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Exploring research trends of technology use in mathematics education: A scoping review using topic modeling

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Abstract

This study performed a scoping review of the literature concerning the use of technology in mathematics education published between January 1981 and March 2022 to explore research trends. After the defined filtering process, we retrieved 2,433 articles from *Web of Science*, *ERIC*, and *PsycInfo* databases and employed Latent Dirichlet Allocation (LDA) topic modeling to extract key terms and topics from the selected articles. The analysis focused on the four aspects: (a) evolution of research trends of technology use in mathematics education, (b) frequently used words, (c) latent research topics, and (d) research trends for particular topics. The findings revealed a steady increase in research interest, and the combination of frequently used words in the article abstracts suggests popular research topics that have been studied during the set period. The results of LDA identified seven research topics that were not precisely aligned with those identified in prior studies on mathematics education or educational technology. This implied technology integration into mathematics education as a distinctive research area. Over time, the seven topics showed different research trends (stable, fluctuating, increasing, and decreasing). We discussed plausible reasons for these varied patterns and proposed implications based on the research findings.

Keywords Latent Dirichlet Allocation · Research trends · Scoping review · Technology use in mathematics education · Topic modeling

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1 Introduction

Human life and society have changed as a result of technological development. Technological devices and apps have affected how people learn, communicate, work, and interact with each other (Chen et al., 2020; Kenski, 2008). In addition to these societal changes, especially the increase in distance education due to the COVID-19 pandemic, it would be safe to say that the use of technology in education is no longer a choice but an essential tool for suitable educational development (Kimmons, 2020). The introduction and expansion of technology in education have tremendously changed the educational environment. It has transformed not only curricula, educational resources, textbooks, and classroom environment but also teacher instructional practices and student learning styles (Akapame et al., 2019; Chen et al., 2020; Clements et al., 2013; Hoyles, 2018; Ozyurt & Ayaz, 2022; Roschelle et al., 2017), which led to different student achievement, motivation, and attitudes (Bicer & Capraro, 2016; Higgins et al., 2019).

Mathematics education is not an exception. In 1980, The National Council of Teachers of Mathematics (NCTM) proposed an agenda for the development of mathematics education and highlighted the importance of using technological tools (e.g., calculators and computers) in mathematics teaching and learning at all grade levels. Moreover, NCTM (2014) reported that the use of technology could improve teachers' instructional quality and student mathematics learning, which assists in achieving educational equity. In this perspective, researchers in mathematics education have conducted various studies to examine features, opportunities, challenges, methods, resources, implementation, and outcomes of technology use in mathematics education. For example, the *Third International Handbook of Mathematics Education* (Clements et al., 2013) extensively explained how the use of technology influences mathematics curriculum, teaching, learning (e.g., modeling, reasoning, and algebra), and assessment. Such efforts have changed the entire landscape of mathematics education (Hoyles, 2018; Roschelle et al., 2017).

In response to the popularity and importance of technology use, diverse literature reviews were conducted in mathematics education. The topics covered both general educational technology, such as artificial intelligence (Hwang & Tu, 2021), educational robotics (Zhong & Xia, 2020), tablets (Svela et al., 2019), and mathematics-specific technology, such as GeoGebra (Yohannes & Chen, 2021) and graphing calculators. Furthermore, researchers have reviewed mathematics teachers' technological pedagogical and content knowledge (TPACK; Zou et al., 2022) and the effectiveness of technology use in mathematics achievement (Cheung & Slavin, 2013).

These studies provided information on the current status of technology use in mathematics education and directions for future studies. However, most review studies have examined research trends on a particular topic. Thus, we still have limited information on overall research topics on technology use in mathematics education and how they have evolved. Previous studies have analyzed less than 100 articles with manual coding methods to synthesize previous studies, which might lead to inaccurate outcomes due to a prolonged process and an insufficient number of articles (Chen et al., 2020; Yin & Yuan, 2022). Kimmons (2020) emphasized the importance of reliable review studies revealing research trends of technology in education. However, only a few studies have extensively examined what research topics have been examined and how they evolved regarding technology use in mathematics education.

This study aims to fill this gap and synthesize relevant studies on the use of technology in mathematics education published in the last four decades (1981–2022) after the publication of the NCTM's (1980) document. We employed topic modeling to automatically analyze a large corpus of text data to efficiently examine a large volume of articles (Blei, 2012). The findings of this study could provide information on past and present research trends of technology use in mathematics education and directions for future studies.

2 Literature review

To enlighten readers about what mathematics educators have researched, we first provided the research trends in mathematical education. Then, we discussed research trends of overall educational technology, which might provide insight regarding the research trends of technology use in mathematics education. Additionally, we reviewed literature that utilized topic modeling that informed the data analysis approach in our study.

2.1 Research trends in mathematics education

Researchers have synthesized peer-reviewed articles to identify research trends in mathematics education (e.g., Foster & Inglis, 2019; Gökçe & Güner, 2021; Inglis & Foster, 2018). These studies have found several domains consisting of dozens of topics. For example, Inglis and Foster (2018) examined articles published in two leading mathematics education journals (*Educational Studies in Mathematics* and *Journal for Research in Mathematics Education*) between 1968 and 2015 and employed topic modeling. They identified 28 topics across four domains. The domains included mathematical content (e.g., algebra and geometry), mathematical process (e.g., proof and argument), teaching and learning environments (e.g., teachers' knowledge and beliefs, reform curriculum, and novel assessment), and hard cores and heuristics (e.g., research theory and methods). They reported that topics about algebra, proof and argumentation, teachers' knowledge and beliefs, reform curriculum, classroom discussion, and sociocultural theory had received increasing attention. In contrast, the interest in geometry, constructivism, and experimental design topics has declined over time. Later, Foster and Inglis (2019) analyzed two mathematics education journals in the UK *(Mathematics Teaching* and *Mathematics in School*). They again reported similar findings.

Similarly, Gökçe and Güner (2021) examined 1,021 mathematics education articles published between 1980 and 2019. They found the following four research domains: foundation (e.g., theory, perspective, and standard), implementation (e.g., effect, performance, and intervention), association (e.g., science, technology, and grade), and evaluation (e.g., success, policy, and program). They also reported that the research focus has shifted from individual student learning and generalization to curriculum and teacher-related factors, equity, and cognitive and affective skills (e.g., motivation, attitude, and self-efficacy).

These research trends can be explained by a paradigm shift in mathematics education (Bray & Tangney, 2017; Gökçe & Güner, 2021; Stinson & Bullock, 2012). In the early stage, mathematics education researchers focused on examining the effect of a certain program in predicting student achievement with quasi-experimental methods. However, with the demise of the process–product movement, researchers have paid more attention to examining individual students' problem-solving. Various studies have been conducted to understand how students construct new knowledge and reorganize the existing knowledge (Bray & Tangney, 2017; Inglis & Foster, 2018). Moreover, with the effect of sociocultural theory (Vygotsky, 1986), researchers have examined the effects of sociocultural factors and classroom environments on mathematics teaching and learning processes (Inglis & Foster, 2018). The topic included classroom discourse and norms (Yackel & Cobb, 1996), curriculum materials (Remillard, 2005), teacher knowledge (Ball et al., 2008), student background and identity (Hand & Gresalfi, 2015), and technology (Drijvers, 2015).

