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A systematic review of technology use in middle and high school mathematics education: insights from contextual, methodological, and evaluation characteristics

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In this systematic literature review, we analyzed empirical studies on the use of technology in mathematics education at the secondary and high school levels in period of 2019-2024. Utilizing the PRISMA flow diagram, we identified 300 studies from three major academic databases: Web of Science, Scopus, and Google Scholar. After applying our inclusion and exclusion criteria, we ultimately selected 25 relevant empirical studies. The entire paper is divided into two parts: the first part focuses on the bibliometric and contextual characteristics of the selected studies, while the second part examines the methodological and evaluative approaches used by researchers to assess the impact of technology on students' attitudes, beliefs, and academic performance in mathematics. Our findings show that a significant portion of the work in this area involves the use of interactive platforms such as GeoGebra and Kahoot. Moreover, the role of augmented reality in mathematics education has also been investigated to a considerable extent. High school-level content is studied more frequently than middle school content. Regarding methodological approaches, we found a noticeable lack of qualitative and longitudinal studies. Furthermore, there is a need to develop and validate measurement tools across diverse educational settings to ensure comparability and rigor. Finally, certain learning outcomes—such as retention, attitudes, and teamwork—are rarely assessed.

KEYWORDS

technology use in mathematics, systematic literature review, evaluation of technology use, secondary mathematics education, review of mathematics education

1 Introduction

Educational technologies have transformed traditional views of teaching and learning, enabling students and teachers to experiment with various types of technologies in their practice (Geiger et al., 2012). In this context, the use of educational technologies in mathematics education holds a special place. For example, GeoGebra enhances students' problem-solving skills by providing visual and manipulative representations of geometric problems (Rosyidi et al., 2024). Similarly, Kahoot and Quizizz software help students address their mistakes by providing instant feedback while also facilitating teachers' formative assessment, making the assessment process fast, effective, and engaging (Göksün and Gürsoy, 2019).

The extensive role of mathematics in students' school life necessitates careful attention to the effective delivery of knowledge. Mathematics is a pervasive subject, and without it, other science subjects would lack meaningful explanations. As a fundamental tool in science learning, mathematics requires technological tools more than other subjects because learning math often involves the need for visual representation (Rosyidi et al., 2024; Chechan et al., 2023). It also requires interactivity, where students can engage in interactive problem-solving, manipulate variables, and test hypotheses (Arifin et al., 2021). It needs students to explore the real-life applications of mathematics, testing mathematical rules and theorems with the help of virtual simulations in fields such as physics and engineering (Soussi, 2024). Therefore, the use of modern technological tools is essential to facilitate students' learning in mathematics, spark their interest in the subject, and ensure the sustainability of their knowledge (Borba et al., 2017).

To explore the future of technology use in middle and high school mathematics education, many researchers have conducted various studies in the field. Moreover, a vast number of literature review articles summarize the main findings of these studies (Verbruggen et al., 2021; Siswanto et al., 2024). Siswanto et al. (2024) analyzed the use of GeoGebra in mathematics learning at junior high schools in Indonesia and Japan. They found that most publications on the use of GeoGebra began in 2022, and researchers primarily investigated its implementation for topics related to geometry and algebra. Verbruggen et al. (2021) conducted a systematic review of the effectiveness of educational technologies in early mathematics education. They found that educational technologies positively impact young children's mathematical competencies. Similar findings were claimed by many other researchers in their systematic, comprehensive, and scoping reviews of technology use in mathematics education.

However, upon reviewing existing systematic literature reviews in educational databases, we noticed that little attention has been paid to the evaluation of technology use in middle and high school mathematics education (Bulut and Borromeo Ferri, 2023). Based on this, and considering the bibliometric, contextual, and methodological characteristics of the studies in the field, we also include the evaluation of technology use in middle and high school mathematics education as a focus of our work.

This study aims to systematically analyze recent trends, context-specific domains, and research designs related to the use of technology in middle and high school mathematics education. Moreover, we further elaborate on the evaluation strategies used in technology interventions and their effects on students' academic learning outcomes, attitudes, and beliefs toward mathematics. Evaluation, as established over time, is an essential part of the learning process, as it helps determine the effectiveness of teachers' efforts in conveying knowledge to their students. Systematically analyzing the measurement scales will reveal which student skills have been assessed in technology-embedded mathematics classrooms and will help identify aspects that require further attention (Ng et al., 2023).

1.1 Literature review

When implementing any pedagogical strategy, it is important to understand how effectively this strategy works and what outcomes are expected. To assess the effectiveness of a strategy, we can rely on evaluation techniques that were implemented in the study. Additionally, by reviewing the types of evaluations used in studies, we can gain insight into the specific skills that a particular pedagogical strategy fosters in students.

In their systematic literature review on augmented reality in mathematics education, Bulut and Borromeo Ferri (2023) described evaluation-related topics and revealed that the most dominant effects were an increase in academic performance and students' learning gains. They claimed that students who learned mathematics with augmented reality achieved better results in learning mathematics. They also found that using augmented reality in mathematics learning improved students' modeling skills, increased their engagement and motivation, and enhanced their understanding. In their research on the use of digital technology over the last decades, Borba et al. (2017) found that using mobile technologies in teaching and learning mathematics fosters students' application of geometric concepts to real-world objects. They found that, with mobile devices, students could analyze angles in their physical environment and determine whether they conformed to the mathematical properties of an angle.

Previously conducted review articles provide a clear understanding of the impact of technology on students' understanding of mathematical concepts. Drawing from the findings of the review articles, we have identified the following student skills that were evaluated in the use of technology in mathematics teaching and learning: improvement of students' visualization skills, enhancement of understanding, development of mathematical modeling skills, increased interest and engagement, improved collaboration among peers, enhancement of spatial ability, and more.

Moreover, the literature highlights multiple approaches that incorporate quantitative and mixed-method research designs. For example, Kim and Kwon (2025), in their mixed-method study examining the effect of a computer-supported collaborative dynamic learning environment on high school students' success in mathematics, developed the so-called Lines Knowledge Test (Köse and Tatar, 2024) and used an observation form to collect data. Similarly, Romero Albaladejo and García López (2024) implemented a mixed-method research design, incorporating comprehensive classroom observations and interviews. Meanwhile, Carriazo Regino et al. (2024) conducted a case study with a quasi-experimental approach using pretest/posttest assessments.

