanding of abstract concepts and addressing students' lack of motivation, which affects the development of critical thinking and problem-solving skills. In a digital and globalized society, higher education systems are tasked with cultivating critical thinking abilities in graduates to enable them to tackle complex problems through the integration of knowledge across various disciplines (Kalinin & Toropova, 2024). This challenge has been heightened by the rise of generative AI tools such as ChatGPT, which have markedly reduced opportunities for independent thought, necessitating a rethinking of traditional educational strategies (Ueda et al., 2023). The situation has been further impacted by the COVID-19 pandemic, which drastically transformed learning environments, requiring a rapid shift to hybrid and digital teaching modalities (Manuel Ángel et al., 2021).

A significant knowledge gap exists regarding how technological tools impact conceptual understanding and real-world mathematical problem-solving skills at the university level (Sanjari & Manouchehri, 2024). This gap is particularly evident in complex areas such as mathematical analysis, where concepts such as numerical series and convergence present considerable challenges for students (Baran et al., 2019). While the digitalization of education has created new opportunities to harness the didactic potential of digital technologies, it has also necessitated systematic investigations of their effectiveness and adaptability in diverse educational contexts (Vainshtein & Saryglar, 2024).

Recent studies in Latin America have demonstrated that implementing technological tools not only improves mathematics learning but also enhances the development of mathematical competencies and higher-order thinking skills among university students (Baran et al., 2019). Vergel-Ortega et al. (2022) identified a significant functional relationship between the development of mathematical thinking and critical variables such as educational management, teaching tools, and innovation competence. Research during the pandemic has shown that structural discovery-based methods in university mathematics learning require careful adaptation to context and the incorporation of advanced communication technologies to optimize results (Manuel Ángel et al., 2021).

The primary objective of this systematic review is to examine the impact and effectiveness of technological tools in developing mathematical thinking at the university level. This analysis is essential given that modern scientific thought relies on rigorous fact-based analysis and the creation of deep understanding, elements subsequently expressed through mathematical language for verification (Foti et al., 2021). This study innovatively examines specific technological tools such as MATLAB, GeoGebra, Mathematica, Python, and Khan Academy (Arzarello et al., 2012) while considering innovative aspects such as the use of 3D models to foster creativity and communication skills (Masharova et al., 2020).

The theoretical framework integrates Vygotsky's sociocultural theory (1978), which emphasizes the crucial role of social interaction and cultural tools in cognitive development, with activity theory (POZO, 2006) and the transdisciplinary approach proposed by Kalinin and Toropova (2024). This foundation is enriched by modern perspectives on advanced mathematical thinking, emphasizing the importance of visualization and interactive manipulation of abstract concepts (Vainshtein & Saryglar, 2024). These theoretical perspectives align with findings of Masharova et al. (2020) on developing innovative thinking through 3D technologies.

The practical significance of this research lies in addressing the current imperative to integrate technological tools into university mathematics teaching (Trouche & Drijvers, 2010). This study responds to the urgent need to understand how these tools can optimize mathematical learning while fostering experimental and investigative thinking (Vainshtein & Saryglar, 2024). The findings have direct implications for designing educational programs that effectively prepare students for future professional challenges where advanced mathematical skills and critical thinking are increasingly vital.

2. Methodology

This research adopts a quantitative approach (Sautu et al., 2005) with a descriptive and longitudinal design, supported by a systematic exploration of scientific literature on technological tools employed in fostering mathematical thinking at the university level. As Hernández Sampieri & Mendoza Torres (2018) explain, this approach uses data collection and analysis to answer specific research questions—in this case, what existing tools support mathematical thinking? a¿and What are the best practical and recommended tools for integration into mathematical thinking?

A systematic review was implemented, following PRISMA methodology guidelines (Page et al., 2021), with a preregistered protocol to ensure transparency and reproducibility of the process. The study was conducted in three main phases: identification, screening, and selection.