The reform movement in mathematics education has also affected the research trends. The reform movement asked mathematics teachers to shift from traditional teacher-centered instructional practices into student-centered ones (Munter et al., 2015; Schoenfeld, 2004). Drills and exercises based on behaviorism were deemphasized in mathematics classrooms, whereas student autonomy, conceptual understanding, investigations, discussion, and cooperation were emphasized (Munter et al., 2015; NCTM, 2014; Schoenfeld, 2004). Therefore, teachers are expected to teach mathematical content and processes (e.g., problem-solving, reasoning and proof, communication, connections, and representations), which improve students' mathematical competencies (NCTM, 2014). In this process, educational technologies were extensively introduced in mathematics education to support mathematics teaching and learning (Hoyles, 2018). For example, dynamic geometry software (e.g., Cabri and Sketchpad) and mathematical apps could support students' investigation and help them examine and compare various mathematical ideas (Drijvers, 2015).

2.2 The roles of technology use in mathematics education

Mathematics educators have highlighted that mathematical technology should be integrated into mathematics education (Association of Mathematics Teacher Educators [AMTE], 2022; NCTM, 2014). Trends in International Mathematics and Science Study researchers have emphasized using various types of technology for mathematics teaching and learning, such as interactive whiteboards, internet, apps, calculators, computers, and smart tables (Mullis & Martin, 2017). Moreover, from a practical perspective, researchers in OECD countries (2019) reported that technology should be stressed in school mathematics as most workplaces are required to use technological tools.

The introduction of technology in mathematics education transforms mathematics teaching and learning environments (Clements et al., 2013; Roschelle et al., 2017). Students could investigate conceptual knowledge, practice problems, justify mathematical ideas, and communicate with their peers and teachers using various technology tools (Higgins et al., 2019; Roschelle et al., 2017). Thus, Cullen et al. (2020) proposed four roles of technology use in mathematics education, including supporting proof, presenting, and relating representations, enhancing reasoning, and working as a tutee.

Similarly, Drijverse (2015) examined student learning and proposed the following three didactical functions of technology use in mathematics education: doing mathematics, practicing skills, and developing conceptual understanding. Doing mathematics indicates using technology to outsource works that could be done by hand (e.g., drawing a figure and doing simple computation). The technology for practicing mathematics refers to using technology to improve speed, accuracy, and proficiency of mathematical skills and providing instructions and feedback to support mathematics learning (e.g., online-tutoring system). The technology for developing conceptual understanding provides students with more autonomy and flexibility in the construction of mathematical knowledge. Examples of this type of technology are dynamic geometry software, such as Cabri, Desmos, Geogebra, and Sketchpad. Later, Roschelle et al. (2017) proposed another category regarding the roles of technology in mathematics education: the context for interest-driven mathematics. This technology is designed to enhance students' motivation and interest in mathematics learning, such as 3D printers, games, and Lego Mindstorms. However, using technology in the mathematics classroom is affected by technology type and knowledge, beliefs, and curriculum (Akapame et al., 2019; Gökçe & Güner, 2021; NCTM, 2014). Thus, researchers have also examined how those factors facilitate or hinder using technology in mathematics education (e.g., Hu et al., 2020; Radmehr & Goodchild, 2022).

2.3 Research trends in educational technology

The research trends of educational technology have shown a shift from studies on individual student learning and assessment to studies on collaboration and new learning strategies with emerging technology. Zawacki-Richter and Latchem (2018) examined articles published in *Computers and Education* between 1976 and 2016. They reported that the research trends have changed across four stages: computer-assisted teaching, stand-alone multimedia learning, network computer use for collaboration, and online learning. Chen et al. (2020) examined the 50 years (1971–2018) of research trends in *the British Journal of Educational Technology (BJET)* with topic modeling. They found that topics related to student collaboration (e.g., online social communication and socialized e-learning) and emerging technologies (e.g., mobile-assisted language learning and game-based learning) have received increasing attention over time.

Tatnall and Fluck (2022) examined articles published in *Education and the Information Technologies (EAIT).* They reported the following research trends: evaluation and software (1996–2000), case study and pedagogy (2001–2005), collaboration and learning efficacy (2006–2010), the emergence of e-learning (2011–2015), and mobile and blended learning (2015–2020). Similarly, Ozyurt and Ayaz (2022) analyzed research trends in the *EAIT* journal and reported that technology acceptance and social network-based learning were the most studied topics during the past 25 years. Additionally, the gamification topic showed the highest acceleration rate in popularity.

Unlike studies examining research trends in a journal, Kimmons (2020) analyzed 7,708 educational technology articles published between 2015 and 2019. Kimmons found that current studies have focused on three topics: (a) learning environments as modalities (e.g., mobile, flipped, and online learning), (b) achieving learning goals of school subjects (e.g., language learning and mathematics), and (c) using emerging technology for educational purposes (e.g., augmented reality [AR] and virtual reality [VR]). Similarly, Dağhan and Gündüz (2022) examined 10,386 articles in educational technology journals published during 2000–2018 and reported that interactive learning environments were the most frequently used keywords, followed by teaching/learning strategies, higher education, online learning, and e-learning. Moreover, flipped classroom, social media, and game-based learning keywords showed a considerable increase over time.

2.4 Topic modeling

Topic modeling is one of the analytical methods in text mining methodology. Computer scientists created this natural language processing technique, and social scientists have used topic models to understand certain phenomena in the world through the text people have written (Ramage et al., 2009). Topic modeling is a statistical model where topics are treated as latent variables. Each document includes multiple sets of words that have underlying topics. The topic modeling provides a set of words that frequently co-occur with each topic, and a topic represents a recurring pattern in which the words co-occur (Blei, 2012; Yin and Yuan, 2022). While topic modeling is an automated process, researchers label the topic names based on the results of data analysis. Thus, topic modeling is an amalgam of objective data analysis and subjective data labeling processes (Hwang & Cho, 2021). Latent Dirichlet Allocation (LDA) is one of the widely used methods for exploring topic models because LDA is a powerful method for generating a probabilistic model to discover a topic from the corpus (Blei, 2012; Yin & Yuan, 2022).

A scheme of the LDA algorithm with mathematical notations can be addressed as follows. First, creating a topic starts with choosing the collection of documents (i.e., corpus D) to be analyzed. Each document (d) consists of words (N). The observed nth word in document d can be detected ($W_{d,n}$). The LDA algorithms set two hyperparameters (α and η) that act as a prior to the posterior calculation. The α parameter is a Dirichlet parameter for a document-topic density specifying prior beliefs about topic uniformity and sparsity within documents. The η parameter is a representative of topic-word density. This parameter specifies prior beliefs about word uniformity and sparsity within topics. This LDA algorithm assumes that each document displays the topics in different proportions (θ_d). Each word in the document is chosen from one of the topics ($Z_{d,n}$). After repeating this topic generation in each document, researchers obtain document-topic probability distributions (β_k) and topic-per-word probability distributions (θ_d). While these processes provide a probabilistic model, researchers need to determine how many numbers of topics are optimal to represent the dataset. Thus, researchers should decide the optimal number of topics (*k-number*) based on the perplexity value. The lower perplexity value indicates a better model fit (Blei, 2012; Nikita, 2020).

