



TPACK in Mathematics Education: a panorama from a Systematic Literature Review, 2006–2024

TPACK na Educação Matemática: um panorama a partir de uma revisão sistemática de literatura de 2006 a 2024

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Abstract: The integration of Digital Technologies in Mathematics Education has prompted investigations into the knowledge required for teaching, with particular attention to the Technological Pedagogical Content Knowledge (TPACK) framework. Based on this premise, this article presents a systematic literature review analyzing 94 studies published between 2006 and 2024, aiming to map academic production on Technological Pedagogical Content Knowledge in the context of Mathematics Education. The investigation was guided by five questions addressing descriptive characteristics, theoretical foundations, methodological approaches, teacher education, and Digital Technologies. The study identified GeoGebra as the predominant technology and highlights the need to expand the focus to other technologies. The review revealed a lack of research on initial and continuing education about and with digital technologies in teaching, as well as gaps in the knowledge articulated by teachers, which hinders understanding of educational processes and the replicability of practices. These findings indicate a need for mathematics teacher education supported by Mathematics TPACK.

Keywords: mathematics teaching, technological pedagogical content knowledge, digital technologies, teacher education.

Resumo: A integração das Tecnologias Digitais no ensino de Matemática tem impulsionado investigações sobre os conhecimentos necessários à docência, com destaque para o modelo Conhecimento Tecnológico e Pedagógico do Conteúdo (TPACK). Assumindo essa premissa, este artigo apresenta uma revisão sistemática de literatura que analisa 94 estudos publicados entre 2006 e 2024, objetivando mapear o panorama das produções acadêmicas do Conhecimento Tecnológico e Pedagógico do Conteúdo, no contexto da Educação Matemática. A investigação se baseou em cinco questões que abordaram as características descritivas, fundamentos teóricos, procedimentos metodológicos, formação docente e Tecnologias Digitais. O estudo indicou o GeoGebra como tecnologia predominante e

evidencia a necessidade de expandir o foco para outras tecnologias. Do *corpus*, destacou-se carência de pesquisas em formação inicial e continuada *sobre e com* Tecnologias Digitais no ensino, além de lacunas em relação ao conhecimento articulado pelos professores, o que dificulta a compreensão dos processos formativos e a replicabilidade das práticas. Esses achados indicam a demanda de uma formação docente em Matemática, apoiada no *Mathematics TPACK*.

Palavras-chave: ensino de matemática, conhecimento tecnológico e pedagógico do conteúdo, tecnologias digitais, formação com professores.

Introduction

The encouragement and expansion of Digital Technologies (TD) in Education still present limitations regarding pedagogical integration due, among other factors, to the low investment in both initial and continuing teacher education on this topic. Studies such as those by Vieira (2013), Cibotto (2015), Oliveira (2017), Colling (2017), Silva (2018), Bianchini (2020), and Gutiérrez-Fallas and Henriques (2020, 2021) point to difficulties in experiencing technologies during teacher education, especially in Mathematics teaching, and emphasize the need for research — such as that conducted by Niess (2005, 2012), Palis (2010), Araújo (2015), Richit (2015), Porto (2016), Lima (2019), and Purificação (2022) — aimed at curriculum reformulation and pedagogical dynamics that incorporate TD .

In this context, the theoretical-methodological model proposed by Punya Mishra and Matthew J. Koehler (2006) stands out by proposing the integration of technologies with a focus on “how” and “why” to use them, suggesting modifications in teacher education curricula and teaching methodologies. We adopt this theoretical perspective in which the knowledge necessary to teach with and about technology, especially in Mathematics, is rooted in Pedagogical Content Knowledge (PCK), as proposed by Lee Shulman (1986, 1987), a concept expanded by Technological Pedagogical Content Knowledge (TPACK), developed by Mishra and Koehler (2006). Within the context of Mathematics Education, Mathematics TPACK¹ (Palis, 2010) provides a basis for assessing the knowledge that teachers who teach Mathematics² need to develop when integrating and experiencing TD in their pedagogical practices.

We will use the expression “experiencing Digital Technologies in Mathematics Education,” which refers to the process of interacting intentionally, enabling the construction of theoretical and practical knowledge with and about TD in the educational context. This concept is grounded in Bondía’s (2002) notion of

¹ Refers to Technological Pedagogical Content Knowledge in Mathematics and will be retained in this text due to its international recognition and widespread use.