2.1 Search strategy

The systematic search was carried out on April 13, 2024, across the Scopus, SciELO, and Web of Science databases, with a focus on publications from 2019--2024 to ensure current information. The search strategy used the following keyword combinations with Boolean operators:

- technology AND "mathematical thinking"`
- computation AND "mathematical thinking"`
- technology AND "mathematical thinking" AND "higher level"`

Searches were conducted in both English and Spanish, with the following filters applied:

- Document type: Research articles and conference papers
- Subject areas: education, mathematics, computer science
- Educational level: higher education

2.2 Selection criteria

The following specific criteria were established:

Inclusion criteria:

- Studies focused on university-level education
- Research in the field of mathematics education
- Studies evaluating specific technological tools
- Articles with clearly described methodology
- Publications in indexed journals

Exclusion criteria:

- Studies at nonuniversity educational levels
- Research in areas unrelated to mathematics education
- Gray literature or publications not peer-reviewed
- Articles without full-text access
- Duplicate studies

The justification for these selection criteria is based on guaranteeing the maximum scientific rigor and relevance of the findings. The decision to focus exclusively on university studies responds to the specific characteristics and unique challenges of mathematical thinking at this educational level, which differ significantly from other levels of education. The restriction to research in mathematics education ensures direct relevance to the object of study. The exclusive inclusion of peer-reviewed articles is crucial to guarantee the methodological quality and validity of the findings, since this process subjects each study to rigorous scrutiny by experts in the field before publication. The exclusion of gray literature is due to the difficulty in verifying its methodological rigor and possible inconsistency in the quality of the data presented. The requirement of access to the full text allows an exhaustive analysis of the methodology and results, avoiding bias due to incomplete information. The

elimination of duplicates prevents overrepresentation of specific findings that could distort the conclusions of the review. Together, these criteria ensure that the conclusions of the study are based on solid and verifiable scientific evidence.

2.3 Review and analysis process

Article selection was conducted by three independent researchers via a standardized data extraction form. Discrepancies were resolved by consensus, with a fourth researcher acting as an arbitrator when necessary. Interrater reliability was calculated (Cohen's kappa > 0.80).

The bibliometric analysis was performed via VOSviewer software (version 1.6.18), allowing for the generation of co-occurrence maps of terms and collaboration networks. Data extraction and categorization were conducted via an expert-validated matrix, including the following fields:

- Basic bibliometric information
- Methodological characteristics
- Studied technological tools
- Main findings
- Limitations and recommendations

2.4 Quality Control and Bias Assessment

The methodological quality of the selected studies was assessed via the Mixed Methods Appraisal Tool (MMAT). Publication bias was evaluated with funnel plots and Egger's test, where applicable. Two independent reviewers assessed each study's quality, with a third reviewer resolving any discrepancies.

2.5 Data analysis

A descriptive analysis of the bibliometric characteristics was performed alongside a narrative synthesis of the main findings. For result integration, a methodological triangulation approach was used, which combines the following:

- Quantitative bibliometric analysis
- Qualitative content analysis
- Systematic evidence mapping

The analysis process was meticulously documented to ensure reproducibility, including the creation of a codebook for information categorization.

2.6 Ethical considerations

Although formal ethical approval was not required for this systematic review, as it did not involve human subjects, ethical research principles were adhered to, including the following:

- Transparency in reporting results
- Appropriate recognition of authors
- Conflict of interest declaration
- Responsible data management

The initial search yielded 123 articles in Scopus, two in SciELO, and none in Web of Science, resulting in a total of 125 articles for the initial analysis. The search results and selection process were documented according to the PRISMA flowchart, providing a clear overview of study selection and ensuring methodological rigor.

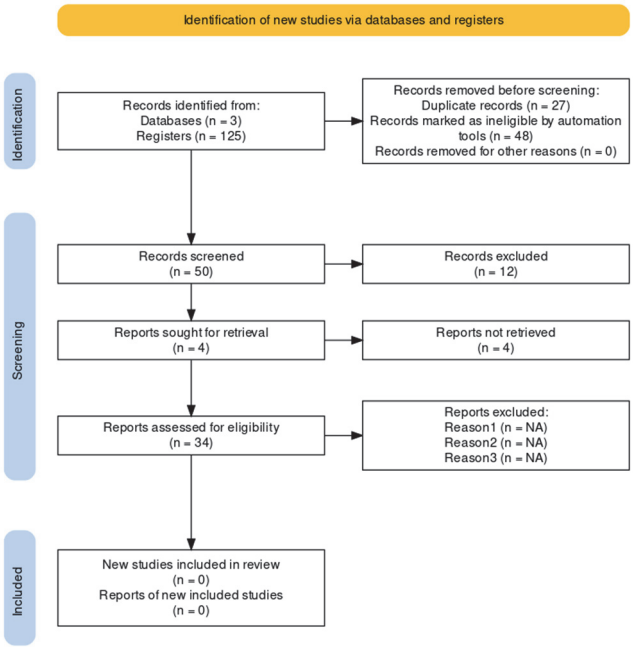

Figure 1. Flow chart.
Note. Prisma Flowchart (2024)