2.5 The current study

Several review studies have been conducted to examine the research trends of technology use in mathematics education (e.g., Zhong & Xia, 2020). However, these studies have examined the research trends of limited topics with a small number of articles. Therefore, as a scoping review, this study collected articles regarding the use of technology in mathematics education after the publication of the NCTM (1980) document and synthesized them. Scoping reviews refer to exploratory research that aims to “determine the scope or coverage of a body of literature on a given topic and give clear indications of the volume of literature and studies available” (Munn et al., 2018, p. 2). Thus, scoping reviews address broad research questions and are helpful in systematically analyzing a wide range of extant work to assess the extent of the available evidence and highlight gaps (Arksey & O’Malley, 2005; Major et al., 2018; Munn et al., 2018). Arksey and O’Malley (2005) proposed a framework to conduct scoping reviews: (1) identifying research questions, (2) identifying related literature, (3) collecting studies, (4) charting the collected data, and (5) synthesizing, summarizing, and reporting the findings. Following this framework, the sections below describe how we collected, analyzed, charted, and synthesized data and what the major findings of this study were. Moreover, this study used topic modeling which helps us to identify latent research topics and examine how they evolve, which might not have been discussed in previous studies (Blei, 2012; Chen et al., 2020; Yin & Yuan, 2022). The research questions of this study are as follows:

Q1. How did overall research trends of technology use in mathematics education evolve?
Q2. Which words were frequently used in previous studies?
Q3. What were the latent research topics?
Q4. What were the research trends for individual topics?

3 Methodology

3.1 Data collection and retrieving process

We implemented four steps to collect articles on technology use in mathematics education (Fig. 1). First, we used three research databases, *Web of Science, ERIC,* and *PsycInfo,* to search for relevant articles and selected articles containing "mathematics or math" and "technology or technologies" in the abstract and "education" in any field of the document. Second, we excluded dissertations and theses and only included peer-reviewed articles to ensure scholarly quality (Hwang & Cho, 2021). In addition, we excluded non-English written articles. As NCTM's (1980) document that emphasizes technology use in mathematics education was first published in 1980, we only included articles published after 1980 (January 1981– March 2022). After this process, we obtained 13,886 research articles (*Web of Science:* 4,861, *ERIC:* 5,482, and *PsycInfo:* 3,543). Third, the EndNote 20 software was used to import articles obtained. After deleting the duplicated articles, we obtained 5,687 articles. Fourth, the titles, abstracts, and full texts of each article were reviewed, and the articles that were irrelevant to technology use in mathematics education (e.g., technology use in engineering education) were excluded. A total of 2,433 articles were retrieved through this filtering process.

3.2 Data analysis

3.2.1 Pre-processing

We adopted the programming language *R* and conducted two pre-processing steps: stop words removal and stemming (Yin & Yuan, 2022). We first eliminated stop words (e.g., pronouns, conjunctions, and prepositions) that do not represent the topic of the research articles. We also eliminated the terms usually included in an abstract but contain low information about the article, such as ''study,'' ''database,'' ''journal,'' ''paper,'' and ''author.'' Second, we conducted a stemming process where it reduced a word to its word stem (e.g., the term "technologies" is transformed into "technology."). This text normalization technique is necessary for the use of the LDA algorithm to enhance the efficiency and accuracy of the data analysis. Words such as "teacher" and "teachers" will be reduced to the word "teacher." Figs. 3, 5, and Table 3 technically show the word stems that were undertaken in the stemming process. For the stemming technique, we used a *SnowballC* package in *R*. Through these pre-processing steps, we retrieved 136,262 words.

3.2.2 Perplexity analysis

To determine the optimal number of topics (k), we used a *ldatuning* package in *R*, which provides model fitness scores for the given topics (Nikita, 2020). We calculated a model fitness score using *CaoJuan2009*, which provided the information on

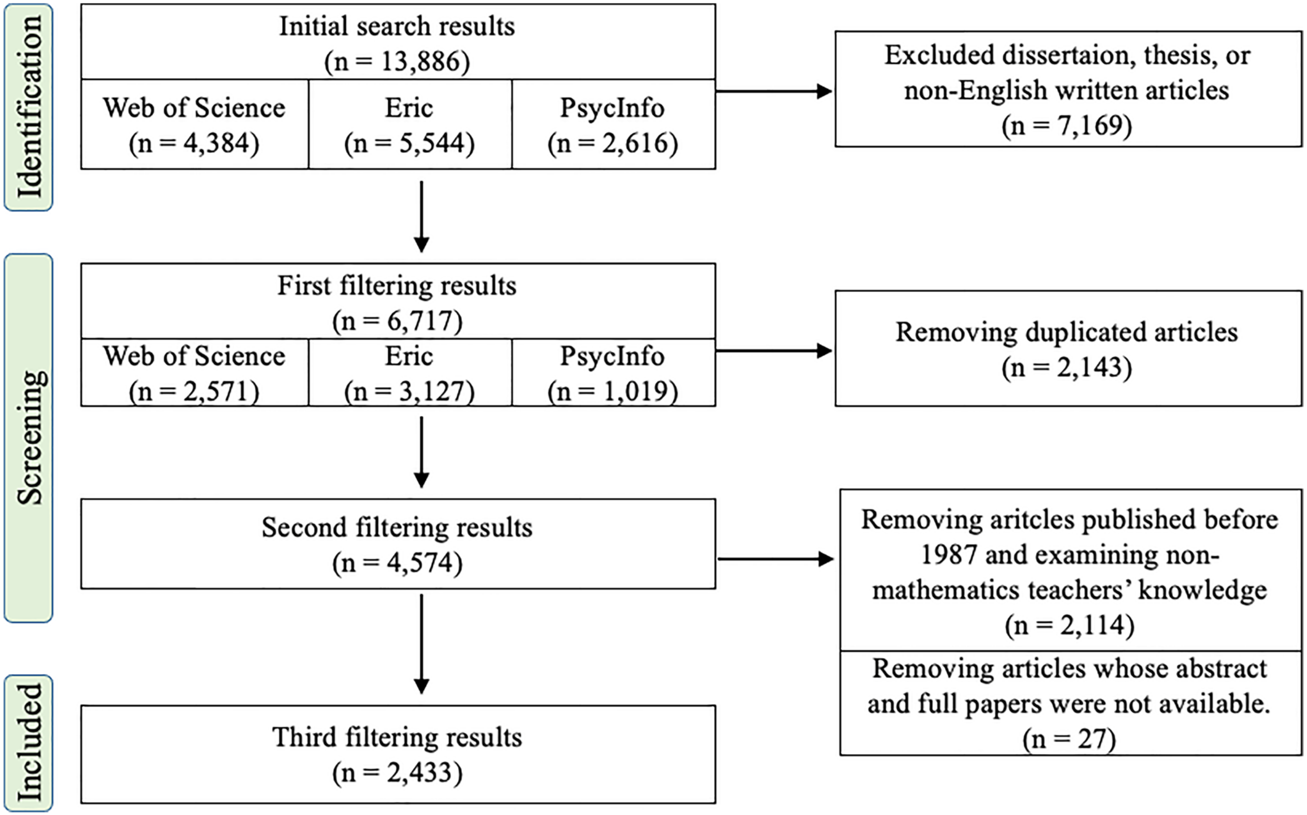


Fig. 1 Data retrieving process following the guidelines of the PRISMA group (Moher et al., 2009). *Note.* The data that support the findings of this study are available on request from the authors