² Includes those in initial teacher education, continuing professional development, and in-service teaching, as well as those who teach across different educational contexts, modalities, and levels, regardless of their academic background.

experience, for whom experiencing is not simply witnessing or performing something, but rather being touched and transformed by what happens, thus promoting a change in the subject himself or herself.

From this perspective, experiencing TD goes beyond technical contact: it involves the constitution of the teacher as a subject who integrates technology, pedagogy, and content in an articulated manner, since, as Paulo Freire (1996, p. 34) states, “it is not enough to know what to do; one must know how to do it and how to experience doing it.” This implies a pedagogical intentionality that shifts the focus from which and how many TD are available to how and why they are used (Palis, 2010), an orientation already advocated by the International Society for Technology in Education (ISTE³) since the early 2000s and reaffirmed by the National Council of Teachers of Mathematics (NCTM⁴, 2014). When integrated with such intentionality, TD transcend the condition of complementary tools and begin to act as mediators in the construction of mathematical knowledge with and about technology (Cunha, 2018; Paiva et al., 2023).

According to Niess (2005), in order to teach Mathematics, teachers need to understand mathematical content (Content Knowledge: CK), pedagogical processes (Pedagogical Knowledge: PK), and available technologies (Technological Knowledge: TK), understandings that may be progressively developed through intentional educational processes. TPACK can be integrated into the teaching of any area of knowledge and highlights the importance of experiencing these forms of knowledge individually, in pairs⁵, and in an integrated manner. This enables teachers to consider how to teach mathematical concepts with the support of technology, making the content accessible to students (Mishra & Koehler, 2006).

Therefore, mapping the panorama of academic production on TPACK in Mathematics Education becomes relevant, as it allows the identification of gaps, trends, and possibilities for teacher education with TD. To this end, the Systematic Literature Review (SLR) presented here analyzes 94 studies published between 2006 and April 2024, both nationally and internationally, selected according to specific inclusion and exclusion criteria. The investigation was guided by questions

³ A non-profit organization founded by K–12 and higher education educators with an interest in the integration of technology in education. It publishes the ISTE Standards, a set of frameworks designed to guide educators, leaders, and teacher educators in the pedagogical use of Digital Technologies (ISTE, 2023).

⁴ A global organization dedicated to the teaching and learning of Mathematics in K–12 education. It publishes scholarly journals, curriculum standards, and guidance documents for mathematics education (NCTM, 2014).

⁵ Pedagogical Content Knowledge (PCK), Technological Pedagogical Knowledge (TPK), and Technological Content Knowledge (TCK).

related to the characteristics, theoretical foundations, methodological approaches, contributions, and impacts of pedagogical interventions based on TPACK in teacher education, as well as the use of TD in Mathematics TPACK. Based on these questions, five categories of analysis were defined: Descriptive Data, Theoretical Foundations, Methodological Procedures, Teacher Education, and Practical Application.

Methodology

The eight stages of the SLR process suggested by Ramos et al. (2014) were considered: (i) Objectives; (ii) Research Equations; (iii) Research Scope; (iv) Inclusion Criteria; (v) Exclusion Criteria; (vi) Methodological Validity Criteria; (vii) Results; and (viii) Data Processing.

The Objectives stage refers to the definition of goals that guide the review and includes open-ended questions that may be answered with qualitative information obtained from the analysis of sources (Morandi & Camargo, 2015). Five questions were developed to guide the SLR: (i) What are the descriptive characteristics of TPACK studies in Mathematics Education? (ii) What theoretical foundations support these studies? (iii) What methodological approaches are employed? (iv) What are the contributions and impacts of TPACK-based pedagogical interventions in teacher education? (v) Which TD are being experienced in Mathematics TPACK studies, and how are they being experienced?

The Research Equations stage defines the scope of the investigation and employs keywords and operators such as AND and OR to direct the search for theoretical or empirical studies related to the theme. The central terms selected were: ((TPCK OR TPACK) AND (Mathematics Education OR Mathematics Teaching OR Mathematics OR Mathematics OR Math Teacher* OR Mathematics Teacher*)) OR ((Technological Pedagogical Content Knowledge) AND (Mathematics Education OR Mathematics Teaching OR Mathematics OR Mathematics OR Math Teacher* OR Mathematics Teacher*)).

