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TRENDS AND MAPPING OF TPACK STUDIES IN MATHEMATICS EDUCATION: A BIBLIOMETRIC ANALYSIS

TREN DAN PEMETAAN PENELITIAN TPACK DALAM PENDIDIKAN MATEMATIKA: ANALISIS BIBLIOMETRIK

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Abstract

This study aims to map the development and research trends related to TPACK in mathematics education over the past ten years. Using bibliometric analysis supported by Biblioshiny (bibliometrix, R), a total of 124 English-language articles from the Scopus database for the 2015–2025 period were analyzed through the PRISMA approach to ensure a systematic and transparent literature selection process. Publications grew at an annual rate of 21.13%, and 57.3% of all articles were published in 2023–2025, indicating that the field is entering an acceleration phase following the pandemic and the advent of generative AI. The results show that Monash University is the most productive institution, reflecting Australia's prominence as a contributing country, and Mao Li is the most productive author. The intellectual base of the field is formed by foundational TPACK works are Angeli and Valanides, Chai et al., Mishra and Koehler. The thematic and network visualizations reveal that the core themes center on technology integration in mathematics learning, with strong emphasis on teacher competence development, pre-service teacher training, and the use of digital tools such as GeoGebra. The emergence of topics such as Artificial Intelligence (AI) and curriculum innovation indicates a shift toward exploring transformative technologies. The relationship between TPACK and students' higher-order thinking skills, AI-based TPACK, secondary level contexts, and cross-country comparative studies are still rarely studied. The findings are expected to provide a clear scientific map for researchers, educators, and policymakers in designing TPACK-based mathematics learning strategies that are relevant to 21st-century education.

Keywords: TPACK, Mathematics Education, Bibliometric Analysis.

Abstrak

Penelitian ini bertujuan untuk memetakan perkembangan dan tren penelitian terkait TPACK dalam pendidikan matematika dalam kurun waktu 10 tahun terakhir. Dengan menggunakan analisis bibliometrik berbantuan Biblioshiny (bibliometrix, R), sebanyak 124 artikel berbahasa Inggris dari database Scopus periode 2015–2025 dianalisis melalui pendekatan PRISMA untuk memastikan proses seleksi literatur yang sistematis dan

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transparan. Publikasi tumbuh dengan laju tahunan 21,13%, dan 57,3% dari seluruh artikel terbit pada 2023–2025, menandakan bahwa bidang ini memasuki fase akselerasi setelah pandemi dan hadirnya AI generatif. Hasil analisis menunjukkan bahwa Monash University menjadi institusi yang mendominasi produktivitas dan mencerminkan keunggulan Australia di tingkat negara kontributor, dan Mao Li adalah penulis yang paling produktif. Dasar intelektual bidang ini dibentuk oleh karya-karya fundamental TPACK seperti Angeli dan Valanides, Chai dkk., Mishra dan Koehler. Visualisasi tematik dan jaringan mengungkap bahwa tema inti berpusat pada integrasi teknologi dalam pembelajaran matematika, dengan fokus kuat pada pengembangan kompetensi guru, pelatihan calon guru, serta penggunaan alat digital seperti GeoGebra. Munculnya topik seperti kecerdasan buatan dan inovasi kurikulum menunjukkan pergeseran riset menuju eksplorasi teknologi transformatif. Keterkaitan TPACK dan kemampuan berpikir tingkat tinggi siswa, TPACK berbasis AI, konteks jenjang menengah, serta kajian komparatif lintas negara masih jarang diteliti. Hasil studi diharapkan mampu memberikan peta ilmiah yang jelas bagi peneliti, pendidik, dan pembuat kebijakan dalam merancang strategi pembelajaran matematika berbasis TPACK yang relevan dengan abad ke-21.

Kata kunci: TPACK, Pendidikan Matematika, Analisis Bibliometrik.

INTRODUCTION

The Fourth Industrial Revolution has brought digital technology, artificial intelligence, and big data into almost every aspect of life (Suprapto et al., 2021). Consequently, Education 4.0 requires the integration of digital technology into learning (Hussin, 2018). Teachers are no longer expected only to master pedagogy (*pedagogical knowledge*) and subject matter (*content knowledge*), but also to use technology so that learning keeps pace with the times (Yurinda & Widyasari, 2022). These three domains of knowledge and their intersections are formulated in the *Technological Pedagogical Content Knowledge* (TPACK) framework introduced by Mishra and Koehler (2006).

TPACK is the knowledge teachers need to integrate technology, pedagogy, and content coherently in instruction (Mishra & Koehler, 2006; Yurinda & Widyasari, 2022). In mathematics learning, TPACK helps teachers present representations that students can understand more easily (Sintawati & Abdurrahman, 2020) and serves as a guide for designing effective and engaging instructional models (Finger et al., 2010; Hartati et al., 2018). Mastery of TPACK matters not only for in-service teachers but also for pre-service teachers, because technology can bridge abstract mathematical concepts and more concrete representations (Niess, 2005). The use of technology aligned with digital developments has also been reported to increase students' learning motivation (Sintawati & Abdurrahman, 2020).

Despite its importance, implementing TPACK in practice is not easy (Bancong & Hambali, 2023). Face-to-face learning teachers were not yet able to optimise all TPACK components, whereas in online learning its application was limited to *Technological Knowledge* (TK) and *Technological Content Knowledge* (TCK). This situation has prompted various strengthening efforts, such as TPACK training that helps teachers combine technology, learning materials, and instructional strategies more effectively (Pahlevi, 2021). Several researchers also position TPACK as a reference for 21st-century learning across subject areas (Aditama & Pratiwi, 2021; Munajib et al., 2021; Mutiani et al., 2021).

Research on TPACK has continued to grow since the framework was introduced (Bancong & Hambali, 2023; Voogt et al., 2013), yet comprehensive global mapping focused specifically on mathematics education remains limited. Most studies are partial and focus on particular contexts, for

example the relationship between TPACK and learning outcomes in general (Absari et al., 2020; Eng & Keong, 2019; Santos & Castro, 2021). A systematic review of 25 articles published in 2018–2022 mapped the development of TPACK in mathematics education and its barriers, such as teachers' low confidence, resistance to change, weak institutional support, and limited resources (Kholid et al., 2023). However, that review covered a limited number of articles and did not map the intellectual structure or thematic evolution of the field bibliometrically. A review is therefore needed that provides a complete picture of the field's direction, knowledge structure, and unexplored areas. Bibliometric analysis is suitable for this purpose because it can quantitatively analyse large volumes of publications in a field (Muhammad et al., 2022), reveal trends and intellectual structures (Donthu et al., 2021), and map developments systematically and measurably (González-Alcaide, 2021).