Analyzing the research design and evaluation tools used by researchers to assess technology use in mathematics, we have noticed that most authors employed a mixed-method approach. This approach helped researchers enhance the validity of their evaluation strategies by providing a wide range of data collection methods.

Interestingly, upon analyzing the existing literature in the field, we found that despite the variety of theories—such as Constructivism, Multimedia Learning, Self-Determination Theory, Behaviorism, and Social Constructivism—that have been applied to justify the effects of technology use on students' cognitive development in mathematics, there is a lack of studies that utilize Vygotsky's Zone of Proximal Development (ZPD) theory to theorize students' learning experiences. In considering the appropriate use of technology for students' age and developmental stage during mathematics instruction, it is reasonable to justify the increased use of technology at the middle and high school levels through the lens of Vygotsky's Zone of Proximal Development. As stated by Vygotsky in his Zone of Proximal

Development theory, students at this stage begin to understand abstract mathematical concepts, develop problem-solving skills, and engage in logical reasoning (Chaiklin, 2003).

This aligns with the findings of Brooke et al. (2020), who stated that middle school students tend to engage more with technology. Brooke et al. (2020) found that children in middle school are more likely to use smartphones. Moreover, the mathematics curriculum in middle school becomes more complex compared to that of younger students. As a result, teachers at the middle and high school levels are encouraged to implement new pedagogical approaches to enhance student engagement and sustain their interest in learning (Wentzel, 1997). Furthermore, a strong foundational understanding of mathematical concepts during middle and high school can significantly influence students' future interest in STEM careers (Balta et al., 2023).

Therefore, assuming that studying middle and high school students is particularly important for understanding the impact of technology use in mathematics education, we formulated the following research questions:

1. What were the bibliometric and contextual characteristics of the studies in technology use in mathematics education, such as the countries where the studies were conducted, the journals in which they were published, the years of publication, the grade levels they addressed, and the types of technology used in the studies?
2. What were the methodological and evaluation characteristics of the studies on technology use in mathematics education, such as the research designs implemented, the reliability and validity of assessment tools, and the learning outcomes assessed?

2 Methodology

In this systematic review, we aimed to investigate the bibliometric, contextual, methodological, and evaluation characteristics of studies on technology use in mathematics education. To ensure the quality of the systematic review, we initially formed a research team with appropriate interdisciplinary expertise. Our research team consists of three professors in Education and one doctoral student pursuing a degree in Mathematics Education. The professors are experts in the field of teaching and learning, while the doctoral student is new to the field of digital tools in mathematics education. Building up the research team and identifying the study aim, we consulted with a librarian to ensure the correctness of our search strategy. After maintaining our search strategy, we started working on our systematic review, which we will describe in detail.

2.1 Search strategy

Our search strategy was based on the PRISMA four-phase diagram (see Figure 1) (Takkouche and Norman, 2011), which embraces identification, screening, eligibility, and inclusion stages. In the identification stage, one of the authors of this research and the academic librarian conducted a scoping review using the Web of Science, Scopus, and Google Scholar databases. The reason for choosing these three databases is that they are the most popular and reliable in any research area. Also, these three databases cover a considerable number of publications in the related field. All journals in these databases select articles through a high-quality review procedure. The authors used institutional access to complete a search for the literature.

To conduct an initial search, we used Boolean operators AND/OR. First, we entered terms related to digital tools with the Boolean operator OR, as shown in Table 1. Then, we added terms related to the education level of students with the help of the AND operator. Lastly, using the AND operator again, we added educational term restriction parameters to our search list.

Furthermore, we set our inclusion and exclusion criteria as shown in Table 2. We decided to sort out publications by: (a) document type – in our research, we only focused on research articles, neglecting conference papers and book chapters. The reason for choosing only research articles is their high quality and reliability; (b) we included English articles published from 2019 to January 2025. The reason for choosing the period 2019–2024 is that technology in education is rapidly changing year by year; we aimed to cover the most recent papers that study technology-embedded mathematics education; therefore, we considered it reasonable to focus on this timeframe. (c) explicitly address teaching or learning strategies and plans, or provide detailed information on how to conduct courses or projects related to digital tools; and (d) be an empirical study that includes comprehensive descriptions of the research question, settings, participants, and results, or articles where digital tools in math literacy, attitude, motivation scales were developed.

2.2 Screening studies

The initial search using the above conditions led us to 316 publications in the Web of Science, Scopus, and Google Scholar databases. To ensure effective work, we combined all these publications and entered them into Zotero software[1]. We used Zotero software to remove duplicates and screened articles by Title, Abstract, and Keywords. After identifying a sufficient number of articles, we removed any possible duplicates and ended up with 308 articles in all databases. We considered these 302 articles for the screening process.

Here, we aimed to define appropriate literature and map it to provide a conceptual synthesis for future research. After the duplication removal procedure, an author and an external expert carefully selected publications based on Title, Abstract, and Keywords. Following the initial screening procedure, we identified 97 potential studies. While discussing the content of the research, our research team decided to remove 76 inappropriate studies. Among these 66 articles, 62 studies were review articles, and the other 10 studies were not related to digital tools for teaching and learning.