The Research Scope considered documents available in databases and repositories such as the CAPES Journal Portal, the Brazilian Digital Library of Theses and Dissertations (BDTD), the Scientific Electronic Library Online (SciELO), the Education Resources Information Center (ERIC), and Google Scholar.

The Inclusion and Exclusion Criteria stages function as filters for selecting theoretical or empirical studies to be analyzed (Costa & Zoltowski, 2014). The

application of these criteria involves reading titles, keywords, and abstracts in order to identify relevant similarities (Morandi & Camargo, 2015).

The Inclusion Criteria adopted were: (i) free and complete theoretical or empirical studies; (ii) publications between 2006 and April 2024, a time frame justified by the fact that 2006 corresponds to the year in which the TPACK model was published by Mishra and Koehler, marking the beginning of the field, and April 2024 corresponds to the month in which the searches were conducted; (iii) the presence of the selected terms in titles, keywords, or abstracts; (iv) textual elements answering the research questions, initially identified through an exploratory reading of the title, abstract, and introduction; and (v) publications in Portuguese, English, or Spanish. The Exclusion Criteria were: (i) absence of the central terms in the title, abstract, or keywords; (ii) publications outside the defined time frame; (iii) duplicate studies; (iv) materials not freely and fully available; and (v) studies that mention TPACK and/or Mathematics Education without constituting them as the central object of investigation, that is, without theoretical articulation or data analysis linked to these constructs.

The Methodological Validity Criteria stage sought to ensure the quality of the selected studies. To evaluate validity, the following aspects were considered: clarity of objectives; coherence between objectives, methods, and results; and contribution to Mathematics Education based on the TPACK framework. As an indicator of validity, it was considered that scientific articles had undergone peer review and that theses and dissertations had been evaluated by an Examination Committee. The sequential application of the search filters, inclusion and exclusion criteria, and validity criteria resulted in the structure presented in Table 1.

Table 1

Number of documents retrieved from databases

Database	Search strategy results	After inclusion criteria	After exclusion criteria
Google Scholar	5090	175	31
Capes	139	35	10
BDTD	109	38	27
ERIC	43	25	19
SciELO	13	9	7
Total	5394	282	94

Note. Prepared by the authors (2025).

In the Results stage, 94 publications were selected to compose the corpus of this research and will be analyzed below.

Analysis and Discussion of Results

Table 2 organizes the 94 publications according to code, authors, year, and location, comprising 58 journal articles, 18 doctoral theses, 10 master's dissertations, 7 conference papers, and 1 book chapter. The publications were coded to facilitate identification: AE for conference papers, A for journal articles, CL for book chapters, D for dissertations, and T for thesis. For example, D1 indicates the first dissertation, and A23 the twenty-third journal article, according to chronological organization.