Previous bibliometric studies of TPACK have been cross-disciplinary, such as Suprapto et al., (2021) who mapped the 2015–2019 period, and Nasir et al., who mapped 2013–2022. Neither captured the surge in publications after 2022 or the emergence of *artificial intelligence* (AI) as a theme now being linked to TPACK and mathematics teachers' readiness (Celik, 2023; Mishra et al., 2023). The novelty of this study lies in a mapping focused specifically on mathematics education up to 2025, a distinction between productivity and intellectual influence, and an explicit identification of research gaps as the basis for a research agenda. The analysis was carried out with Biblioshiny from the bibliometrix package in R (Aria & Cuccurullo, 2017) on Scopus publication data for 2015–2025. The results are expected to provide a clear scientific map for researchers, educators, and policymakers in designing TPACK-based mathematics learning strategies relevant to the 21st century.

RESEARCH METHODS

This study employed a bibliometric design using data from the Scopus database. Bibliometrics is a quantitative approach for understanding the development of a scientific field, its research structure, the dissemination of information, the influence of publication sources, and long-term citation patterns (González-Alcaide, 2021; Zupic & Čater, 2015). This approach allows researchers to observe emerging research patterns, the most contributing actors, and shifts in research interest over time (Donthu et al., 2021).

Literature selection followed the PRISMA 2020 flow so that the identification and screening of documents were transparent and replicable (Page et al., 2022). Combining a systematic selection flow with bibliometric analysis helps researchers summarise findings while mapping the main contributors, knowledge structure, and future directions of a field (Marzi et al., 2025). Keywords were selected using a *top-down* approach, combining the name of the framework ("TPACK") with the field context ("mathematics education") in article titles, abstracts, and keywords. The inclusion criteria were journal

articles written in English, published in 2015–2025, and focused on TPACK in mathematics education. The characteristics of the data are summarised in Table 1.

The data were exported in CSV format and processed with Biblioshiny, the web interface of the bibliometrix package run through R (Aria & Cuccurullo, 2017). Annual trends and affiliations were processed with the Scopus *Analyze Search Results* feature, while the other analyses used Biblioshiny. To distinguish productivity from impact, the number of publications per author (productivity) was compared with the references most frequently co-cited by the corpus (*co-citation*) as an indicator of intellectual influence (Chen et al., 2024; Small, 1973), with average citations per document as an impact indicator at the corpus level. Relationships among references, countries, and keywords were visualised with a *three-field plot* (Sankey diagram) (Lupton & Allwood, 2017). The thematic structure was analysed with a strategic map based on *centrality* (degree of relevance) and *density* (degree of development) that divides themes into four quadrants (Cobo et al., 2011), and the topic structure was analysed through a keyword co-occurrence network.

Table 1. Summary of Bibliometric Study Data Characteristics

Category	Specific Standard Requirements
Research Database	Scopus
Search Query	(Title-Abs-Key ("TPACK") And ("Mathematics Education"))
Searching Periode	2015-2025
Dokuments Type	Articles
Language	English
Data Export Format	Csv

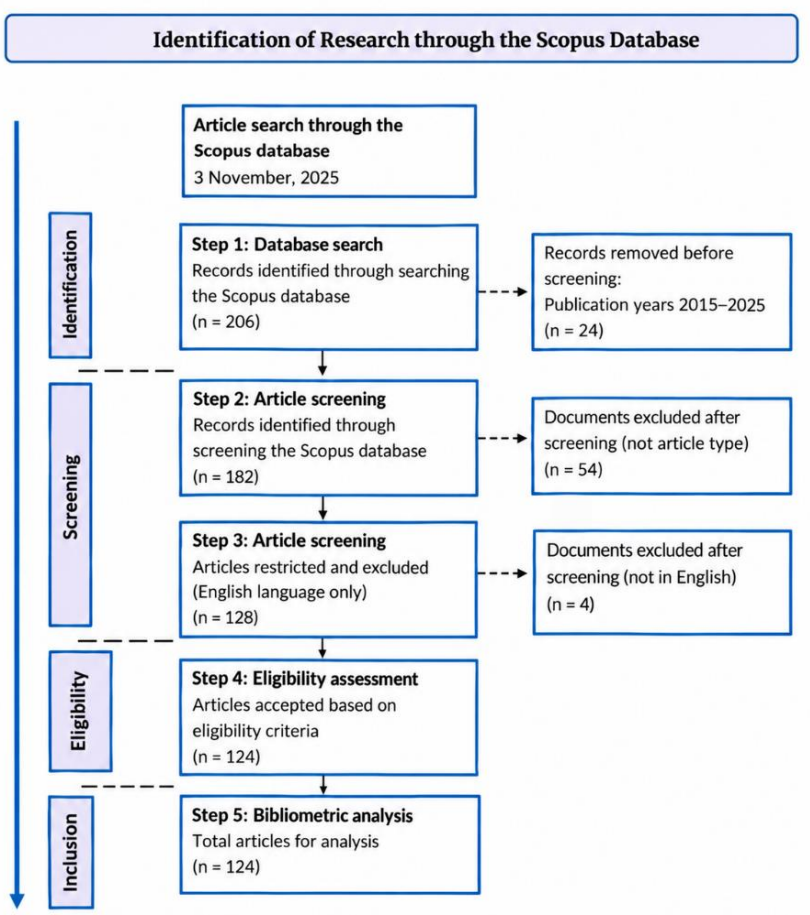


Figure 1. Process of Selecting Research Articles via the Scopus Database

A Scopus search on 3 November 2025 using the keywords "TPACK" and "mathematics education" in article titles, abstracts, and keywords returned 206 documents (Figure 1). Twenty-five documents published outside the 2015–2025 period were removed, leaving 181 documents. Screening by document type then excluded 53 documents that were not journal articles, namely 26 conference papers, 19 book chapters, 5 reviews, and 3 conference reviews, leaving 128 journal articles. Screening by language excluded 3 articles in Spanish and 1 in Serbian, resulting in 124 English-language articles that met the eligibility criteria. These 124 articles were analysed to answer the following research questions.

RQ1 : What main information describes the development of TPACK research in mathematics education?

RQ2 : How has the volume of TPACK research publications in mathematics education developed during 2015–2025?

RQ3 : Which institutions and authors are the most productive, and is this productivity consistent with their intellectual influence?

RQ4 : How are references, countries, and keywords interrelated, and what is the thematic structure of TPACK research in mathematics education?