3. Results

Table 2. Tools used

Tools	Description
MATLAB	Title of the research
GeoGebra|	Dynamic mathematics software that integrates geometry, algebra, statistical graphics, spreadsheets.
mathematica	Description of the research
	Research approach
Python	Symbolic and numerical computation software used for data visualization.
Khan Academy	Online educational platform offering interactive lessons and resources in multiple areas.
Chat GPT	Future research proposals

The tools used to improve mathematical thinking and perform RS are presented in Table 2, where an exhaustive search and comparison of the articles found were carried out and the following software was found.

3.1 Results of the bibliometric analysis

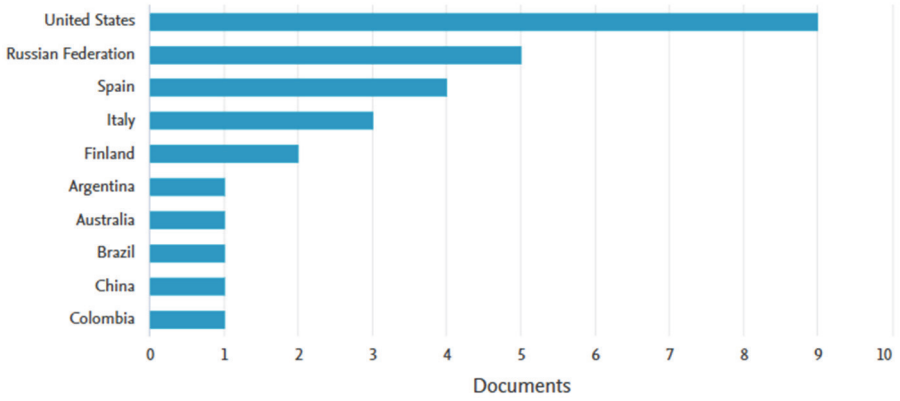

Figure 2. Documents by territory or country of origin

Figure 2 presents the bibliometric analysis of documents grouped by country or region of origin. This figure shows that the United States leads significantly in academic production, with approximately 10 documents related to the study topic. Next, the Russian Federation makes substantial contributions, followed by Spain and Italy, each with a notable number of documents. Additionally, countries such as Finland, Argentina, Australia, Brazil, China, and Colombia have contributed to research in this area, although to a lesser extent than the leading countries.

This distribution pattern suggests a greater concentration of studies in certain regions, particularly in the United States and Europe, which may be attributed to factors such as access to resources, academic infrastructure, and a strong interest in research on education and technology as applied to mathematical thinking in the university context.

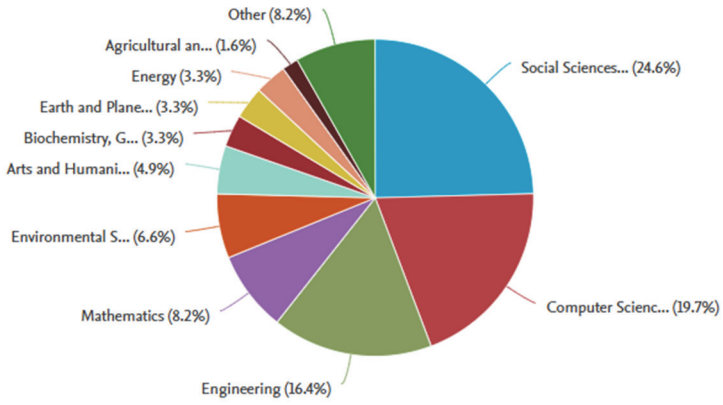

Figure 3. Documents by area of study

Figure 3 presents the distribution of reviewed documents by field of study, highlighting the disciplines most involved in research on technological tools applied to mathematical thinking at the university level. The findings indicate that the social sciences account for 24.6% of the total documents, followed closely by computer science, which accounts for 19.7%. Engineering also represents a substantial portion, comprising 16.4% of the documents, underscoring its importance in the application of technological tools within educational contexts. Mathematics and environmental sciences constitute a notable share, with 8.2% and 6.6%, respectively, reflecting their roles in fostering critical thinking and problem-solving skills among students.