the optimal topic number. Cao et al. (2009) validated that the best *k* number of LDA is correlated with the distances between topics. This metric uses the average cosine distance between every pair of topics to measure the stability of the topic structure. A smaller average distance represents that the topic structure is more stable. Therefore, in the *CaoJuan2009* metric, the lower value represents a better model fit. Figure 2 depicts that a line level falls off (the lowest value) when the number of topics is 7. This shows that the study data at hand had the best generalization performance with seven topics. Thus, we decided to categorize the collected articles into seven topics.

3.2.3 Determining research topic name

We used three types of information to determine the name of each topic: (a) top 15 characteristic words, (b) word clouds, and (c) top 20 representative articles. We first examined each topic's top 15 characteristic words to initiate our idea around the possible topic names. The top 15 characteristic words refer to the words with the highest term-topic probability words (β_k), which were frequently revealed in the abstract. Second, we created a word cloud of each topic with the top 50 words. The size of a term in a word cloud reflects the value of a term-topic probability, and a larger term indicates a higher term-topic probability. This visualization made it easier to see which terms (or research areas) are more representative than other terms within the topic. Third, we read the top 20 articles (θ_d) with the highest proportion of words. This process helped us understand the narratives of each topic (e.g., research purpose and findings) and determine the research topic name.

For example, topic 5 was named "teacher instruction and TPACK" for the following reasons. First, the top 15 terms obtained by the LDA algorithm were ‘‘teacher,’’ ‘‘teach,’’ ‘‘integrate,’’ ‘‘classroom,’’ ‘‘practice,’’ ‘‘knowledge,’’ ‘‘preservice,’’ ‘‘content,’’ ‘‘lesson,’’ ‘‘pedagogy,’’ ‘‘participate,’’ ‘‘pd [professional development],’’ ‘‘train,’’ and ‘‘instruct.’’ The combination of these terms would be the name of the topic. Second, the word cloud analysis (see Fig. 3) revealed that ‘teacher’ took the larger proportion, followed by ‘‘teach,’’ ‘‘integrate,’’ ‘‘classroom,’’ ‘‘practice,’’ ‘‘knowledge,’’ ‘‘preservice,’’ and ‘‘content.’’ Third, the articles with the highest topic-article probability examined teachers' technology use for mathematics instructions and their TPACK (e.g., Akapame et al., 2019).

4 Results

4.1 Overall research trends and word frequency

This study examined 2,433 articles published between January 1981 and March 2022. Table 1 and Fig. 4 show the number of articles by 10-year period and a year. As the table and figure show, the number of articles has gradually increased over time, indicating the popularity of this field. In the 1980s, only 26 articles (1.1%) examined technology use in mathematics education. However, since 2009, more than 100 articles have been published every year. For example, in the 2010s, 1,408

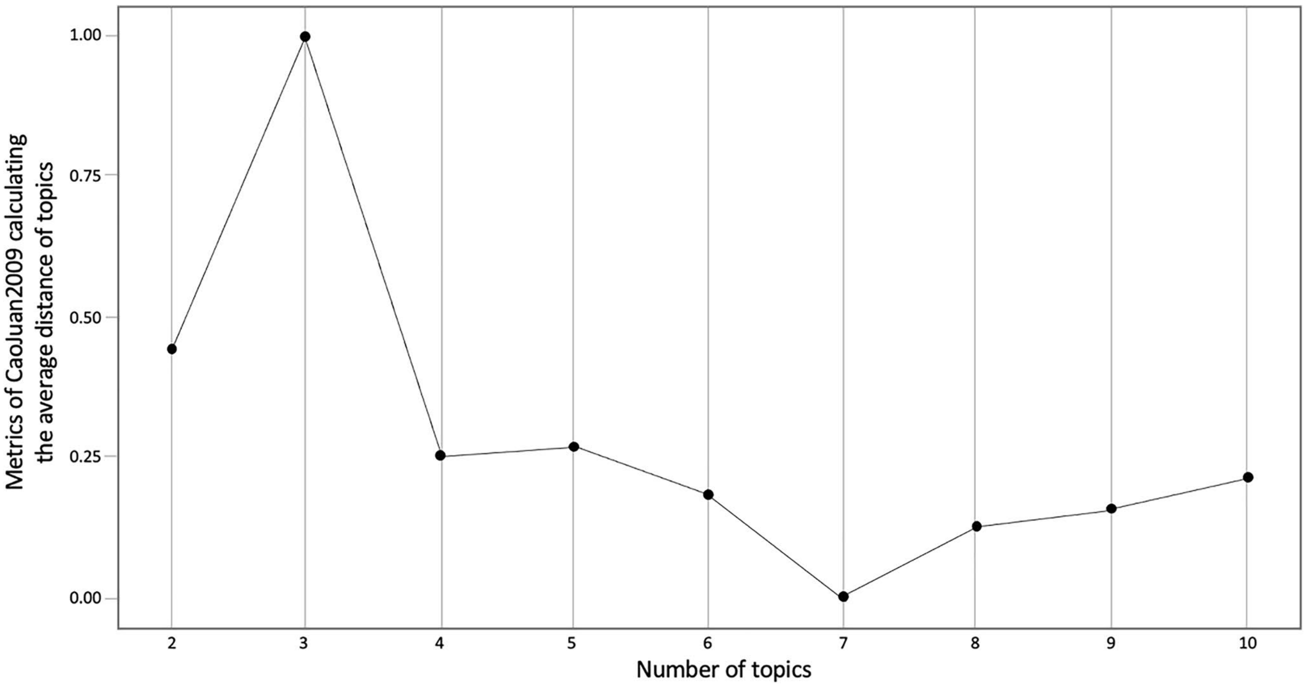


Fig. 2 Perplexity of topic model

Fig. 3 A word cloud of topic 5 with the fifty highest term-topic probability words. *Note*. The bigger and bolder the word stem appears, the higher the word stem's term-topic probability

Table 1 The Number of Articles Over a 10-Year Period

Year Range	Number (%)
1981–1989	26 (1.1%)
1990–1999	97 (4.0%)
2000–2009	569 (23.4%)
2010–2019	1,408 (57.8%)
2020 – March 2022	333 (13.7%)
Total	2,433 (100.0%)

articles were published (57.8%). These results were aligned with previous studies reporting that since the 1980s, educational technology has facilitated integration in mathematics education (Bray & Tangney, 2017; Roschelle et al., 2017).