RQ5 : Which keywords are prominent, how is the network of relationships among topics formed, and what research gaps are evident?

RESEARCH RESULTS AND DISCUSSION

Main Information

The main information describes the data corpus produced by the Biblioshiny analysis and answers RQ1. A summary of the main information is presented in Table 2.

Table 2. Main Information of the Bibliometric Data

Category	Description	Value
Main information about data	Timespan	2015–2025
	Sources (journals)	74
	Documents (articles)	124
	Annual growth rate	21.13%
	Document average age (years)	3.19
	Average citations per document	10.95
	References	959
Document contents	Keywords Plus (ID)	75
	Author's keywords (DE)	351
Authors	Authors	420
	Authors of single-authored documents	0
Authors collaboration	Single-authored documents	0
	Co-authors per document	5.87
	International co-authorships	21.77%

Table 2 shows that the corpus consists of 124 articles from 74 sources written by 420 authors and containing 959 references. The ratio of 1.68 articles per source indicates that publications are spread across many journals and are not yet concentrated in particular core journals. This is natural for a field at the intersection of mathematics education, educational technology, and teacher education, but it also means that researchers need to search many sources to obtain a complete picture.

The annual growth rate of 21.13% is equivalent to compound growth from 5 articles in 2015 to 34 articles in 2025, so the number of publications increased almost sevenfold in a decade. The average document age is only 3.19 years, confirming that the corpus is dominated by recent publications. With an average of 10.95 citations per document, each article receives roughly 3.4 citations per year. Because most articles are still recent, this citation figure does not yet reflect long-term impact and is likely to keep increasing.

In terms of collaboration, no single-authored articles were found, and there were on average 5.87 authors per article. International co-authorship reached 21.77%, or about 27 articles. This means that TPACK research in mathematics education is generally conducted in teams, but most collaboration still takes place within a single country. Keyword diversity is also high, with 351 author keywords and 75

Keywords Plus. The large number of author keywords relative to the number of articles indicates non-uniform terminology; for example, "TPACK", "TPCK", and "technological pedagogical content knowledge" appear as different keywords. This variation in terms should be kept in mind when reading the thematic map and the network.

Annual Publication Trend

The annual number of publications answers RQ2 and is presented in Figure 2. In Figure 2 shows two distinct phases. In the first phase (2015–2022), the number of publications was relatively flat at 5–8 articles per year, totalling 53 articles (42.7%), or an average of 6.6 articles per year. Small peaks occurred in 2016, 2018, and 2021 (8 articles each). In the second phase (2023–2025), publications jumped from 7 articles in 2022 to 16 in 2023 (an increase of 129%), 21 in 2024, and 34 in 2025. This phase accounts for 71 articles (57.3%), averaging 23.7 articles per year, or about 3.6 times the first phase. Because the data were retrieved on 3 November 2025, the number of publications for 2025 may still increase.

The surge after 2022 can be explained by at least two factors. First, the experience of emergency remote teaching during the 2020–2021 pandemic forced mathematics teachers to use technology on a massive scale and changed how the mathematics education community viewed the role of technology (Engelbrecht et al., 2020). Given the lag between data collection and publication, research from that period was mostly published in 2023–2024. Second, the emergence of generative AI from late 2022 raised new questions about the knowledge teachers need to teach alongside AI (Celik, 2023; Mishra et al., 2023). An exploration of the future of mathematics teaching with ChatGPT also anticipates stronger AI-supported personalised learning, hybrid classroom models, and greater emphasis on computational thinking and data literacy, provided that teachers receive continuous training so that pedagogical quality is maintained (Supriyadi & Kuncoro, 2023). This is consistent with the appearance of "artificial intelligence" as a motor theme in the thematic map (Figure 6). Thus, the increase in publications reflects not only growing interest but also a shift in research questions from *whether* technology should be integrated to *how* teachers prepare their knowledge for constantly changing technology.

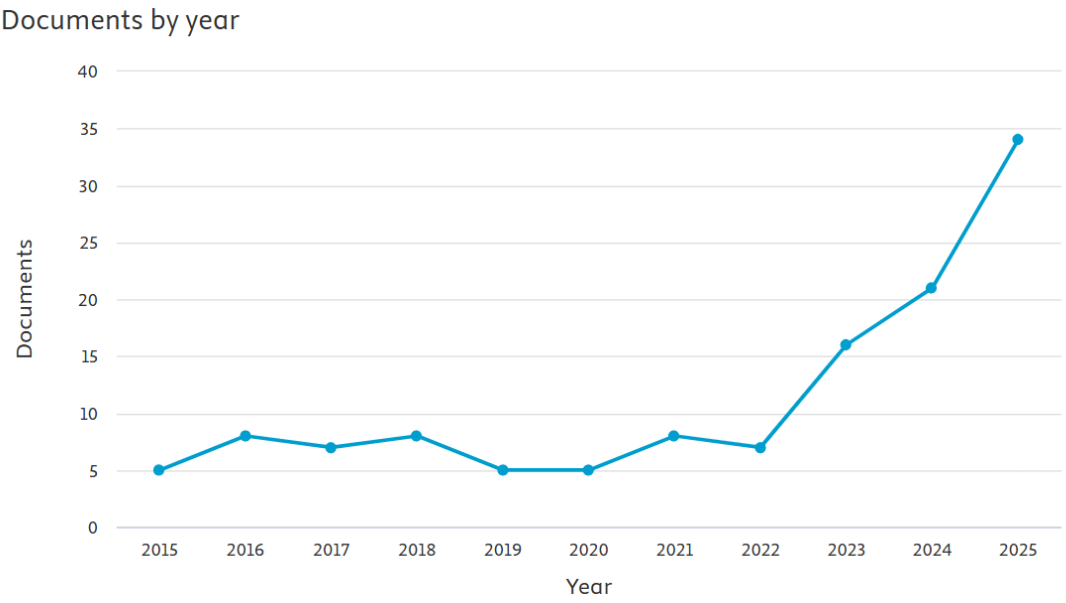


Figure 2. Annual Number of Publications

Most Productive Affiliations

Institutional productivity forms the first part of the answer to RQ3. Figure 3 presents the ten affiliations with the largest number of articles.