Table 2

References of publications by year and ascending order

Cod e	Author(s)	Ano	Country	Cod e	Author(s)	Ano	Country
A1	Niess <i>et al.</i>	2009	USA	A23	Young <i>et al.</i>	2019	USA
A2	Erdogan, Sahin	2010	Turkey	A24	Morales-López	2019	Costa Rica
A3	Palis	2010	Brazil	A25	Hernawati	2019	Indonesia
A4	Bowers, Stephens	2011	USA	A26	Colling&Richit	2019	Brazil
A5	Agyei&Voogt	2012	Australia	A27	Bakar	2019	Malaysia
D1	Mazon	2012	Brazil	AE7	Davis	2020	USA
D2	Lima	2013	Brazil	A28	Mastroianni & Oliveira	2020	Brazil
T1	Vieira	2013	Brazil	A29	Gutiérrez-Fallas& Henriques	2020	Portugal
AE1	Belfiori	2014	Argentina	A30	Colling&Richit	2020	Brazil
A6	Sampaio & Coutinho	2014	Portugal	A31	Abdul Halim <i>et al.</i>	2020	Malaysia
T2	Baldini	2014	Brazil	D8	Bianchini	2020	Brazil
A7	Powell	2014	Brazil	A32	Farias <i>et al.</i>	2020	Brazil
A8	Bittar	2015	Brazil	A33	Nonato & Lobo da Costa	2020	Brazil
AE2	Costa Neto <i>et al.</i>	2015	Brazil	A34	Nantschevet <i>al.</i>	2020	9 european countries
A9	Sampaio & Coutinho	2015	Portugal	A35	Bakaret <i>al.</i>	2020	Malaysia
T3	Alcântara	2015	Brazil	A36	Gutiérrez-Fallas& Henriques	2021	Portugal
T4	Esquincalha	2015	Brazil	A37	Maldonado & Solís	2021	Israel
T5	Rocha	2015	Brazil	A38	Costa	2021	Brazil
T6	Padilha	2015	Brazil	T13	Gutiérrez-Fallas	2021	Portugal
T7	Araújo	2015	Brazil	D9	Silva	2021	Brazil
T8	Cibotto	2015	Brazil	T14	Sampaio	2021	Portugal
T9	Richit	2015	Brazil	T15	Teixeira	2021	Brazil
A10	Martínez-Hernández & Aké	2016	Mexico	A39	Marbán&Sintema	2021	Spain
A11	Sampaio	2016	Portugal	A40	Gonzales & Gonzales	2021	Philippines
D3	Porto	2016	Brazil	A41	Ribeiro & Piedade	2021	Brazil
A12	Oller-Marcén& Arnal-Bailera	2017	Spain	A42	Morales-López <i>et al.</i>	2021	Costa Rica
A13	Cyrino & Baldini	2017	Brazil	A43	Rakeset <i>al.</i>	2022	USA
D4	Alexandrino	2017	Brazil	A44	Bueno <i>et al.</i>	2022	Brazil
D5	Oliveira	2017	Brazil	A45	Purificação & Amado	2022	Portugal
D6	Colling	2017	Brazil	A46	Meza <i>et al.</i>	2022	Peru
A14	Oliveira <i>et al.</i>	2018	Portugal	A47	Santo <i>et al.</i>	2022	Brazil
A15	Rocha & Prado	2018	Brazil	A48	Bretscher	2022	United Kingdom

A16	Salas-Rueda	2018	Mexico	A49	Pelizzaro <i>et al.</i>	2022	Brazil
AE3	Gutiérrez-Fallas & Henriques	2018	Portugal	T16	Abreu	2022	Brazil
A17	Alizadeh-Jamal <i>et al.</i>	2018	Iran	T17	Purificação	2022	Brazil
A18	Basniak & Estevam	2018	Brazil	CL1	Prioló <i>et al.</i>	2023	Colombia
A19	Trujillo <i>et al.</i>	2018	Cuba	A50	Carneiro & Souza Junior	2023	Brazil
A20	Durusoy & Karamete	2018	Turkey	A51	Carneiro & Souza Júnior	2023	Brazil
A21	Karakus	2018	Turkey	A52	Purificação & Amado	2023	Brazil
A22	Kim	2018	USA	A53	Silva <i>et al.</i>	2023	Brazil
AE4	Niess & Roschelle	2018	USA	A54	Juandiet <i>et al.</i>	2023	Indonesia
AE5	Morelatti & Fujita	2018	Brazil	A55	Slaviero <i>et al.</i>	2023	Brazil
T10	Nunes	2018	Brazil	A56	Hamidy & Wibowo	2023	Indonesia
T11	Silva	2018	Brazil	A57	Kittivarakulet <i>et al.</i>	2023	Thailand
D7	Lima	2019	Brazil	D10	Souza	2023	Brazil
T12	Araújo Filho	2019	Brazil	A58	Ruas <i>et al.</i>	2024	Brazil
AE6	Richit & Miskulin	2019	Brazil	T18	Kleemann	2024	Brazil

Note. Prepared by the authors (2025).

The categories of analysis were defined as a priori based on the guiding questions and organized into five groups: Descriptive Data, Theoretical Foundations, Methodological Procedures, Teacher Education, and Practical Applications. The analysis was conducted through a systematic reading of the studies in full, with the extraction and organization of information into summary tables, followed by a qualitative interpretation of the patterns identified in each category.

Descriptive Characteristics of TPACK in Mathematics Education

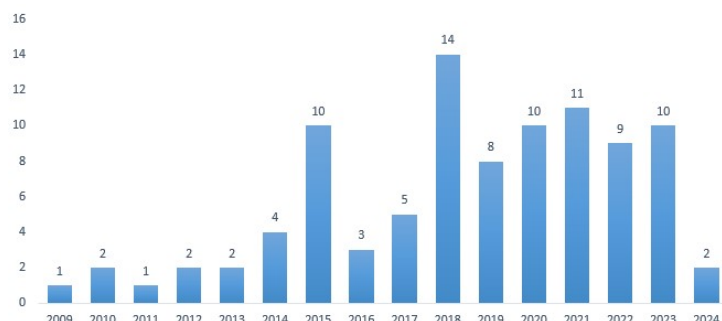
This section addresses the following question: What are the descriptive characteristics of TPACK studies in Mathematics Education? To this end, data regarding publication type, temporal and geographical distribution, recurrence of authors, and educational levels covered in the analyzed corpus are presented.