2.3 Coding, data extraction, and analysis studies

Finally, we chose 25 articles for the study. To extract data from 25 articles, we divided the studies by country, publication year, study design, school type, data measurement type, purpose of

1 https://www.zotero.org/

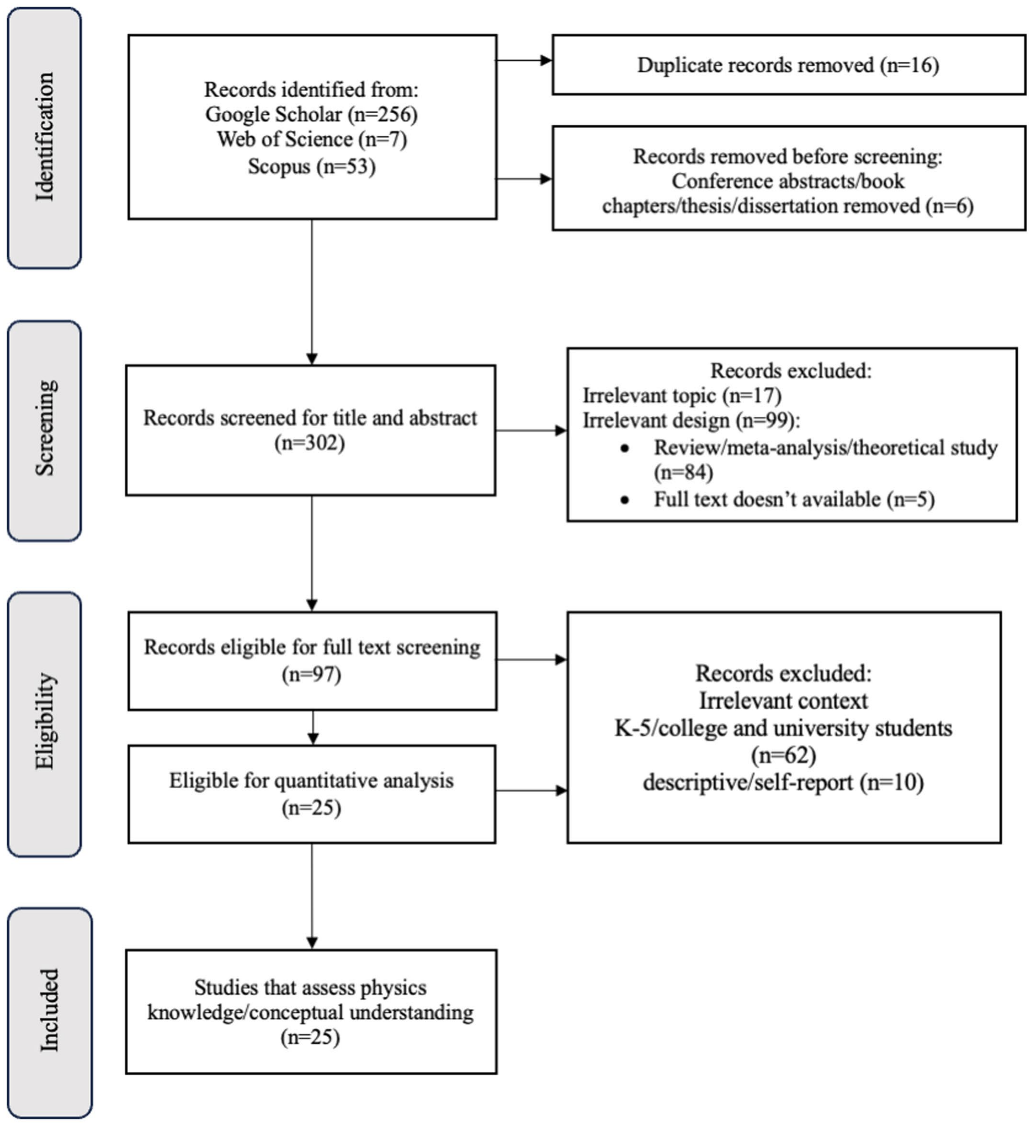

FIGURE 1
PRISMA flow diagram of the study.

measuring instruments, types of measuring instruments, and validity and reliability of the measuring instruments. To rectify the dataset in the included research, our team established categories for each section and determined the definitions of the categories (See Appendix A). To our convenience to shorten their title, we coded articles as it is shown in Appendix B. To segment the dataset, comprising all included research, all authors read each study and placed appropriate information for each research into spreadsheets separately; the three database sheets were integrated into one sheet (see Appendix C). This helped us to establish the inter-reliability of the analyzed data. In this stage, we could obtain inter-rater agreement on each research question with Cohen's kappa coefficient (0.85), which ensures good inter-rater reliability (Miles and Huberman, 1994). Cohen's kappa is a reliable way to measure how much two people (or systems) agree when rating or labeling the same items. The Cohen's kappa coefficient ranges from 0 to 1, where 1 indicates perfect agreement.

The selected 25 articles were qualitatively synthesized using the constant comparative analysis method proposed by Glaser (1965). For example, to classify the purpose of a measuring instrument, we first agreed on the different measurement types and selected samples for each to develop a scheme. After classifying the remaining articles based on the scheme, we calculated the interrater agreement.

3 Findings

3.1 Bibliometric and contextual characteristics of the studies

To highlight the background of the articles, we first sorted them by country (Figure 2), journal type (Table 3), publication year (Figure 3), and the grade level where technologies were implemented in mathematics classes (Figure 4), technology type used in Mathematics

TABLE 1 Search parameter applied in the study.

Topic	Code
Digital tools in teaching and learning mathematics	TITLE-ABSTRACT-KEY: "digital tools in learning math" OR "digital tools in teaching math" OR "educational technology in math" OR "technology-enhanced learning in mathematics" OR "technology-enhanced teaching mathematics" OR "math technology tools in education" OR "ICT in math" OR "technology used mathematics classroom" OR "evaluation of technology use in mathematics" OR "assessment of technology use in math" OR "Kahoot" OR "Desmos" OR "Padlet" OR "GeoGebra" OR "Quizlet" OR "Sketchpad" OR "Smart Board" OR "PhET Interactive Simulation" OR "Cabri Geometry" OR "Augmented reality" OR "AR"
Digital tools AND middle and high schools	"Middle school" OR "high school"
Digital tools AND middle and high schools AND Teaching and Learning	"Learning" OR "teaching" OR "Knowledge"

TABLE 2 Inclusion and exclusion criteria used in searching for empirical studies.

Inclusion criteria	Exclusion criteria
• Papers in English • Peer-reviewed journal articles • Involves middle school and high school teaching and learning • Using digital tools to perform a function in middle school and high school the context • Journals articles published between 2019 and 2025 • Focus on digital tools education or ICT T&L math • Explicitly address teaching or learning strategies and plans, or provide detailed information on how to conduct the courses or projects related to digital tools T&L • Be an empirical study that includes comprehensive descriptions of the research question, settings, participants, and results • Education area • Social sciences area	• Research that includes students in a K-5, college and university students setting only learning about what digital tools is and not using it for learning • Review, editorials and theoretical papers were excluded because they are not empirical studies • Journal articles published before 2019

Education (Table 4). This classification of the articles provides a clear understanding for evaluating the background characteristics of published papers, identifying the specific areas in which they were published, and determining which areas lack publications.