We also examined the most frequently used words in the collected data. Figure 5 depicts the words with more than 500 frequencies in abstracts. There were 53 words found, such as ‘‘student,’’ ‘‘teacher,’’ ‘‘learn,’’ ‘‘teach,’’ ‘‘school,’’ ‘‘develop,’’ ‘‘classroom,’’ ‘‘effect,’’ ‘‘design,’’ and ‘instruct.’’ Note that while ‘‘technology’’ and ‘‘mathematics’’ were not included in Fig. 5, all articles included the two terms as we only selected articles that included them in abstracts. The combination of these words allowed us to build an idea of what research topics might have been studied. The words ‘‘student,’’ ‘‘classroom,’’ ‘‘effect,’’ and ‘‘learning’’ might represent a topic that examines the effect of technology use on student mathematics learning (e.g., Bicer & Capraro, 2016).

4.2 Determining research topics names

Tables 2 and 3 show the information on seven topics derived from the LDA algorithm. Table 2 presents topic names, top 15 words, and a sample representative article of each topic. Table 3 provides word clouds that visualized each topic with the top 50 frequently used words. Topic 1 (T1) was named “using technology to support mathematics learning.” The articles in T1 were concerned with using technology to foster student engagement, interaction, and investigations in mathematics learning (e.g., Cheng-Huan et al., 2017). Topic 2 (T2) was labeled “technology in K-12 curriculum.” The articles in T2 examined how technology resources in curriculum materials related to teacher instruction and student learning (e.g., Hu et al., 2020). Topic 3 (T3) was labeled as “computers and ICT (information and communication technology) use at school.” Articles in T3 examined mathematics students’ or teachers’ attitudes, perceptions, readiness of using computers and ICT, and factors affecting them (e.g., Birgin et al., 2020).

Topic 4 (T4) was named “technology use at higher education.’’ The representative studies primarily concerned technology use in college and university environments, which utilized online mediation techniques or computer-assisted methods for teaching and learning mathematics (e.g., Radmehr & Goodchild, 2022). Topic 5 (T5) was labeled as “teacher instruction and TPACK.” Articles on this topic

Fig. 4 The number of articles by a year

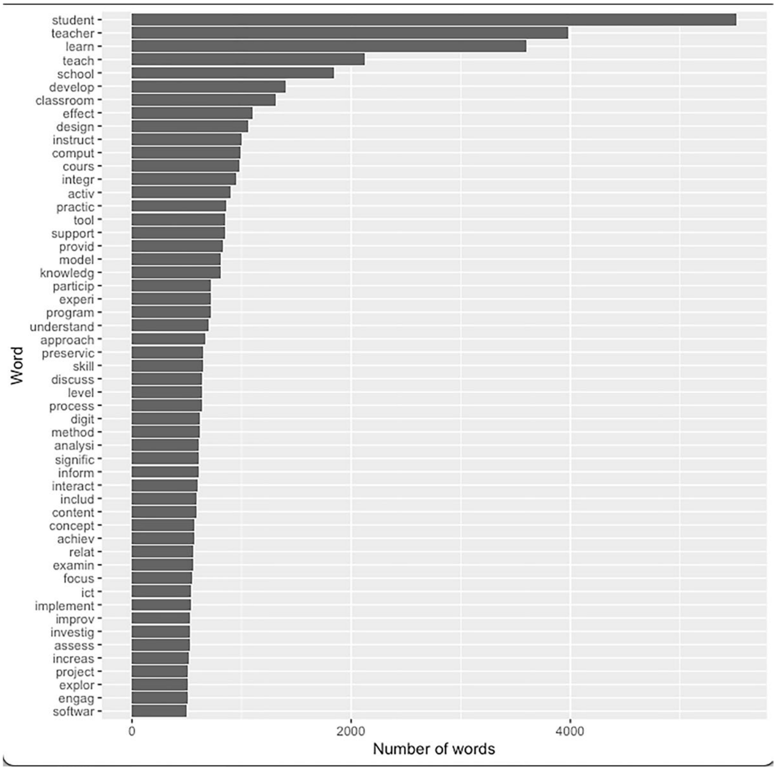


Fig. 5 Frequently used words in the abstract. *Note*. The words shown in Fig. 5 are technically word stems. For example, 'includ' is a word stem of include, includes, included, and including that reduces the suffixes

examined in-service and pre-service mathematics teachers' instructional practices with technology and their TPACK (e.g., Akapame et al., 2019).

Topic 6 (T6) was named "using technology for conceptual understanding." This topic discussed the use of technology for teaching and learning mathematical content and process, which improve students' conceptual understanding of solving mathematical tasks (e.g., Urban-Woldron, 2015). Topic 7 (T7) was labeled "examining the effect of technology on cognitive and affective development." This topic mainly examined the effect of technology use on students' cognitive and affective development (e.g., Bicer & Capraro, 2016).

4.3 Research trend analysis

We analyzed the proportion of each topic by a 10-Year Period to understand the research trend (see Table 4 and Fig. 6). The greater topic proportion showed that the topic had received more attention from researchers in that period. According to the 2010s data, the difference between the highest (T5 and T6, 14.7%) and the

Table 2 Topic Names, Characteristic Words, and a Sample Representative Article of Each Topic

Topic Name	Top 15 Characteristic Words	A Sample Representative Article
T1. Using technology to support mathematics learning	learn, design, approach, support, active, interact, process, digit(al), engage, environment, develop, model, context, system, base	Students' attention when using touchscreens and pen tablets in a mathematics classroom (Cheng-Huan et al., 2017)
T2. Technology in K-12 curriculum	school, skill, curriculum, resource, inform, children, develop, access, social, provide, communicate, issue, question, increase, language	From cloud to classroom: Mathematics teachers' planning and enactment of resources accessed within virtual spaces (Hu et al., 2020)
T3. Computers and ICT use at schools	school, computer, ict, attitude, model, analysis, investigate, level, factor, posit(ive), purpose, influence, subject, statistics, survey	Investigation of Turkish mathematics teachers' proficiency perceptions in using information and communication technologies in teaching (Birgin et al., 2020)
T4. Technology use in higher education	course, student, program, project, online, university, engine, experience, develop, describe, college, discuss, change, challenge, include	Switching to fully online teaching and learning of mathematics: The case of Norwegian mathematics lecturers and university students during the COVID-19 pandemic (Radmehr & Goodchild, 2022)
T5. Teacher instruction and TPACK	Teacher, teach, integrate, classroom, practice, knowledge, preservice, content, lesson, pedagogy, participate, pd (professional development), train, instruct, observe	A clash between knowledge and practice: A case study of TPACK in three pre-service secondary mathematics teachers (Akapame et al., 2019)
T6. Using technology for conceptual understanding	tool, understand, concept, software, student, solve, explore, task, calculus, geometry, active, dynamic, algebra, reason, represent, computer	Motion sensors in mathematics teaching: Learning tools for understanding general math concepts? (Urban-Woldron, 2015)
T7. Examining the effect of technology on cognitive and affective development	student, effect, instruct, achieve, assess, perform, test, learn, improve, significance, class, tradition, control, motivation, intervention	Longitudinal effects of technology integration and teacher professional development on students' mathematics achievement (Bicer & Capraro, 2016)