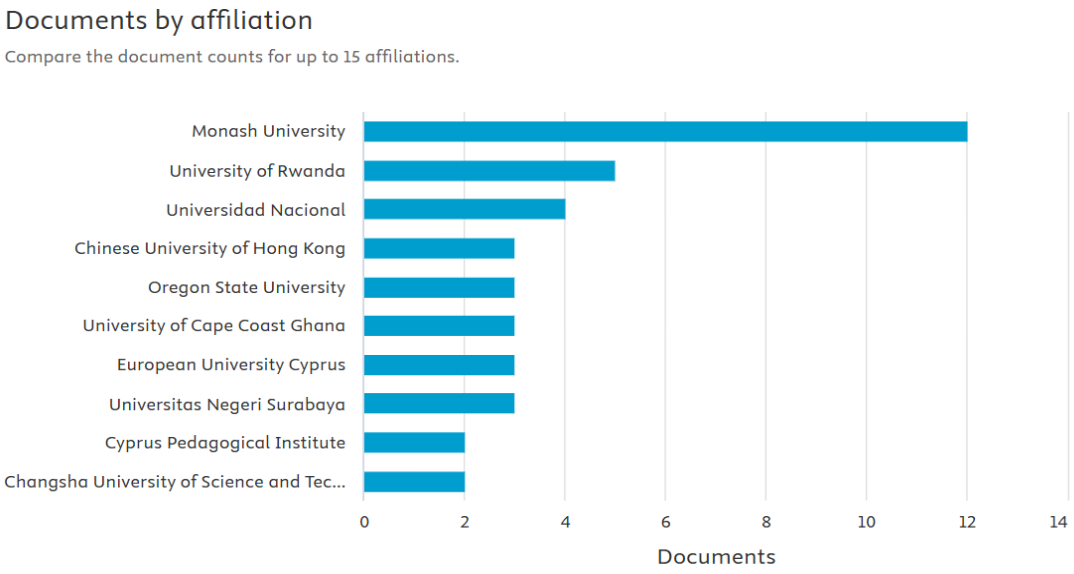


Figure 3. Most Productive Affiliations

Monash University (Australia) leads with 12 articles, or 9.7% of the corpus, more than twice the University of Rwanda in second place (5 articles). The next positions are held by Universidad Nacional, Costa Rica (4 articles); the Chinese University of Hong Kong, Oregon State University, the University of Cape Coast (Ghana), European University Cyprus, and Universitas Negeri Surabaya (3 articles each); and the Cyprus Pedagogical Institute and Changsha University of Science and Technology (2 articles each). These top ten affiliations come from nine countries or regions on five continents.

This pattern suggests that institutional productivity tends to be driven by research groups or key researchers rather than by institutional size. Several affiliations correspond to productive authors in Figure 4, for example Oregon State University with Margaret L. Niess, European University Cyprus with Maria Meletiou-Mavrotheris, Universidad Nacional with Yuri Morales-López, and the University of Cape Coast with Douglas Darko Agyei. The presence of institutions from Rwanda, Ghana, Costa Rica, and Indonesia among the top ranks shows that mathematics teachers' readiness to integrate technology is also a priority in developing countries. For Indonesia, the position of Universitas Negeri Surabaya shows that the national contribution is visible but still relies on a small number of institutions.

Most Productive Authors

The second part of RQ3 concerns authors. Figure 4 presents the ten most productive authors during 2015–2025.

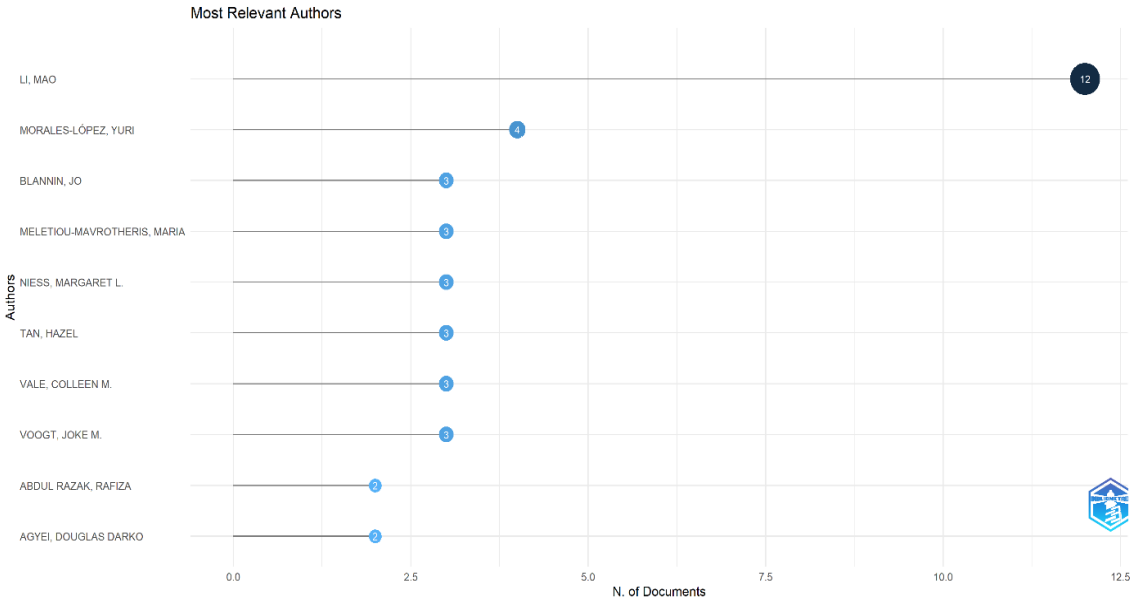


Figure 4. Most Productive Authors

Mao Li is the most productive author with 12 articles, far ahead of Yuri Morales-López (4 articles). Jo Blannin, Maria Meletiou-Mavrotheris, Margaret L. Niess, Hazel Tan, Colleen M. Vale, and Joke M. Voogt each wrote 3 articles, while Rafiza Abdul Razak and Douglas Darko Agyei each wrote 2. This distribution is highly skewed: one author contributes almost 10% of the corpus, while most of the 420 authors appear only once. This pattern is typical of a growing field, in which many new researchers enter but only a few build sustained research programmes.

Productivity is not the same as influence. To distinguish the two, the list of productive authors was compared with the references most frequently co-cited by the corpus in the *three-field plot* (Figure 5), as summarised in Table 3. The references with the thickest flows are Angeli and Valanides (2009) on ICT-TPCK, Chai and colleagues on the development of pre-service teachers' TPACK (Chai et al., 2011), the foundational work of Mishra and Koehler (2006), Agyei and Voogt (2012) on developing pre-service mathematics teachers' TPACK through collaborative design, and Archambault and Barnett (2010) on

measuring TPACK. Except for Agyei, these most-cited authors are not among the most productive authors in the corpus. In other words, the conceptual framework of the field was built by foundational works published before 2015, whereas today's productive authors mainly apply that framework in mathematics education contexts. Agyei and Voogt are an important exception, appearing both as productive authors and as influential references, and can therefore be seen as a bridge between theoretical foundations and applications in mathematics education.