Figure 2 shows that in recent years, studies on technology use have been particularly relevant among researchers in Spain. Spanish researchers lead the bar chart with five published papers in the field. Turkey and China take the second place, each with three published papers in the last 5 years. Additionally, the figure indicates that researchers from other countries have each published one empirical article in the same period. Unfortunately, three articles did not explicitly mention the countries in which the research was conducted; therefore, we did not include them in the list.

Determining the appropriate journal for specific purposes is especially important. In particular, this helps researchers find a suitable journal for their future publications. Therefore, in our systematic review, we aim to highlight which journals have been chosen in the last 5 years for publishing empirical studies (Table 3). Among the different types of journals, we observe that two articles were published in Education Sciences and the International Journal of Emerging Technologies in Learning over the last 5 years. However, we would like to emphasize that the International Journal of Emerging Technologies in Learning, the British Journal of Educational Technology, Research and Practice in Technology-Enhanced Learning, the International Journal of Information and Education Technology, and Education and Information Technologies are appropriate venues for publishing studies related to educational technologies.

Sorting articles by publication year helps researchers evaluate the frequency of studies over time. From Figure 5, we can see that in the last year, the publication frequency tripled, reaching a total of eight empirical studies in 2024. Additionally, we notice that research activity in this field was high before the pandemic. As evidence, we observe that six empirical papers were published in 2019. We assume that many empirical studies were conducted before the pandemic, leading to an increased number of publications in 2019. Also, Figure 5 shows that publication frequency gradually decreased during the pandemic period and began to rise again in 2023.

To answer our research questions, we purposefully selected empirical studies conducted at the secondary and high school levels. Figure 3 shows that among the 25 selected articles, 8 studies were conducted at the middle school level, while 17 were conducted at the high school level. The data shows that the share of high school research is twice as large as that of middle school research.

In Table 4, we summarized the technologies and software used to support mathematics instruction. As the findings show, augmented reality is widely used in mathematics by practitioners. We also found that the online software Kahoot! is commonly used among secondary mathematics teachers. GeoGebra ranked third among the most frequently used technological tools in mathematics education. Finally, we observed that products such as SmartBoard and Desmos have been featured in studies on technology use in mathematics over the past 5 years.

3.2 Methodological and evaluation characteristics of the studies

In the methodological and evaluation characteristics section, we elaborate on the measurement strategies used to assess technology use in mathematics education. This section serves as the core of our paper, addressing our second research question: What were the methodological and evaluation characteristics of the studies on technology use in mathematics education, such as the research designs implemented, the reliability and validity of assessment tools, and the learning outcomes assessed?

Figure 4 presents the distribution of research methods used across the reviewed studies. It shows a strong preference for Mixed Methods, with 14 publications employing this approach. This suggests that researchers are increasingly combining both qualitative and quantitative data to provide a more comprehensive understanding of

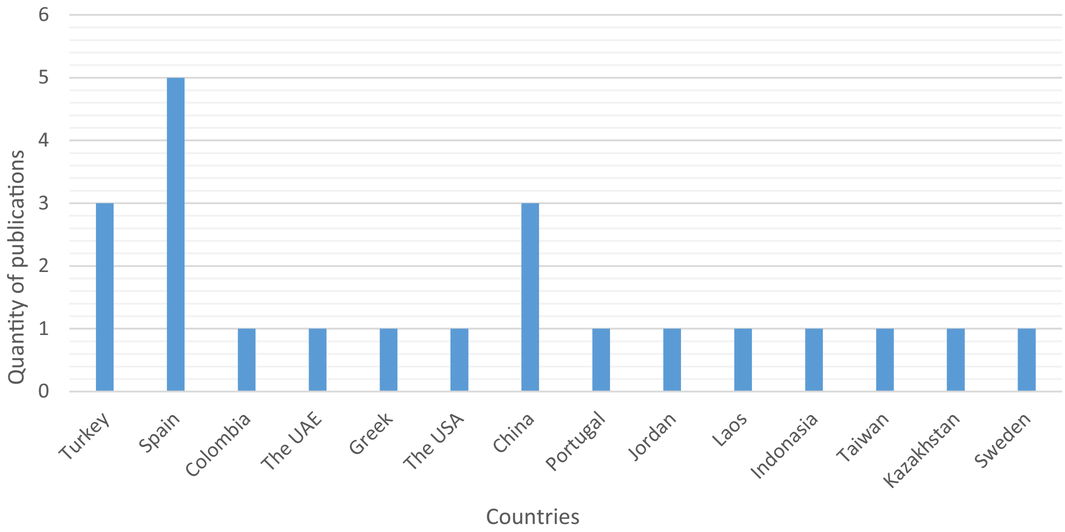

FIGURE 2
Articles categorized by country of study.

TABLE 3 Articles grouped by journal of publication.

Journals	No
MATHEMATICS TEACHING RESEARCH JOURNAL	1
Education and Information Technologies	1
International Journal of Evaluation and Research in Education (IJERE)	1
Journal of Education and Learning (EduLearn)	1
International Journal of Information and Education Technology	1
Research and Practice in Technology Enhanced Learning	1
Education sciences	2
Computers and Education	1
Electronic Journal of e-Learning	1
International Journal of Education in Mathematics, Science and Technology	1
Journal of Learning Disabilities	1
Mathematics	1
International Journal of Advanced Computer Science and Applications	1
British Journal of Educational Technology	1
INTERACTIVE LEARNING ENVIRONMENTS	1
KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS	1
Journal on Mathematics Education	1
Intelligence Augmented Reality Tutoring System for Mathematics	1
International Journal of Emerging Technology in Learning	2
HAL open science	1
Human Computer Interaction	1
QUBAHAN ACADEMIC JOURNAL	1
EURASIA Journal of Mathematics, Science and Technology Education	1

technology use in mathematics education. In contrast, Quantitative Methods were used in 10 studies, indicating a significant reliance on numerical data, statistical analysis, and measurement tools such as tests or surveys. Interestingly, no studies employed Qualitative Methods alone, highlighting a potential gap in the literature. This absence suggests an opportunity for future research to explore in-depth, context-rich insights through interviews, observations, or case studies.