Table 3 Word Clouds of Each Topic with the Fifty Highest Term-Topic Probability Words

T1. Using technology to support mathematics learning

T2. Technology in K-12 curriculum

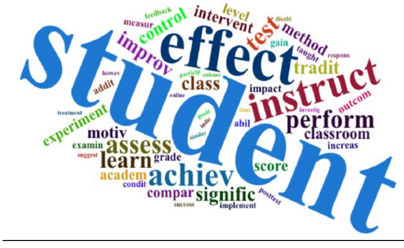
T3. Computers and ICT at schools

T4. Technology use in higher education

T5. Teacher instruction and TPACK

T6. Using technology for conceptual understanding

T7. Examining the effect of technology on cognitive and affective development



Note. The bigger and bolder the word stem appears, the higher the word stem's term-topic probability.

lowest (T3, 13.7%) topic proportion was negligible (1%). However, different patterns were observed when we analyzed the topic proportion between January 1981 and March 2022. For example, the topic proportions of T5 have slightly decreased over time. In the 1980s, T5 took 16.5% of the total publication. However, in the 2010s and 2020–2022 March, T5 took 14.7% and 14.0%, respectively. Moreover, while the topic proportion of T6 has steadily increased over time (9.6% in the 1980s and 15.4% in 2020–2022 March), T2, T3, and T7 showed fluctuation patterns. For example, T7 took 13.3% in the 1980s, followed by 17.7% in the 1990s and 14.0%

Table 4 Topic Proportion by a 10-Year Period

	The 1980s	The 1990s	The 2000s	The 2010s	2020–2022 March	Mean	Research Trends
T1	14.6%	14.2%	14.9%	14.6%	14.2%	14.5%	Stable
T2	18.7%	13.6%	13.3%	14.3%	15.6%	14.8%	Fluctuating
T3	13.4%	13.8%	15.3%	13.7%	12.9%	14.0%	Fluctuating
T4	13.9%	13.9%	13.5%	14.0%	14.7%	13.9%	Stable
T5	16.5%	14.3%	14.6%	14.7%	14.0%	14.9%	Decreasing
T6	9.6%	12.5%	12.3%	14.7%	15.4%	12.7%	Increasing
T7	13.3%	17.7%	16.1%	14.0%	13.2%	15.2%	Fluctuating

in the 2010s. The analysis of research trends of each topic by a year also revealed similar patterns (see Table 5). Except for outliers, two topics (T1 and T4), showed a relatively stable change over time. However, other topics revealed decreasing (T5), increasing (T6), or fluctuating (T2, T3, and T7) patterns.

To understand the research trends more closely, we calculated the Pearson correlation between the topics using the *R* package *psych*. Table 6 shows that T1 and T4 (0.36*, stable pattern) and T3 and T7 (0.39*, fluctuating pattern) had positive relationships, showing that they had similar research trends. However, T2 was negatively associated with T1 (-0.37*), T3 (-0.34*), T4 (-0.61***), and T7 (-0.38*), while T1 and T6 (-0.41**), and T5 and T7 (-0.51***) were negatively related, indicating opposite research interests over time.

Overall, the research trends analysis showed different emphases over time (see Fig. 6). In the 1980s, T2 and T5 were the most popular topics. However, during the 1990s and 2000s, T7 was the most popular topic while the trendline gradually decreased over time and interest diminished in the 2010s. In addition, T1 and T3 have received increasing attention in the 2000s. Since the 2010s, T2 and T6 have received increasing attention. In particular, the research interest on T6 has grown steadily from the 1980s until March 2022.

5 Discussion

The study aimed to analyze research trends of technology use in mathematics education from 1981 to March 2022. The study has the following four research questions: (1) How did overall research trends of technology use in mathematics education evolve? (2) Which words were frequently used in previous studies? (3) What were the latent research topics? (4) What were the research trends for individual topics? To solve the research questions, we retrieved relevant articles from *Web of Science, ERIC,* and *PsycInfo* databases and selected 2,433 peer-review English-written articles published between January 1981 and March 2022. Then, we examined their abstracts using topic modeling (Blei, 2012).

The findings of the first research question revealed that research interest in technology use in mathematics education has steadily increased. During the 1980s, only

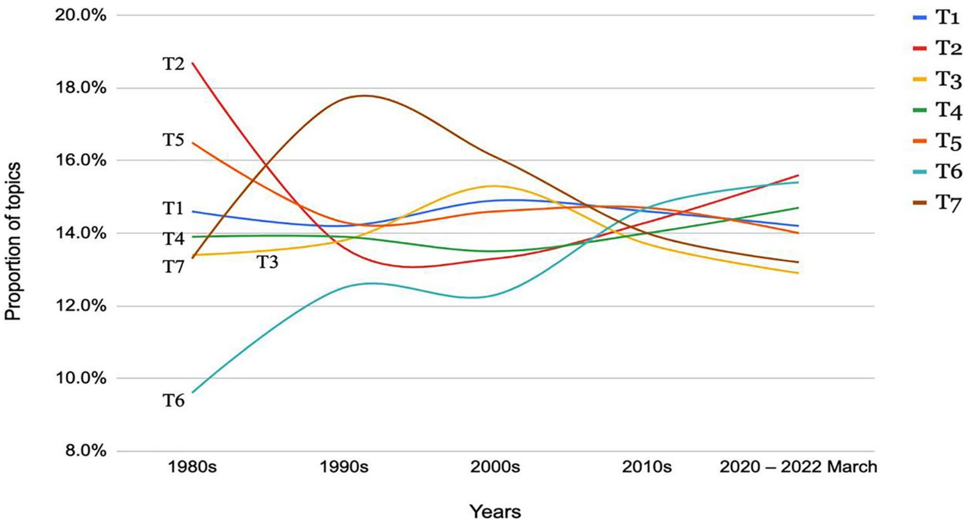
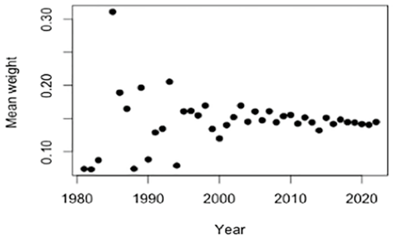
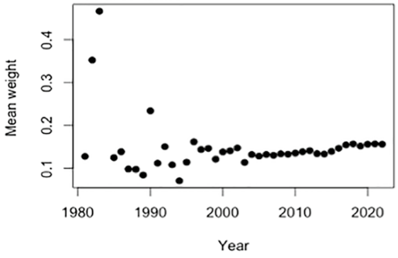
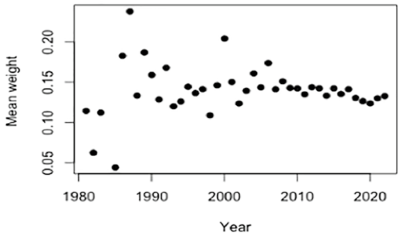