Other fields, such as Arts and Humanities (4.9%), Biochemistry and Genetics (3.3%), Earth and Planetary Sciences (3.3%), Energy (3.3%), and Agriculture (1.6%), make smaller but valuable contributions, suggesting an interdisciplinary approach in this area of research. Finally, 8.2% of the documents fall under "Other" fields, indicating the diverse range of disciplines interested in the impact of technology on mathematics education.

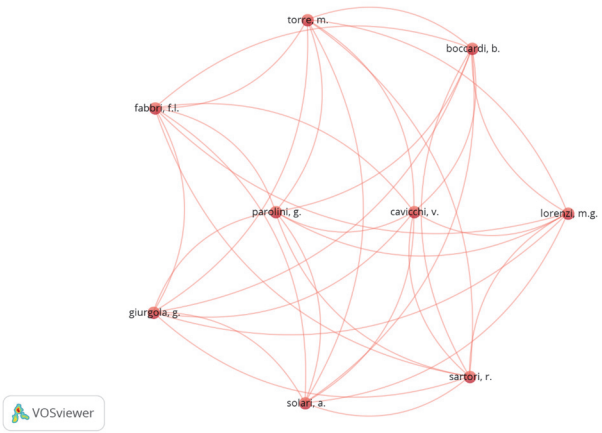

Figure 4. Bibliometric map of coauthorship

Figure 4 presents a bibliometric coauthorship map generated via VOSviewer software, which visualizes collaborative relationships among authors involved in research on technological tools applied to mathematical thinking at the university level. In the map, each node represents an author, and the lines connecting nodes indicate collaborative relationships in scientific publications.

The size and proximity of the nodes reflect the intensity of these collaborations. In this instance, a core group of active coauthors is evident, including authors such as "Torre, M.," "Fabbr, F.I.," "Parolini, G.," "Boccardi, B.," "Lorenz, M.G.," and "Sartori, R.," among others, who maintain interconnections, indicating a strong and recurring network of collaboration. This suggests that these authors have frequently collaborated on multiple studies or projects, significantly contributing to the advancement of research in this area.

The dense connections on the map highlight the cohesion within this research group and suggest the presence of a well-established team or network of researchers who collaborate regularly. This coauthorship network potentially facilitates the generation of integrated knowledge and strengthens the field through the convergence of diverse perspectives and areas of expertise.

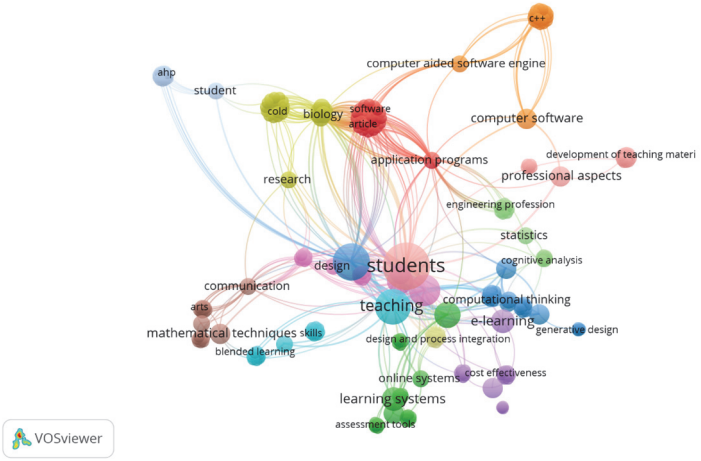

Figure 5. Bibliometric keyword map

Figure 5 presents a bibliometric keyword map generated through VOSviewer software, which helps to identify the most relevant terms and their relationships in research on technological tools applied to mathematical thinking in higher education. In this map, each node represents a keyword, with colors grouping related themes, whereas lines indicate the co-occurrence of terms within the same articles, reflecting both the frequency and conceptual proximity of topics.

Notable terms such as "students" and "teaching" appear centrally and in larger font, signifying their central importance in the reviewed studies. These terms are linked to concepts such as "learning systems," "e-learning," "computational thinking," "mathematical techniques," and "application programs," which represent key areas in the application of technology to enhance mathematical learning and foster digital competencies.

The color-coded areas, such as the cluster related to "computer software" and "application programs," suggest a strong focus on the use of educational software and digital tools in teaching. Other terms such as "statistics," "professional aspects," "online systems," and "assessment tools" illustrate the breadth of topics associated with integrating technology into learning and evaluation processes.