Since 2006, when Punya Mishra and Matthew J. Koehler published the seminal article on TPACK, a progressive global growth in references to the topic in Mathematics Education has been observed, as evidenced in Figure 1. The annual distribution of publications reveals gradual growth over the years, with a notable increase beginning in 2014. The year 2018 concentrated the highest number of publications, totaling 14 studies. Since 2020, the number of publications has increased considerably due to the popularization of mobile devices and digital platforms in classrooms, possibly reinforced by the emerging demands of remote

teaching. This movement suggests a growing research interest in expanding access to TD.

Figure 1

Graph of publications per year



Note. The figure shows the annual variation in publications, highlighting periods of growth and greater concentration of studies in certain years.

Figure 2 presents a broad geographical distribution, encompassing several continents. In South America, Brazil leads with 53 studies; the variety of countries represented in the international scenario indicates the relevance of the topic in distinct contexts, including both developed and developing nations, which highlights its global reach.

Figure 2

Distribution of publications by continent



Note. The figure demonstrates the presence of publications across different continents, showing the international reach of research on the topic.

The corpus indicates the following distribution by educational level: 2 studies focused on the Early Years of Elementary Education, 5 on Elementary Education, 6 on Secondary Education, and 4 encompassing Basic Education in general. Higher Education concentrated 25 publications aimed at pre-service teachers, reflecting the

emphasis placed on this educational level. The remaining 52 studies did not address a specific educational level. Only 17 studies focused on Basic Education, the educational modality in which teachers who teach Mathematics carry out their professional practice. These teachers are challenged to integrate diverse digital platforms, often without adequate preparation or educational support. This scenario reveals a mismatch between academic production on TPACK and the concrete demands of the classroom.

Theoretical Foundations of TPACK in Mathematics Education

This section addresses the research question: What theoretical foundations support these studies? To this end, the terms, frameworks, and theoretical approaches identified in the corpus are analyzed, beginning with the terminological diversity surrounding the concept of technology.

Several synonyms and variations are used for the term “technology,” such as digital and technological resources, digital technologies, technological tools, technological applications, technological knowledge, equipment, TIC, TDIC, among others. Terms such as insertion, integration, incorporation, use, appropriation, utilization, and articulation are frequently associated with the word technology and highlight different approaches and contexts.

Within the corpus, the terms “integration” and “use” appear most frequently. According to Bittar (2010), integrating technology consists of mobilizing it to contribute to student learning. Costa and Prado (2015) emphasize that integrating technology goes beyond merely placing it in the classroom; it requires exploring its potential in Mathematics teaching, something that many teachers did not have the opportunity to practice during their education (A1). The authors of A41 suggest that the development of TPACK may lead teachers to experience TD in their pedagogical practices.

Despite terminological variations and, at times, the interchangeable use of certain terms, all approaches in the corpus refer to TK, one of the pillars of TPACK, although technologies may, in some cases, be employed only for teachers’ bureaucratic work, a use that Bueno et al. (2023) describe as peripheral, distant from intentional pedagogical integration.

The theoretical foundation of these studies reveals that only works A16, A37, A38, A56, and AR7 do not cite the seminal article by Punya Mishra and Matthew J. Koehler (2006). The theoretical-methodological model derived from Lee Shulman

(1986) is represented in all dissertations and theses through the Venn Diagram illustrating the interrelationships among pedagogical, technological, and content knowledge. Thirty-nine publications include this visual representation, with variations in some layouts, while the others maintain the original design. Altogether, 67 studies incorporated the figure, emphasizing its theoretical and practical relevance and its widespread acceptance among researchers.

This finding, however, requires critical interpretation. Mishra and Koehler (2006) conceive TPACK not as a static representation of teachers' knowledge, but as a dynamic model constituted through the situated articulation among content, pedagogy, and technology within specific teaching and learning contexts. In this sense, the recurrence of the Venn Diagram without a corresponding explanation of the knowledge mobilized in educational processes may indicate a predominantly illustrative appropriation of the framework, converging with the gap identified in the corpus: the insufficient description of how this knowledge is integrated into teaching practice.