Figure 6 represents the validity and reliability of the measurement instruments used to assess students' perceptions of technology use in mathematics (Figure 4). We categorized a tool as validated if the original research reported that the measurement scales were validated. We considered a tool reliable if the research included checks for the reliability of the measurement scales. Finally, we categorized studies as using adopted validated scales if the research employed measurement tools that had been previously validated in other studies.

So far, we have identified 22 studies that implemented valid measurement tools, suggesting that many researchers are grounding their instruments in established frameworks and ensuring conceptual soundness. Additionally, we found that in three studies, instruments for measuring students' learning outcomes were developed by adopting validated scales from previous research. This suggests that many researchers still develop their tools, which can be beneficial for contextual relevance, but may also reduce comparability and increase the risk of construct ambiguity if not properly validated. Finally, we observed that only 16 studies explicitly described the reliability of the instruments used in their research. However, nine studies did not clearly indicate whether their instruments were reliable or not.

As Table 5 shows, the Pre-Post-Test was the most frequently used measurement tool, appearing in 20 articles (e.g., A1, A3–A6, A8–A16, A18, A20–A22, A24–A25), indicating a strong emphasis on evaluating learning gains or instructional impact. Questionnaires were also widely used in 17 studies, highlighting their popularity for capturing student or teacher perceptions. Surveys were implemented in 14 studies, often overlapping with questionnaires, and commonly used for large-scale data collection. Artifact Analysis was employed in 19 articles, indicating a strong interest in examining student work,

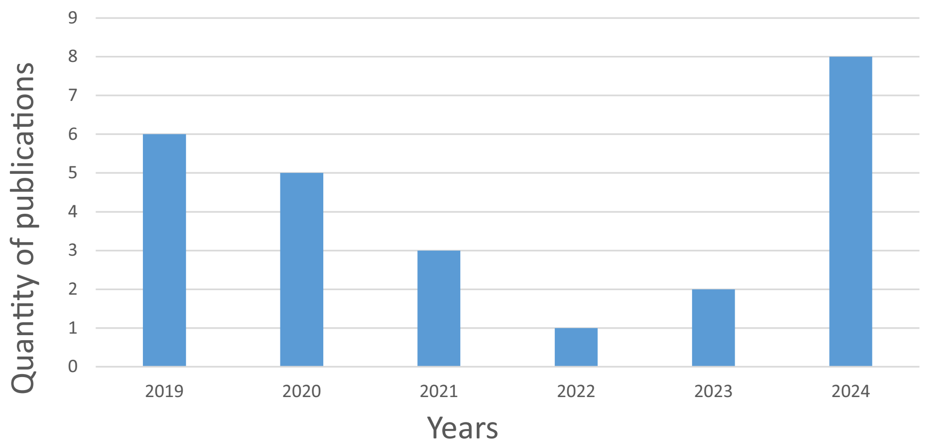

FIGURE 3
Articles organized by year of publication.

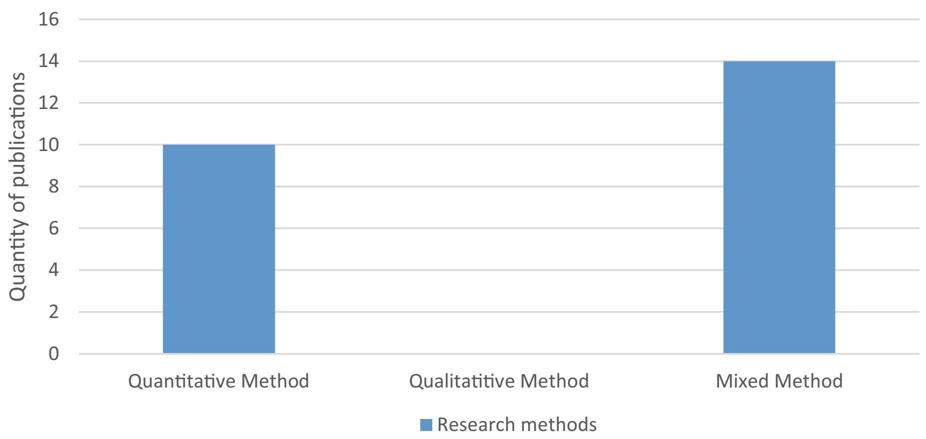

FIGURE 4
Articles organized by research design.

lesson plans, or digital traces to evaluate educational processes. Interviews appeared in 10 articles, showing a commitment to gaining deeper, qualitative insights into participants' perspectives. Post- or End-tests were found in 12 articles, used to assess final learning outcomes or retention. Performance Assessments were included in 9 studies, focusing on practical or applied demonstrations of student learning. Classroom Observations were conducted in 6 articles, providing direct insights into classroom practices and technology integration. Process Observations appeared in 8 studies, capturing dynamic, real-time data during instruction or learning activities. Finally, we want to mention that all definitions of the terms used in this paragraph are provided in Appendix A.

The reviewed studies examined a range of student learning outcomes associated with the use of technology in mathematics education (Table 6). The most frequently assessed outcome was students' understanding, appearing in 16 studies, highlighting the field's emphasis on conceptual learning. Motivation (18 studies) and problem-solving skills (11 studies) were also prominent, reflecting a focus on both affective engagement and cognitive application. Engagement was addressed in 12 studies, followed closely by interest and visualization skills (10 studies each), suggesting that researchers value both emotional involvement and visual thinking in math learning. Enjoyment (4 studies), spatial ability (4 studies), and academic performance (3 studies) were also measured, though less frequently. Less commonly explored outcomes included cooperation and teamwork (2 studies), student retention of math formulas (1 study), and students' perceptions and attitudes (2 studies). Interestingly, the effectiveness of instruction was listed but not directly represented in the coded articles, suggesting an area for future inquiry. Overall, the findings show a strong research interest in how technology influences students' understanding, motivation, and problem-solving, with growing attention to emotional and collaborative aspects of learning.