Table 3. Comparison of Author Productivity and Intellectual Influence

Aspect	Most productive authors (Figure 4)	Most influential/co-cited references (Figure 5)
Indicator	Number of articles in the 2015–2025 corpus	Thickness of citation flows in the three-field plot
Key figures	Mao Li (12); Morales-López (4); Blannin, Meletiou-Mavrotheris, Niess, Tan, Vale, Voogt (3 each); Abdul Razak, Agyei (2 each)	Angeli & Valanides; Chai et al.; Mishra & Koehler; Agyei (& Voogt); Archambault; Ball; Abbitt; Borko
Period of work	Mostly 2015–2025	Mostly before 2015 (foundational works)
Role in the field	Applying and testing TPACK in mathematics education contexts	Defining, measuring, and operationalising the TPACK construct
Overlap	Agyei and Voogt	Agyei and Voogt

Relationships among References, Countries, and Keywords

The relationships among cited references (CR_SO), author countries (AU_CO), and keywords (KW_Merged) answer the first part of RQ4 and are presented in Figure 5. This is a Sankey diagram that displays the magnitude of flows between categories through line thickness (Lupton & Allwood, 2017).

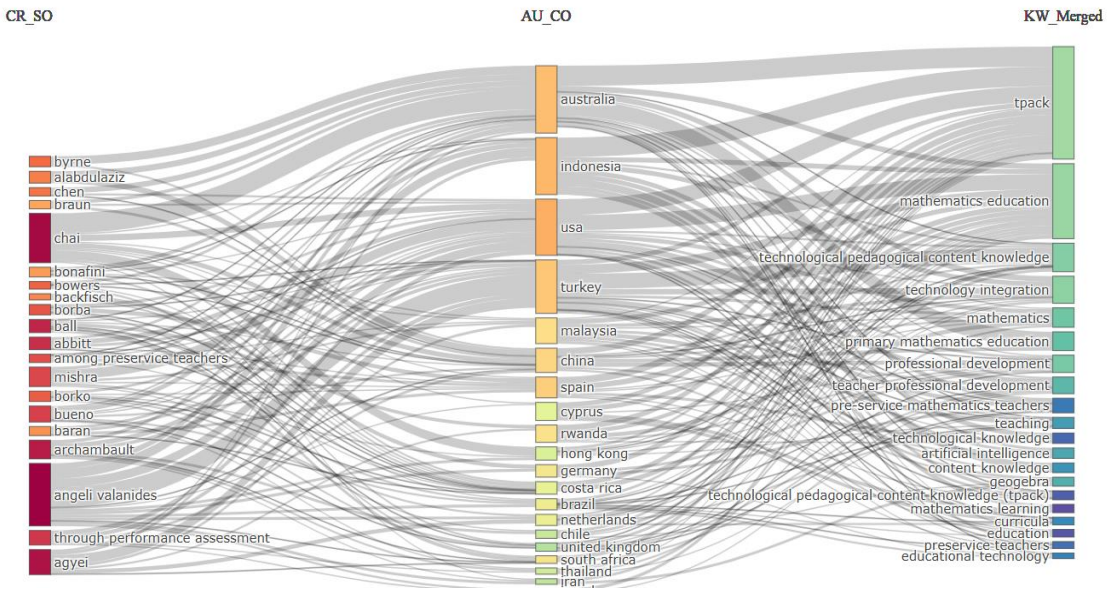


Figure 5. Three-Field Plot of References (CR_SO), Countries (AU_CO), and Keywords (KW_Merged)

In the left column, the largest flows come from Angeli and Valanides and from Chai, followed by Mishra, Agyei, Archambault, and Ball. The flows from the two main references spread to almost all countries in the middle column, including Australia, Indonesia, the United States, and Turkey, indicating that the field shares the same theoretical foundation across countries. References to Ball et al., (2008), who developed the concept of *mathematical knowledge for teaching*, show that some researchers have begun to link TPACK with mathematics-specific theories of teacher knowledge, although this flow is still thin. In contrast, references such as Byrne flow to only one or a few countries, so their influence is more local.

In the middle column, Australia, Indonesia, the United States, and Turkey have the largest flows, followed by Malaysia, China, Spain, Cyprus, and Rwanda. This distribution is consistent with the systematic review by Kholid et al., (2023), which found that TPACK studies in mathematics education were most often conducted in Turkey, the United States, Costa Rica, and Malaysia. Indonesia's position as the second-largest contributor is notable because it is not matched by many Indonesian institutions in the top ten (only Universitas Negeri Surabaya). This means that Indonesia's contribution is spread across many institutions, each with a small number of articles. In the right column, besides the umbrella keywords "tpack" and "mathematics education", flows from almost all countries lead to "technology integration", "primary mathematics education", "teacher professional development", and "pre-service mathematics teachers". Meanwhile, "artificial intelligence", "geogebra", and "curricula" receive only thin flows from a few countries. This pattern shows that the shared agenda across countries is teacher preparation and professional development, whereas AI and specific tools are still addressed by a small number of communities.

Thematic Map

The thematic map answers the second part of RQ4. The map positions each theme cluster by *centrality* (horizontal axis), that is, how strongly a theme is connected to other themes, and by *density* (vertical axis), that is, how mature a theme is internally (Cobo et al., 2011). The results are presented in Figure 6.



Figure 6. Thematic Map

Figure 6 shows that the largest themes lie on the right-hand side of the map. The *basic themes* (high centrality, low density) consist of the "tpack–mathematics education–technology integration" cluster, which is the largest cluster, as well as the "educational technology–mathematics teaching–teacher professional development" and "preservice teachers–improving classroom teaching" clusters. This position means that these themes form a foundation referred to by almost all studies but have not yet developed into in-depth, specific lines of inquiry. The *motor themes* (high centrality and density) comprise the "curricula–mathematics learning–mathematics teachers" cluster and the "mathematics–primary mathematics education–artificial intelligence" cluster. These two clusters drive the field, namely TPACK studies linked to curricula, primary school mathematics learning, and the use of AI.