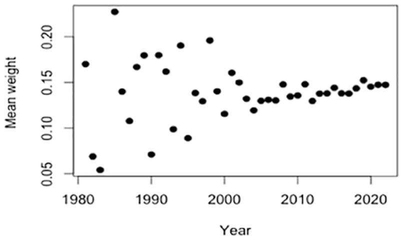
Fig. 6 Research trends of each topic by a 10-year period

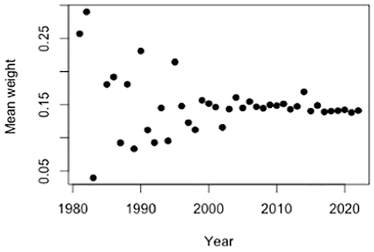
Table 5 Research Trends of Each Topic by a Year

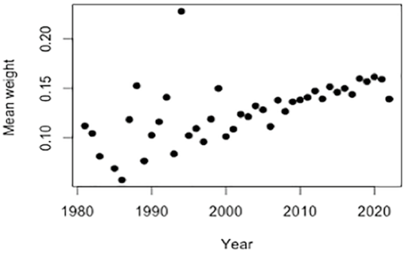

T1. Using technology to support mathematics learning

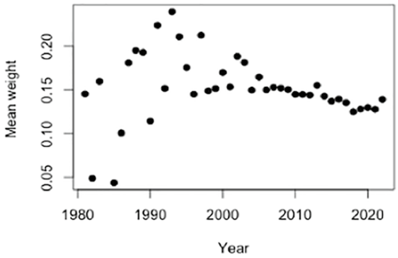

T2. Technology in K-12 curriculum


T3. Computers and ICT use at schools


T4. Technology use in higher education


T5. Teacher instruction and TPACK


T6. Using technology for conceptual understanding


T7. Examining the effect of technology on cognitive and affective development

26 articles examined using technology in mathematics education, whereas more than 100 articles have been published yearly since 2007. These increasing research trends aligned with the arguments of NCTM (1980, 2014) and the Programme for International Student Assessment (OECD, 2019) documents emphasizing the importance of technology use in mathematics education. This could be because researchers have

Table 6 The Correlation Between Research Topics

	T2	T3	T4	T5	T6	T7
T1	-.37*	-.07	.36*	-.17	-.41**	-.15
T2		-.34*	-.61**	.05	-.26	-.38**
T3			-.20	-.30	-.04	.39*
T4				-.20	.23	.01
T5					-.17	-.51**
T6						.11

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$

found new opportunities and positive effects of technology use on teacher instruction (Hoyles, 2018; Hu et al., 2020) and student learning outcomes (Higgins et al., 2019). Consequently, other relevant studies, such as mathematics teachers' perception of ICT (Birgin et al., 2020), professional development (Bicer & Capraro, 2016), TPACK (Akapame et al., 2019), and online teaching and learning (Radmehr & Goodchild, 2022), have been conducted.

To delve into the second research question, we identified 53 frequently used words with more than 500 frequencies. The words included ''student,'' ''teacher,'' ''learn,'' ''teach,'' ''school,'' ''develop,'' ''classroom,'' ''effect,'' ''design,'' and ''instruct.'' The combination of these words (e.g., the effects of teacher instruction with technology on student learning) can represent important research topics on technology use in mathematics education.

As for the third research question, we examined the major research topics and found seven topics: "Using technology to support mathematics learning" (T1), "technology in K-12 curriculum" (T2), "computers and ICT use in schools" (T3), "technology use in higher education" (T4), "teacher instruction and TPACK" (T5), "using technology for conceptual understanding" (T6), and "examining the effect of technology on cognitive and affective development" (T7). However, these topic classifications were not neatly aligned with the previous topic classification of mathematics education research (e.g., Gökçe & Güner, 2021; Inglis & Foster, 2018). Inglis and Foster (2018) classified research on mathematics education into the following four domains: mathematical content, mathematical process, teaching and learning environments, and hard cores and heuristics. However, our analysis did not show topics related to hard cores and heuristics examining research theories and methods. Moreover, some topics were linked to more than two domains. For example, T4 included calculus (mathematical content), discussion and communication (mathematical process), and course and online (teaching and learning environments) as top characteristic words (see Tables 2 and 3). This result may stem from the difference in the scope of data used for the study. Our study includes articles examining technology use in mathematics education, while Inglis and Foster (2018) examined articles in two mathematics education journals only.

The seven topics found in this study were not aligned with previous literature reviews on educational technology (e.g., Chen et al., 2020; Ozyurt & Ayaz, 2022;

Tatnall & Fluck, 2022). In a study examining research trends of *BJET*, Chen et al. (2020) identified 15 topics relating to a teacher (e.g., teacher education), learning strategies (e.g., problem-based learning, game-based learning, mobile-assisted language learning, socialized e-learning), learning environment (e.g., online social communities), evaluation (assessment and feedback), and other areas (e.g., early childhood education in the digital age and review studies). However, their analysis could not find topics related to conceptual understanding (T6) and K-12 curriculum (T2). Additionally, early childhood education, review studies, and learning strategies with emerging technologies were not identified in this study.

These differences are not unplausible because individual studies have analyzed different datasets according to different research purposes. However, these differences also indicate that research on technology use in mathematics education has distinctive research topics. While there are amalgams between mathematics education and educational technology, researchers have developed their distinctive research areas to enhance mathematics teaching and learning with technology use. Thus, researchers who are interested in technology use in mathematics education need to study mathematics education and educational technology and the integration of technology into mathematics education as a distinctive research area.

To delve into the fourth research question, we examined the number of publications on each topic over a year and a 10-year period. The findings revealed four different patterns, including stable (T1 and T4), decreasing (T5), increasing (T6), and fluctuating (T2, T3, and T7) patterns. The popular topics have changed from T2 and T5 (the 1980s) to T1, T3, and T7 (between the 1990s and the 2000s) to T2 and T6 (between the 2010s and March 2022). Interestingly, T6, the least studied topic in the 1980s, has received steadily increasing attention over four decades. Additionally, T2 has received the most research interest in the early (1980s) and later periods (since 2010).

These results are plausible. Since 1980, researchers have paid much more attention to enhancing student conceptual understanding by developing the reform-based curriculum and improving teacher instructional skills and knowledge (Bray & Tangney, 2017; Inglis & Foster, 2018). In this process, technological resources presented in mathematics curriculum (T2) and teachers' technology use in mathematics classrooms and their TPACK (T5), which could facilitate or hinder the development of students' conceptual understanding, were extensively analyzed. According to Remillard (2005), the curriculum included formal curriculum (e.g., printed documents) and teachers' intended (e.g., teaching goals) and enacted curriculum (i.e., actually teaching in the classroom). Furthermore, mathematics teachers' instruction and pedagogical content knowledge were related to teachers' knowledge of curriculum (Ball et al., 2008). In sum, the similar research trends of T2 and T5 between the 1980s and 1990s were reasonable.