Additionally, concepts such as "blended learning," "communication," and "design and process integration" reveal a focus on pedagogical methods that combine in-person and digital components, promoting communication and design skills. This keyword map indicates an interdisciplinary research approach that addresses both the technical implementation of tools and the pedagogical and professional aspects of university-level mathematics education, reflecting a comprehensive perspective on educational technology.

4. Discussion

This research identified and analyzed the main technological tools employed in the development of mathematical thinking at the university level. The findings reveal five fundamental tools that transform mathematics education: MATLAB, GeoGebra, Mathematica, Python, and Khan Academy.
Our findings align with those of Hanselman & Littlefield (2012) regarding the widespread use of MATLAB in scientific research and higher education. MATLAB's capacity for complex numerical computations and data visualization makes it an essential tool for advancing mathematical thinking.

However, unlike previous studies, our results highlight its integration with other programming languages as a crucial feature for interdisciplinary learning, an aspect also emphasized by Higham & Higham (2005).

GeoGebra emerges as a particularly relevant tool, corroborating the findings of Ogan & Ibibo (2018) on its impact in transforming mathematics teaching. Our results extend this understanding by underscoring its cross-platform accessibility and its integrative potential across various mathematical areas. However, we identified limitations not mentioned in prior studies, such as its dependence on internet connectivity and the need for suitable technological resources, which could hinder its implementation in resource-constrained settings.

With respect to Mathematica, our findings support the conclusions of Mikhailovna & Pugachev (2018) regarding its revolutionary capabilities in tackling complex mathematical problems. Nonetheless, our research adds a crucial dimension by identifying its specific impact on developing critical thinking and problem-solving skills among university students, which aligns with Kramarski & Hirsch's (2003) findings on the importance of visualization in mathematical learning.

A particularly noteworthy finding is the role of Khan Academy in democratizing access to quality mathematics education (Khan, 2024). Our results complement the studies by Murphy et al. (2014), emphasizing the importance of instant feedback and student progress monitoring. This platform represents a breakthrough in accessibility and personalized learning, although its effectiveness is highly dependent on internet access, a limitation that must be considered in diverse educational contexts.

Unlike prior studies that focused on individual tools, our research provides a comprehensive view of how these various technologies can complement one another to strengthen mathematical thinking. This holistic perspective suggests that the effectiveness of developing mathematical thinking does not depend on a single tool but rather on the strategic integration of various technological resources according to specific learning objectives.

The analysis reveals significant barriers that may hinder the effective implementation of these technological tools in university-level mathematics education. The first major barrier is the digital divide, which manifests at three levels: access to devices, internet connectivity, and digital literacy. Our findings indicate that even institutions with access to tools such as MATLAB or Mathematica face challenges in their implementation due to limitations in technological infrastructure and available bandwidth. The second critical barrier is inadequate teacher preparation, an aspect that aligns with the findings of Kramarski & Hirsch (2003) regarding the need for specific professional development in educational technology.

To overcome these obstacles, we propose a multilevel approach that includes (1) the development of offline versions of the most widely used tools, following the adaptive model suggested by Murphy et al. (2014); (2) the implementation of teacher training programs that integrate both technical and pedagogical aspects; (3) the creation of support networks among institutions to share resources and best practices; and (4) the establishment of strategic partnerships with software providers to develop more accessible educational licenses. These strategies should be implemented considering the specific context of each institution and region, as suggested by the studies of Mikhailovna & Pugachev (2018) on the adaptation of mathematical tools to different educational environments.

The implications of these findings are significant for educational practice. First, they suggest the need for a more integrated approach to implementing technological tools in university mathematics education. Second, they underscore the importance of considering both the capabilities and limitations of each tool when designing learning experiences. Third, they emphasize the need to address technological access barriers to ensure the equitable implementation of these tools.

The limitations of our study include the rapid evolution of technological tools, which may necessitate frequent updates to some findings. Additionally, most of the studies reviewed originate from contexts with adequate technological resources, which may limit the generalizability of the results to environments with fewer resources.

5. Theoretical Implications

This research makes a significant contribution to the existing theoretical framework on the integration of technological tools in university-level mathematics education. The findings expand the socioconstructivist framework of Vygotsky by illustrating how digital tools serve as mediators in the construction of mathematical knowledge. The evidence supports the idea that tools such as GeoGebra and Mathematica facilitate proximal development by providing digital scaffolding that enables students to approach complex mathematical concepts in a gradual and meaningful way.