The *niche themes* (high density, low centrality) include "blended learning", "digital tools", "mathematical knowledge for teaching", "initial teacher training", "digital technology", and "game-based learning". These themes have been studied in depth by specific communities but are weakly connected to the TPACK mainstream. The *emerging or declining themes* quadrant contains "tpack framework" and "higher-order thinking skills". "Tpack framework" is better read as a declining theme because the conceptual debate on the TPACK framework has subsided, whereas "higher-order thinking skills" lies right on the border with the *niche themes* and is better read as an emerging theme. Table 4 summarises the four quadrants together with topics that have been widely studied and those that have not.

Table 4. Four Categories of Research Themes on TPACK in Mathematics Education

Quadrant	Themes (Figure 6)	Widely studied	Not yet/rarely studied
Motor themes	Curricula; mathematics learning; mathematics teachers; primary mathematics education; artificial intelligence	Mathematics teachers' tpack in curriculum and lesson design, particularly in primary schools; early exploration of ai use	Impact of ai-assisted learning on students' mathematics learning outcomes; teachers' ai ethics and literacy; tpack-based curriculum development at the secondary level
Basic themes	Tpack; mathematics education; technology integration; teacher professional development; preservice teachers; improving classroom teaching	Measurement of teachers' and pre-service teachers' tpack (mostly surveys), professional development programmes, and general technology integration	Longitudinal studies of training impact; evidence of tpack from classroom observation rather than self-report only; links between tpack and improved teaching practice
Niche themes	Blended learning; digital tools; mathematical knowledge for teaching; initial teacher training; digital technology; game-based learning	Case studies in specific learning contexts (blended, game-based) and specific digital tools	Integration of tpack with mathematics-specific knowledge theory (mkt); game-based learning and blended learning linked to tpack development
Emerging or declining themes	Tpack framework (declining); higher-order thinking skills (emerging)	Conceptual discussion of the tpack framework (saturated)	Influence of teachers' tpack on students' higher-order thinking, reasoning, and mathematical problem solving

Table 4 reveals a consistent pattern: existing research focuses more on the teacher side (knowledge, perceptions, and training) than on the student side (learning outcomes and thinking skills). Themes directly related to students, such as *higher-order thinking skills*, *game-based learning*, and the improvement of classroom practice, lie in or near the peripheral quadrants. Moreover, AI has become a motor theme, but its weight is still small and it still centres on teachers' use of tools rather than on a framework of teacher knowledge specifically adapted to AI, such as *Intelligent-TPACK* (Celik, 2023).

WordCloud

The *WordCloud* answers the first part of RQ5, namely the most prominent keywords. The results are presented in Figure 7.

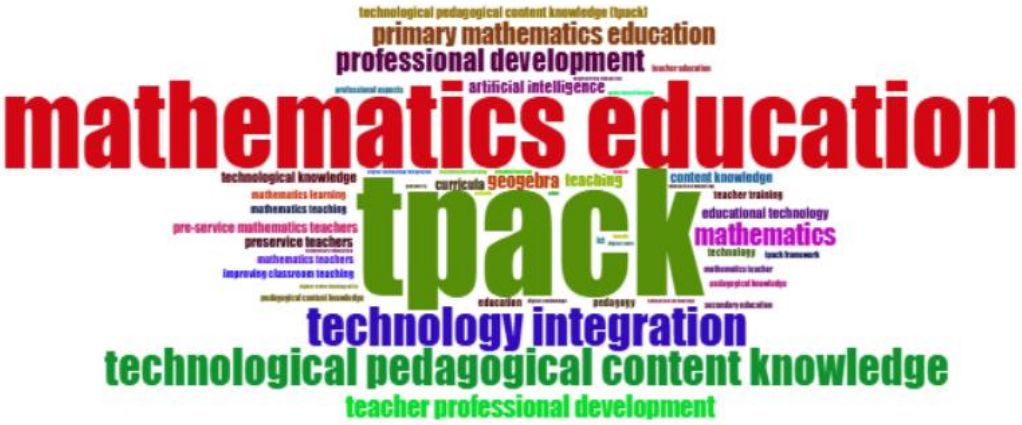


Figure 7. Keyword WordCloud

Figure 7 shows that "mathematics education" and "tpack" dominate, followed by "technology integration", "technological pedagogical content knowledge", "teacher professional development", "professional development", and "primary mathematics education". Second-tier keywords include "mathematics", "artificial intelligence", "geogebra", "curricula", "pre-service mathematics teachers", "preservice teachers", "content knowledge", and "technological knowledge". The dominance of keywords related to teacher development confirms that the main focus of the literature is the preparation and improvement of teacher competence.

What rarely appears is as important as what dominates. "Primary mathematics education" is prominent, whereas "secondary education" appears only in small type. GeoGebra is the only specific tool that stands out, so other tools such as statistical software, computer algebra systems, or AI platforms have received little attention. Yet development research in Indonesia has used a variety of digital media, such as Instagram Reels short videos for straight-line equations in junior high school (Wulandari et al., 2022) and an ethnomathematics-based electronic worksheet for geometry and measurement (Widodo et al., 2026), although such studies are generally not framed within TPACK. Keywords referring to specific mathematical topics (e.g., algebra, statistics, or calculus) are almost absent. A praxeological analysis of the presentation of linear algebra in Indonesian mathematics textbooks (Agustito et al., 2025) shows that topic-specific analysis can reveal how mathematical knowledge is organised for teaching; such a topic-specific approach has rarely been applied in TPACK research. Keywords related to students, such as learning outcomes or higher-order thinking skills, are also rare. Yet studies of students' cognitive processes in solving algebraic numeracy problems (Kinanti et al., 2023), higher-order problem solving (Irfan et al., 2023; Sulistyowati et al., 2019) and of teaching materials developed to improve pre-service teachers' critical thinking (Agustito et al., 2022) show that the thinking of students and pre-service teachers can be examined in depth and could potentially be linked to TPACK. This pattern reinforces the thematic map finding that TPACK research in mathematics education is still general and teacher-oriented, not yet topic-specific, and has rarely traced its impact on students. By comparison, TPACK studies that

focus on specific mathematical activities, such as mathematical inquiry with authentic problems, have been shown to produce richer forms of teacher knowledge (Koh, 2019).

Network Visualisation

The keyword co-occurrence network answers the second part of RQ5. The network visualisation is presented in Figure 8, where node colour indicates the cluster, node size indicates frequency, and line thickness indicates the strength of association.