4 Discussion

4.1 Discussion of the key findings

In this section, we discuss the research gaps identified through the results of the systematic literature review. By synthesizing the findings, we identified several prominent gaps in the literature on technology use in secondary and high school mathematics education. First, a significant number of countries, particularly in Africa, Central Asia, and Latin America, are underrepresented. Second, high school-level content is more frequently studied than middle school content. Third, there is a lack of qualitative and longitudinal studies. Fourth, there is a need for developing and validating measurement tools across diverse settings to ensure comparability and rigor. Fifth, some learning outcomes, such as retention, attitudes, and teamwork, are rarely assessed.

TABLE 4 Articles sorted by technology type used in Mathematics Education.

Application	Article code number
GeoGebra	A1, A2, A3, A4
Desmos	A25
Kahoot!	A5, A6, A7, A8, A9
SmartBoard	A10
Augmented reality	A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24

Key findings about the underrepresentation of technology use in mathematics education in countries from Africa, Central Asia, and Latin America can be linked to the economic development of these regions (Selwyn, 2012). Selwyn (2012) argues that socio-economically developed countries are more likely to integrate technologies in education, whereas countries with lower socio-economic status remain underrepresented. As he notes:

> "Much of what is known about the use of digital technologies in education is derived from a small number of affluent, Anglophone countries" (p. 23).

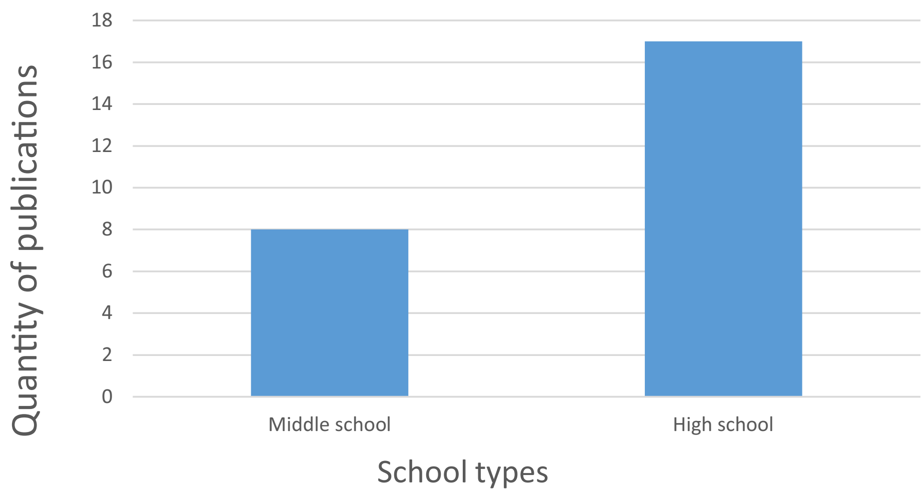

FIGURE 5
Articles organized by grade level.

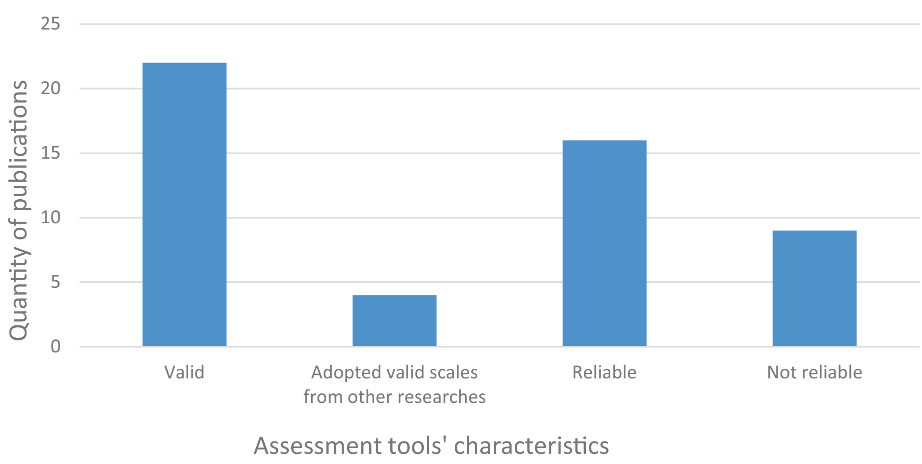

FIGURE 6
Articles organized by assessment tools' reliability and validity.

TABLE 5 Articles organized by types of measurement instruments.

Data	Article code number
Classroom observation	A1, A2, A4, A18, A20, A22
Survey	A7, A8, A9, A11, A12, A13, A15, A16, A17, A18, A19, A22, A24, A25
Pre-post test	A1, A3, A4, A5, A6, A8, A9, A10, A11, A12, A13, A14, A15, A16, A18, A20, A21, A22, A24, A25
Interview	A2, A3, A8, A9, A10, A12, A16, A18, A19, A22
Artifact analysis	A1, A2, A4, A6, A9, A11, A12, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24, A25
Post or end-test	A5, A7, A8, A12, A13, A14, A15, A18, A20, A21, A22, A24
Performance assessment	A1, A3, A5, A11, A12, A18, A22, A24, A25
Questionnaire	A2, A5, A6, A7, A8, A9, A11, A12, A13, A15, A16, A17, A18, A19, A22, A24, A25
Process observation	A1, A2, A3, A11, A12, A18, A20

TABLE 6 Articles organized by students' learning outcomes.

Conclusions of reviewed studies	Article code number
Students' engagement	A1, A8, A9, A12, A13, A16, A17, A18, A19, A20, A22, A25
Students' enjoyment	A9, A11, A13, A22
Visualization skill	A5, A12, A13, A14, A15, A16, A17, A21, A22, A23
Students' interest	A3, A6, A7, A8, A11, A13, A14, A18, A19, A22
Students' understanding	A2, A3, A4, A5, A7, A12, A14, A15, A16, A17, A18, A19, A20, A23, A24, A25
Cooperation and teamwork	A1, A2
Students' academic performance	A1, A11, A19
Spatial ability	A12, A16, A17, A22
Students' motivation	A2, A3, A5, A6, A7, A8, A9, A10, A12, A13, A15, A16, A17, A18, A19, A20, A23, A25
Student retention (help to recall math formulas)	A20
Problem-solving skills	A2, A11, A14, A15, A16, A18, A19, A20, A21, A23, A25
Students' perception and attitude	A12, A15

However, the limited implementation of technology use in education may stem from various factors, not solely from the socioeconomic status of countries or schools. Tondeur et al. (2017) found that factors such as school culture, language barriers, inadequate technological infrastructure, and peer conversations about technology use in the classroom also influence teachers' motivation to implement technological tools in their teaching.