The findings also extend the activity theory proposed by Pozo (2006) by demonstrating how interaction with technological tools transforms the mathematical learning process. This theoretical extension is particularly evident in the use of platforms such as Khan Academy, where students' activity is structured through interaction with adaptive content and immediate feedback.

This research provides new perspectives on the transdisciplinary approach in higher mathematics education, validating the proposal by Kalinin and Toropova (2024) regarding the integration of modeling methodologies and computational mathematics. This expanded theoretical framework suggests that technological tools not only facilitate mathematical learning but also develop essential technological competencies for comprehensive professional training.

5.1 Practical implications

The findings of this research have direct implications for educational practice in university mathematics. Identifying the specific characteristics and limitations of each technological tool enables educators to make informed decisions about their implementation in various educational contexts. For example, understanding the visualization capabilities of MATLAB and GeoGebra facilitates their effective integration into courses that require the graphical representation of complex mathematical concepts.

The evidence suggests a need to develop teacher training programs that address not only the technical aspects of these tools but also their pedagogical foundations. As the research demonstrates, the effectiveness of these tools relies significantly on their implementation within a coherent pedagogical framework that promotes critical thinking and problem-solving skills.

The findings also have implications for curriculum design in university mathematics, indicating the necessity of systematically incorporating these tools into study programs. Research shows that platforms such as Khan Academy can effectively complement traditional instruction, particularly in contexts where personalized learning and additional support outside the classroom are needed.

The identified limitations regarding technological access and connectivity underscore the need to develop institutional strategies to ensure equitable access to these tools. This includes considering offline options and adapting resources for contexts with limited technological infrastructure.

The evidence presented here supports the development of educational policies that promote the systematic integration of technology into higher mathematics education, taking into account both pedagogical aspects and technological infrastructure needs. Such policies should incorporate continuous teacher training and systematic evaluation of the impact of technological tools on mathematical learning.

6. Conclusion and Future Directions

This systematic review of the technological tools used in fostering mathematical thinking at the university level has identified significant findings that contribute to advancing knowledge in this field. Through the analysis of 125 scientific articles, notable patterns and trends have emerged that warrant special attention.

First, the most effective technological tools for developing mathematical thinking combine three fundamental elements: mathematical visualization capability, interactivity, and immediate feedback. This triad, found in software such as GeoGebra and Mathematica, facilitates the

comprehension of abstract concepts and significantly enhances student engagement with mathematical learning.

A notable finding is the evolution in the use of these tools, shifting from mere calculation instruments to comprehensive learning platforms. This transformation is especially evident in MATLAB, which has expanded its capabilities to include not only computational functions but also programming and mathematical modeling elements, enabling a more comprehensive approach to advanced mathematical thinking.

The research also reveals a significant geographical pattern in the scientific output on this topic, with a notable concentration in the United States and Europe, followed by a growing contribution from Latin American countries. This distribution underscores the need to expand research in underrepresented regions to obtain a more global understanding of the impact of these tools across diverse educational contexts.

Bibliometric analysis has identified a growing trend in the publication of studies on technological tools in mathematics, with a notable increase over the past five years. This trend is accompanied by a diversification of application areas, extending beyond pure mathematics to fields such as engineering, computer science, and the social sciences.

The results demonstrate that the effectiveness of technological tools is closely linked to their adaptability to different learning styles and levels of mathematical competence. Platforms such as Khan Academy exemplify this adaptability, offering personalized learning pathways that address the individual needs of students.

On the basis of the findings of this systematic review, we propose the following practical recommendations for educators and educational policymakers. For educators, the recommendations include (1) implementing a gradual approach to the introduction of technological tools, starting with GeoGebra owing to its intuitive interface and accessibility, and progressively advancing toward more complex tools such as MATLAB or Python; (2) developing instructional guides that explicitly integrate the use of these tools into the existing curriculum, aligning each tool with specific learning objectives; and (3) establishing communities of practice to share experiences and effective strategies for using these technologies.

For policymakers, the recommendations are as follows: (1) develop frameworks for the systematic evaluation of the effectiveness of technological tools in university settings; (2) establish continuous professional development programs to train educators not only in technical aspects but also in innovative digital pedagogies; and (3) create institutional incentives for the adoption of educational technologies, including academic recognition and financial support for the acquisition of licenses and equipment.

These recommendations should be implemented with careful consideration of the specific characteristics of each institutional context and the particular needs of the student population, ensuring that technological integration effectively contributes to the development of advanced mathematical thinking.

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