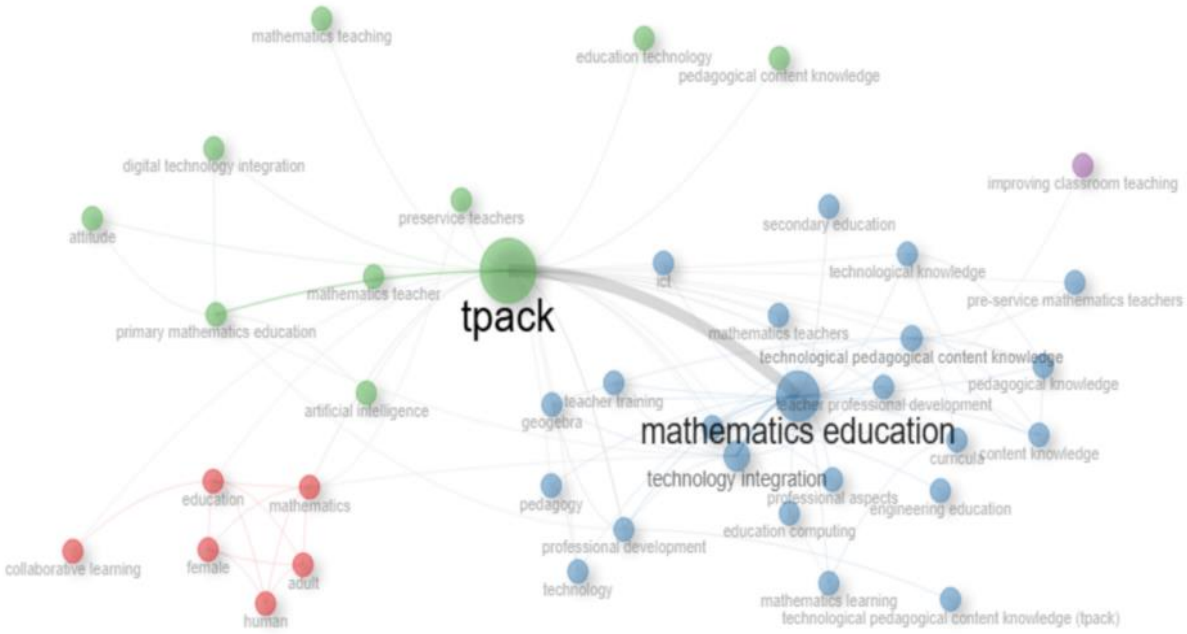


Figure 8. Keyword Co-occurrence Network

Figure 8 shows four clusters. The strongest link is between “tpack” and “mathematics education”, each of which is the centre of a different cluster. This indicates that the network has two centres: TPACK as a construct of teacher knowledge and mathematics education as its context of application. The green cluster is centred on “tpack” and includes “preservice teachers”, “mathematics teacher”, “mathematics teaching”, “primary mathematics education”, “digital technology integration”, “attitude”, “pedagogical content knowledge”, “education technology”, and “artificial intelligence”. This cluster represents studies of teacher characteristics, namely the knowledge, attitudes, and readiness of teachers and pre-service teachers, especially in primary schools. The position of “artificial intelligence” in this cluster shows that AI is still studied from the perspective of teachers’ readiness and attitudes rather than students’ learning processes.

The blue cluster is the largest and is centred on “mathematics education” and “technology integration”. It includes TPACK knowledge components (“technological knowledge”, “pedagogical knowledge”, “content knowledge”), teacher development contexts (“teacher training”, “professional development”, “pre-service mathematics teachers”), tools (“geogebra”, “ict”, “education computing”),

and curricular contexts ("curricula", "mathematics learning", "secondary education", "engineering education"). This cluster represents the operationalisation of TPACK, that is, how its knowledge components are measured and developed through particular training and tools. "Secondary education" lies at the edge of the cluster with few links, consistent with the *WordCloud* finding that the secondary level has rarely been studied.

The red cluster consists of "education", "mathematics", "human", "female", "adult", and "collaborative learning". Most of these terms are index keywords assigned by the database rather than author keywords, so they indicate the characteristics of study participants rather than research topics. This cluster is weakly connected to "tpack", meaning that demographic factors (e.g., gender and teaching experience) and collaborative learning are rarely analysed in relation to TPACK. The purple cluster contains only the isolated node "improving classroom teaching". This isolation is an important finding: improving classroom practice, which should be the ultimate goal of TPACK development, is not yet integrated into the research mainstream. A summary of the clusters is presented in Table 5.

Table 5. Keyword Co-occurrence Network Clusters and Their Meaning

Cluster	Main nodes	Research focus	Implications/gaps
Green	Tpack; preservice teachers; mathematics teacher; primary mathematics education; attitude; artificial intelligence	Knowledge, attitudes, and readiness of teachers and pre-service teachers, especially in primary schools	AI is still studied from the teacher side, not from students' learning processes and outcomes
Blue	Mathematics education; technology integration; technological/pedagogical/content knowledge; teacher training; geogebra; curricula; secondary education	Operationalisation of TPACK components through training, tools, and curricula	The secondary level is peripheral; tools other than geogebra are rarely studied
Red	Education; mathematics; human; female; adult; collaborative learning	Participant characteristics (index keywords) and collaborative learning	Demographic factors and collaborative learning are rarely linked to TPACK
Purple	Improving classroom teaching	Improvement of classroom teaching practice	Isolated; the link between TPACK and improved classroom practice is rarely demonstrated

Synthesis of Answers to the Research Questions

RQ1. TPACK research in mathematics education is a young, rapidly growing, and fully collaborative field. The corpus is dominated by recent publications (average age 3.19 years) spread across 74 sources, with an average of 10.95 citations per document and 21.77% international collaboration.

These characteristics indicate that the field does not yet have core journals or uniform terminology, so consolidating terms and expanding cross-country collaboration are the next needs.

RQ2. The publication trend is divided into a stable phase (2015–2022) and an acceleration phase (2023–2025) that accounts for 57.3% of the corpus. Compared with previous cross-disciplinary TPACK mappings that ended in 2019 (Suprapto et al., 2021) and 2022 (Bancong & Hambali, 2023), this study captures the acceleration phase, which coincides with the post-pandemic transformation of learning (Engelbrecht et al., 2020) and the arrival of generative AI (Mishra et al., 2023).

RQ3. Productivity is concentrated in a few institutions and authors, with Monash University (12 articles) and Mao Li (12 articles) as the most productive. However, the intellectual influence of the field comes from the most co-cited foundational works, namely Angeli and Valanides (2009), Chai et al., (2011), Mishra and Koehler (2006), and Agyei and Voogt (2012). This distinction is important for early-career researchers: productive authors show who is active today, while co-cited references show the theoretical foundations that must be cited.