The finding that high school-level content is more frequently studied than middle school content can be explained from several interrelated perspectives. Here, we elaborate on a few key reasons that may account for this trend. One major factor is the complexity of the mathematics curriculum at the high school level. High school students engage with more advanced topics such as algebra, geometry, calculus, and statistics—subjects that may be perceived as more suitable for technology-enhanced instruction (Pierce and Stacey, 2010). Another reason is that high school students are generally more technologically literate and familiar with digital tools (Zbiek et al., 2007). This makes it easier for educational researchers and practitioners to implement technology-based interventions in their studies and classroom practices.

The lack of qualitative and longitudinal studies limits our understanding of the nuanced, contextual, and evolving nature of technology use in classrooms. Although mixed-method and quantitative research approaches help us explore the field and explain certain phenomena, longitudinal qualitative studies provide a broader and more sustained understanding of the subject matter (Mantula et al., 2024). The limited number of such studies may be attributed to their complex and demanding nature. Qualitative research is often time-consuming and requires significant mental and organizational resources to conduct effectively (Creswell and Poth, 2016).

While analyzing our findings, we emphasize the importance of developing and validating measurement tools across diverse settings to ensure comparability and rigor. Several existing studies that propose the development of valid measurement tools tend to focus primarily on specific contexts, often overlooking the significance of cross-cultural, linguistic, and socio-cultural environments (Tondeur et al., 2017). Developing a standardized and adaptable instrument can facilitate more rigorous and generalizable research. However, the process of developing a valid tool is not straightforward. The complexity of the validation process arises from the need for pilot testing, factor analysis, and repeated trials across varied contexts.

Finally, we discovered that certain learning outcomes, such as retention, attitudes, and teamwork, are seldom assessed. This conclusion came from analyzing the papers in our review, especially those with a longitudinal focus. Some studies mention that using technology in mathematics education can help students remember formulas and concepts. However, even when retention is noted, most studies do not explain how technology supports it, nor do they make it a main focus of their research. This gap may be due to the difficulties of measuring retention over time, which requires more time and resources (Berliner, 2002). Similar methodological issues might also explain why there are few studies on students' teamwork and collaboration.

4.2 Discussion of thematic synthesis of trends

In this section, we identified five major thematic trends that emphasize the transformative role of digital technologies in improving students' learning outcomes, engagement, and learning practices.

Among the most frequently used technologies in mathematics education, we found Augmented Reality (AR) as a trend in the field. AR supports students' visualization as they engage with complex mathematics and geometry problems. Research has shown that, with the use of AR, students can better understand complex concepts that require visualizing shapes of figures and relating mathematical expressions to geometrical characteristics. These findings were also reported by Bulut and Borromeo Ferri (2023) in their systematic review of AR in mathematics education. Aligned with our findings, Bulut and Borromeo Ferri (2023) stated that AR improves understanding, enhances spatial intelligence, and provides concrete examples of mathematical concepts, supporting collaborative learning. However, we also observed that high engagement does not always lead to knowledge gains. Challenges include technical barriers (Fernández-Enríquez and Delgado-Martín, 2020), inequitable access (Thamrongrat and Law, 2019), and varying levels of students' self-efficacy (Cai et al., 2019).

The second trend is the use of GeoGebra as a tool for supporting mathematical reasoning and assessment. In particular, many practitioners have used GeoGebra to enhance students' algorithmic thinking (Carriazo Regino et al., 2024), trigonometric understanding (Rosyidi et al., 2024), and mathematical communication. However, limitations remain in its integration into lower education levels and its effectiveness for individualized learning (Siswanto et al., 2024).

The third trend is the use of gamification through platforms such as Kahoot and Quizizz. Kahoot is recognized as an effective tool for fostering students' motivation, collaborative learning, and academic performance. Its main function is to provide instant feedback through an interactive, competitive, and collaborative assessment platform (Balaskas et al., 2023). However, some studies claim that the competitive elements may cause stress, and platforms such as Quizizz are found to be more effective for providing feedback.

As a fourth trend, we identified the use of Smart Boards and digital tools to facilitate interactive instruction. Studies indicate that these tools enhance students' understanding of mathematical concepts through collaborative interactions with peers and instructors. However, research also highlights that the effectiveness of these technologies in improving student learning outcomes is directly correlated with teachers' ability to successfully integrate them into their instructional practices (Akar, 2020).

The final technology use trend in mathematics education identified in this study is the use of Desmos, which supports students' understanding of functions and graphs. This tool is effectively used in middle and high school curricula to simplify complex mathematical concepts, providing students with a positive learning experience through the visualization of abstract ideas. However, we observed that existing research is largely limited to localized contexts, highlighting the need for broader studies and integration with other digital tools to provide a more comprehensive learning experience (Akar, 2020).

4.3 Discussion of the effect of technology use in mathematics education on conceptual shift in pedagogy

Many studies in the field examine the effectiveness of certain technologies in mathematics education, assessing their impact on student learning, engagement, motivation, collaboration, and more. However, some of these interventions depict technology merely as a tool that replaces traditional teaching resources without changing the underlying pedagogical models. For example, Kahoot is often used to substitute paper-based quizzes with interactive formats, without altering the teaching strategies of mathematics instructors (Balaskas et al., 2023). Similarly, smart boards are frequently used as interactive versions of traditional blackboards, maintaining a teacher-centered approach (Akar, 2020).

In contrast, we have identified technology interventions in mathematics education that contribute to a deeper conceptual shift in pedagogy. For instance, Augmented Reality (AR) shows promise in connecting students' traditional learning approaches with their everyday life experiences, thereby facilitating a culturally relevant learning environment (Anhalt et al., 2018). Likewise, GeoGebra fosters students' collaborative inquiry, supports peer-based investigations, and helps shift the focus from teacher-centered to student-centered instruction. Thus, we argue that the effectiveness of technology should not be limited to replacing traditional resources. It must also address broader contextual issues, such as connecting the classroom atmosphere with students' lived experiences, supporting meaningful cognitive engagement, enabling teachers to become facilitators, and addressing equity and contextual challenges.