However, T2 and T5 have shown different research trends since the 2000s. T2 has revealed increasing research attention (13.3% in the 2000s, 14.3% 2010s, and 15.6% in 2020 – March 2022), whereas the research interest in T5 showed minimal change (14.6% in the 2000s and 14.7% 2010s) or slightly decreased (14.7% in 2010s and 14.0% in 2020–2022 March). Consequently, T2 and T5 showed a fluctuating and decreasing pattern. The revival of research attention on T2 might be affected by the publishment of curriculum documents. The curriculum documents emphasizing technology use in mathematics education have been steadily published. For example, NCTM published curriculum documents and standards emphasizing technology integration in mathematics education (AMTE, 2022; NCTM, 1980, 2014). Similarly, Common Core State Standards for Mathematics highlighted technology's roles in mathematics education (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). However, these documents were published by US mathematics educators. Therefore, further studies are needed to understand the research trends of T2 and T5.

The limited research attention on T6 before the 2000s implied that while researchers had focused on enhancing student conceptual understanding using technology, they were more concerned about examining technology integration into curriculum and teacher instruction than the direct relationship between technology use and students' conceptual understanding. However, since the 2000s, researchers have paid more attention to the direct relationship between them, which indicated a steady increase in T6 over time (9.6% in the 1980s, 12.3% in the 2000s, and 15.4% in 2020–2022 March).

The popularity of T1, T3, and T7 between the 1990s and 2000s showed that researchers were interested in examining the effect of technology at school on student mathematics achievement, motivation, and overall learning experiences. These research trends were aligned with research trends in mathematics education and educational technology. In the early stage, mathematics researchers focused on examining student mathematics achievement using quasi-experimental methods (Bray & Tangney, 2017; Stinson & Bullock, 2012). They aimed to understand individual student learning processes and generalize teacher instructions (Gökçe & Güner, 2021; Inglis & Foster, 2018). Similarly, researchers examining educational technology have focused on evaluation and assessment at the early stage of research (Chen et al., 2020; Tatnall & Fluck, 2022).

However, there were some lags in research trends on the use of technology in mathematics education. Since 1990, as the sociocultural theory has grown in popularity, mathematics educators have placed more emphasis on student collaboration, teacher-student interactions, classroom environments, and student backgrounds than on evaluating student mathematics achievement (Inglis & Foster, 2018). As Table 4 shows, T7 was one of the most popular topics before the 2010s.

Since 2000, researchers studying educational technologies have become more concerned with new learning strategies with emerging technologies that could enhance student collaboration and autonomy, such as e-learning, mobile and blended learning, and social network-based learning (Ozyurt & Ayaz, 2022; Tatnall & Fluck, 2022). These topics, however, were not identified in our study. This implies that the research on technology use in mathematics education is relatively slow in adopting new theories and technologies than research on mathematics education and educational technology.

6 Limitation

This study has four limitations. First, we retrieved the articles from three research databases (*Web of Science, ERIC,* and *PsycInfo*). Also, we included English-written articles published in peer-reviewed journals and excluded dissertations, theses, and non-English written articles. If we had included the excluded articles, our findings might be different. Second, we searched articles containing "mathematics or math" and "technology or technologies" in the abstract. Thus, articles that did not contain those words in abstracts were excluded from this study. For example, a study examining the calculator use for algebra learning might not be included in our data due to our search criteria. Readers should be cautious when interpreting our findings. Third, we only examined the articles' abstracts. While examining abstracts to understand research trends is a common method (e.g., Chen et al., 2020), other important information presented in the different sections, such as findings and conclusions, was excluded during the data analysis process.

Fourth, labeling the topic names was a relatively subjective process. The LDA method is an entirely automatic, unsupervised algorithm (Blei, 2012). However, the topic names should be determined by researchers based on the information of the data, such as the most frequently occurring words and the articles with a high proportion on the topic. While this information enabled us to validate the topic names, other researchers might use different names even when analyzing the same data. Given the limitations of the present study, future studies may employ other research databases, including dissertations, theses, and non-English papers, and examine full texts of articles to verify the findings of this study.

7 Implications and conclusion

The development of technology has changed mathematics teaching and learning environments. Considering the expansion of technology use in mathematics education, this study synthesized previous studies published between January 1981 and March 2022 and examined research trends in the field using topic modeling.

We proposed three implications based on the research findings. First, it would be valuable to examine teaching and learning strategies with emerging technology in mathematics education. This study did not identify topics pertaining to utilizing new technology (e.g., AR, VR, and mobile, game-based, blended, and flipped learning). However, several researchers have emphasized the importance of using new technology in education (Kimmons, 2020; Tatnall & Fluck, 2022), where teachers serve as facilitators and students take the lead in their mathematical learning as investigators. Therefore, further studies on mathematics teachers' and students' use of emerging technology are needed. We can, for instance, examine mathematics teachers' instructional strategies in the virtual environment (e.g., Hu et al., 2020) and AI-based mathematics learning systems (Hwang & Tu, 2021).

Second, it is suggested that researchers consider examining further studies based on sociocultural theory. This study identified topics focusing on individual student mathematics learning, such as examining cognitive and affective development (T7) and conceptual understanding (T6). While these topics are critical issues, it would be productive to examine how technology use affects social interaction in actual and virtual mathematics classrooms (e.g., student collaboration, classroom discourse and norms, and teacher-student interactions). Moreover, it would be innovative to analyze the effect of technology use on the construction of student mathematical identity. Researchers (Hand & Gresalfi, 2015; Yackel & Cobb, 1996) have documented that classroom activities, resources, and culture affect both student cognitive and affective development and their mathematical identity (i.e., how a student acts, engage, position, and interact in mathematics learning). Given that student mathematical identity affects their educational aspirations and future careers (Black et al., 2010), it is valuable to analyze how technology use in mathematics classrooms affects student mathematical identity. Therefore, further studies may examine such issues.

Third, it is important to investigate the relationship between technology use and equity and access in mathematics education. The United Nations (United Nations General Assembly, 2015) suggested quality education as one of the agendas for sustainable development of our society and emphasized the importance of accessing quality education, regardless of student background (e.g., race, gender, and socioeconomic status). Technology can help achieve these goals because all students could be provided opportunities to investigate mathematics problems, present ideas, learn needed instructions, and communicate with peers in technological learning environments (AMTE, 2022; Clements et al., 2013; Higgins et al., 2019; NCTM, 2014). For example, Crawford (2013) validated that a supplementary online mathematics curriculum improved the mathematics achievement of English language learners considerably. Crawford (2013) explained that because students could learn mathematics at their own pace with a web-based curriculum, they could accurately understand mathematical concepts and practice mathematical skills, which enhanced access and equity in mathematics education. Even though this study did not find equity-related topics, the relationship between access, equity, and technology use in mathematics education should be more thoroughly studied to achieve sustainable development.

This study has theoretical and practical significance. Theoretically, this study made a scientific contribution in two ways. First, it provided researchers with overall research trends of technology use in mathematics education. Second, it identified topics that did not precisely align with those identified in previous studies on mathematics education or educational technology (e.g., Chen et al., 2020; Inglis & Foster, 2018). Practically, the study findings have guided further studies and practices to increase the effects of technology use in mathematics teaching and learning.

Data Availiability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

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