RQ4. The same foundational references are used in many countries, with Australia, Indonesia, the United States, and Turkey as the largest contributors. Thematically, the field rests on TPACK, technology integration, and teacher professional development as basic themes, is driven by curricula, primary mathematics education, and AI, and has niche themes such as *blended learning* and *game-based learning* that are not yet connected to the mainstream.

RQ5. Keywords are dominated by terms related to teachers and technology integration. The network forms four clusters with two centres (TPACK and mathematics education), while the secondary level, collaborative learning, and the improvement of classroom practice are peripheral or isolated. These findings directly indicate the research gaps described in the following section.

Research Gaps and Research Agenda

The results above show that TPACK research in mathematics education has shifted from conceptualising the framework to applying it, but this application is still teacher-centred and has rarely been traced through to students and classrooms. This finding is in line with earlier reviews noting that TPACK research relies heavily on teachers' self-report data and seldom links it to actual practice (Voogt et al., 2013; Willermark, 2018). Studies of mathematics teaching with digital technology also emphasise that the added value of technology becomes visible only when it is linked to students' mathematical activity and to the teacher's role in orchestrating it (Clark-Wilson et al., 2020). A systematic review of TPACK in mathematics education likewise stresses the need for continuous technology-pedagogy training for teachers and pre-service teachers to overcome barriers such as low confidence and limited institutional support (Kholid et al., 2023). Based on the evidence from Figures 2–8, Table 6 summarises the research gaps and research recommendations.

Table 6. Research Gaps and Recommendations for Future Research

Aspect	Widely studied	Not yet/rarely studied (evidence)	Research recommendations
Subject and impact	Teachers' and pre-service teachers' TPACK: level of mastery, perceptions, training	Impact of teachers' TPACK on students' learning outcomes and higher-order thinking skills (HOTS in the emerging quadrant; "improving classroom teaching" isolated)	Experimental or quasi-experimental studies and multilevel designs linking teachers' TPACK with students' HOTS, reasoning, and problem solving, including analysis of students' cognitive processes (Kinanti et al., 2023)
Educational level	Primary mathematics education (motor theme)	Secondary and higher education ("secondary education" at the network periphery)	Studies of junior/senior high school mathematics teachers' and lecturers' TPACK on advanced topics such as algebra, calculus, and statistics, including digital media for junior high school (Wulandari et al., 2022)
Technology	General technology integration and GeoGebra	AI-oriented TPACK, including AI ethics and literacy (AI is a motor theme but its weight is small)	Development and validation of TPACK-AI or Intelligent-TPACK instruments and design research on AI-assisted mathematics learning (Celik, 2023; Mishra et al., 2023; Supriyadi & Kuncoro, 2023)
Content specificity	TPACK as a generic framework	Topic-specific mathematical TPACK and its integration with mathematical knowledge for teaching (MKT is in the niche themes)	Topic-based TPACK research (topic-specific TPACK) combining TPACK with MKT (Agustito et al., 2025; Ball et al., 2008; Koh, 2019)
Pedagogy	Teacher training and professional development	Collaborative learning, game-based learning, and blended learning linked to TPACK (red cluster and niche themes)	Intervention studies combining TPACK development with student-centred pedagogies
Methodology	Self-report surveys and case studies	Measurement based on observation, learning artefacts, and longitudinal designs (Willermark, 2018)	Use of mixed methods, classroom observation, and longitudinal studies of TPACK development
Context and collaboration	Single-country studies; dominance of Australia, Indonesia, the US,	Cross-country comparative studies (international collaboration only 21.77%)	Cross-country comparative research, e.g., Indonesia–Malaysia or Asia–Africa, using the same instruments

and Turkey

Implications of the Study

For researchers, Tables 4 and 6 can serve as a map for choosing topics that are not yet saturated, especially the impact of TPACK on students, AI-oriented TPACK, and the secondary level. For teacher education institutions, the dominance of themes on pre-service teachers and professional development indicates that mathematics teacher preparation programmes should include experience in designing technology-enhanced lessons on specific mathematical topics, not merely training in the use of tools. For policymakers in Indonesia, the country's position as a major contributor whose output is spread across many institutions points to the need for national research networks and international collaboration so that research findings are more consolidated.

Limitations of the Study

This study has several limitations. First, the data were drawn only from Scopus and limited to English-language articles, so publications in other databases (e.g., Web of Science, ERIC, or SINTA) and in other languages were not covered. Second, the query used only the phrases "TPACK" and "mathematics education", so articles using other terms such as "TPCK" or "mathematics teacher" without these phrases may have been missed. Third, the 2025 data are incomplete because they were accessed on 3 November 2025. Fourth, synonymous keywords (e.g., "TPACK", "TPCK", and "technological pedagogical content knowledge") were not harmonised with a thesaurus, which may split the same theme into several nodes. Fifth, automatic reference processing produced several artefacts in the *three-field plot*, such as title fragments ("among preservice teachers" and "through performance assessment") read as reference names. In addition, automatic author-name disambiguation may merge different authors with the same name. Sixth, citation indicators tend to undervalue recent articles, and bibliometric analysis maps topics and structures rather than the quality or substantive findings of each study. Future research is advised to use more than one database, harmonise keywords, and combine bibliometrics with content analysis.

CONCLUSION

The bibliometric analysis of 124 Scopus articles shows that TPACK research in mathematics education is developing rapidly, with an annual growth rate of 21.13% and 57.3% of the articles published in 2023–2025 (RQ1 and RQ2). The field is fully collaborative, but its international collaboration remains limited (21.77%). Monash University and Mao Li are the most productive institution and author, whereas intellectual influence derives from the foundational works of Angeli and Valanides, Chai et al., Mishra and Koehler, and Agyei and Voogt. This shows that productivity and influence are two distinct dimensions (RQ3).

Thematically, TPACK, technology integration, and teacher professional development are basic themes, whereas curricula, primary mathematics education, and AI are motor themes. Australia, Indonesia, the United States, and Turkey are the largest contributors and share the same theoretical foundations (RQ4). The keywords and the network show that research is still teacher-centred, while the secondary level, collaborative learning, and the improvement of classroom practice remain peripheral (RQ5). The main gaps identified are the scarcity of research on the impact of teachers' TPACK on students' learning outcomes and higher-order thinking skills, AI-oriented TPACK, secondary-level and topic-specific mathematical contexts, observation-based and longitudinal methods, and cross-country comparative studies. Future research is recommended to address these gaps through experimental or longitudinal designs, the development of TPACK-AI instruments, and cross-country collaboration. This mapping can serve as a reference for researchers, teacher education institutions, and policymakers in setting research agendas and professional development programmes for mathematics teachers.

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