4.4 Discussion of the content from the educational theory lenses

As mentioned in the introduction, our primary goal was to examine the age appropriateness of using technology in mathematics education, which we aligned with Vygotsky's Zone of Proximal Development (ZPD) theory (Chaiklin, 2003). Vygotsky's ZPD refers to the difference between what students can accomplish independently and what they can achieve with the help of instructors or peers, emphasizing the role of social interaction (Silalahi, 2019), scaffolding (Wass et al., 2011), and mediated learning (Fadeev, 2019).

Among the reviewed studies, we found that Augmented Reality (AR) applications align well with the principles of Vygotsky's ZPD. AR helps scaffold complex mathematical problems by reducing students' overreliance on proportionality and offering interactive, step-by-step problem-solving strategies (Arican and Özçakir, 2021). We also found that GeoGebra can serve as a mediated learning tool, providing students with interactive visualizations and real-time feedback to collaboratively explore and understand complex mathematical concepts. For example, in the work of Carriazo Regino et al. (2024), the authors found that GeoGebra improves students' reasoning, argumentation, and problem-solving skills, which are developed through guided exploration and peer discussion, both central to Vygotsky's ZPD theory. Moreover, Desmos enables students to manipulate functions and graphs, supporting exploratory learning. This type of learning is especially helpful for students' memory, understanding, and creative thinking, as teachers or digital scaffolds help them move from concrete to abstract reasoning within their ZPD (Chechan et al., 2023). Finally, digital tools also facilitate peer-to-peer learning, with students acting as more knowledgeable others—another core principle of the ZPD framework.

4.5 Discussion of the implications for educational policy and curriculum development

Summarizing the findings from the studies included in this systematic review, we propose several implications. The digital technologies reviewed in this paper have the potential to transform mathematics education. Realizing this potential, however, requires coordinated efforts in policy reform and curriculum innovation.

Policymakers should develop programs that empower teachers through robust professional development. We reached this conclusion recognizing that, to effectively implement digital technologies in classrooms, teachers must be able to facilitate deeper student learning rather than simply replacing traditional teaching tools with digital ones. Training should go beyond basic tool usage and include strategies for technology-enhanced instruction, assessment design, and student-centered learning. Integrating such content into both pre-service and in-service teacher education is essential—a point also emphasized by Akar (2020). Moreover, the integration of digital devices requires targeted investments in infrastructure, device access, and internet connectivity. This conclusion is based on our finding that some low-income countries remain underrepresented in the field due to limited technological resources.

Educational researchers should focus on developing longitudinal and comparative studies to evaluate the long-term impact of technology integration on student achievement, motivation, retention, attitudes, and teamwork. Additionally, we identified a gap in the existing literature regarding technology use in mathematics that encourages cross-cultural and multi-context studies to better understand how technology impacts learning across diverse educational systems. Researchers should also support policy-relevant studies that explore the cost-effectiveness, scalability, and sustainability of technology integration.

5 Conclusion

In this systematic literature review, we analyzed empirical studies on the use of technology in mathematics education at the secondary and high school levels. To find relevant literature, we conducted a comprehensive search in three major academic databases: Web of Science, Scopus, and Google Scholar. To systematize our literature search, we followed the PRISMA flow diagram. From an initial pool of over 300 articles identified across the three databases, we ultimately selected 25 relevant empirical studies.

Our findings indicate that many countries, especially in Central Asia, Africa, and Latin America, remain underrepresented in research on the use of technology in mathematics education over the past 5 years. This emphasizes the need for more empirical studies spanning different geographic regions. The findings reveal that while digital technologies—such as Augmented Reality, GeoGebra, Desmos, and Smart Boards —have demonstrated strong potential to enhance students' learning, engagement, and conceptual understanding, their implementation across global contexts remains uneven. Additionally, high school-level content is studied more often than middle school content. There is also a clear lack of qualitative and longitudinal studies. Moreover, developing and validating measurement tools across various settings is necessary to ensure comparability and rigor. Finally, some learning outcomes, such as retention, attitudes, and teamwork, are seldom assessed.

The thematic synthesis highlighted a shift from viewing technology as a simple substitute for traditional tools to recognizing its transformative role in reshaping pedagogy. Technologies like AR and GeoGebra promote student-centered learning, collaborative inquiry, and real-time feedback, aligning closely with Vygotsky's Zone of Proximal Development (ZPD). These tools support not only content mastery but also the development of reasoning, problem-solving, and peer learning skills.

Realizing the full potential of educational technology requires coordinated policy efforts, including substantial investment in teacher professional development, digital infrastructure, and inclusive curriculum design. It also necessitates a research agenda that prioritizes cross-cultural, longitudinal, and policy-relevant studies. Future research should move beyond tool effectiveness to examine the broader socio-cultural, pedagogical, and institutional conditions that shape meaningful technology integration in mathematics education.

As a final remark, we would like to highlight a key limitation of this study. The most significant limitation is the exclusion of recent research related to artificial intelligence in mathematics education. This decision was made due to limited resources and our intention to maintain a manageable scope. Additionally, we restricted our review to empirical studies published within the last 5 years.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZD: Supervision, Writing – original draft, Software, Formal analysis, Investigation, Project administration, Methodology, Resources, Visualization, Data curation, Conceptualization, Validation, Writing – review & editing. AA: Writing – review & editing, Validation, Software, Methodology, Formal analysis, Writing – original draft, Resources, Project administration, Data curation, Investigation, Supervision, Conceptualization, Visualization. ZN: Data curation, Software, Investigation, Resources, Conceptualization, Writing – review & editing, Formal analysis, Project administration, Writing – original draft, Visualization, Methodology, Supervision, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that Generative AI was used in the creation of this manuscript Please note that during the preparation of this paper, we used ChatGPT to correct the grammar of the text. After using this tool/service, we reviewed and edited the content as needed and take full responsibility for the originality of the paper. The prompt we used in ChatGPT was: "Please correct the grammar of the text."

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1644284/full#supplementary-material

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