The first studies on TPACK in Mathematics Education emerged in 2009, especially A1. This pioneering article presented a TPACK development model for teachers who teach Mathematics, structured into five levels of TD integration into pedagogical practices: Recognizing (knowledge)⁶, Accepting (persuasion), Adapting (decision), Exploring (implementation), and Advancing (confirmation). It emphasized four essential aspects of teaching practice — Curriculum and Assessment, Learning, Teaching, and Access — which are central elements in the development of TPACK during teacher education. These levels are discussed in A3, A6, A14, A17, A43, A55, D9, T1, T4, T10, T14, and T18.

Study A3 addresses TPACK in a context in which the conceptions of Shulman (1986, 1987) had already been recognized in Brazilian research. The study highlights that, despite progress in knowledge related to TD, teachers are still not prepared to integrate them into pedagogical practices. The author emphasizes the need for teacher education that incorporates TPACK, pointing out that the lack of TD integration in educational activities constitutes an obstacle to the connection between CK and TK. In this context, a development model based on Niess et al. (2009), called Mathematics TPACK, is proposed.

Mathematics TPACK is presented by Palis (2010) as a reference for teachers at all educational levels. Although the Association of Mathematics Teacher Educators (AMTE, 2009) establishes objectives for integrating technologies into teacher

⁶ Original terminology used by Rogers (1995) is presented in parentheses.

education, its three-page document does not detail how teachers may appropriate this knowledge.

To fill this gap, the authors of articles A1 and A3 propose a model describing the progression of Mathematics TPACK through the five previously mentioned levels, emphasizing that this process is neither linear nor uniform among teachers. Bueno et al. (2023), in research involving Brazilian teachers, empirically identified participants still situated at the acceptance level, referring to TD in a peripheral manner, which highlights the relevance of this model for understanding the actual stages of teacher development.

Thesis T1, published in 2013, was the first to address TPACK in Mathematics Education based on A1 and A3. T10 reinforces that, until the publication of these studies, TPACK lacked a solid foundation for integrating TD into the curriculum, revealing that technological advancement in education had not kept pace with its evolution.

Methods and Techniques for Data Collection and Analysis

This section addresses the research question: What methodological approaches are used in TPACK studies in Mathematics Education? From a methodological perspective, quantitative designs predominate (66%), whereas qualitative investigations represent 34%. Questionnaires stood out in 36 studies, often combined with interviews or educational interactions. Other methods included standalone interviews (22 studies), observations (11 studies), document analysis, tests, educational practices, experimental activities, and recordings. The approaches varied among structured, exploratory, and educational methods, reflecting the diversity of techniques employed.

Empirical studies (62) predominate over theoretical ones (32), with 13 focusing on initial teacher education, 18 on continuing education, and two encompassing both. Study A41 emphasizes that, in Brazil, educational initiatives began with specialization and postgraduate programs before being incorporated into initial teacher education curricula, reflecting the growing recognition of technology in teaching. Initial and continuing teacher education therefore constitute a central focus of analysis in this review and are explored in greater depth in the following section.

Teacher Education: Contributions and Impacts of TPACK-Based Pedagogical Interventions

This section addresses the research question: What are the contributions and impacts of TPACK-based pedagogical interventions in teacher education? Of the 94 publications, 33 addresses are initial and continuing teacher education — a considerably low number given the relevance of educational actions for the integration of TD into Mathematics teaching. The first educational-oriented study was published in 2011, as presented in Table 3, and although the number of publications has grown over the years, it is still insufficient to meet the central role of teacher educational processes. Initial teacher education alone does not fulfill educational demands; the scarcity of research on continuing teacher education reveals a gap that requires further investigation and intensified research efforts.

Table 3

Number of Publications on Initial and Continuing Teacher Education

Ano	2011	2013	2014	2015	2016	2017	2018	2019	2020	2021	2023
Number of Pub.	1	1	1	7	1	4	3	5	6	2	2

Note. Prepared by the authors (2025).

The research described in A14 involved 10 teachers in 10 weekly meetings, totaling 30 hours, using Moodle for support materials and focusing on the creation of programs with Scratch integrated into TPACK. During the meetings, the teachers reflected on TPACK and developed software to generalize numerical sequence patterns, integrating TCK and PCK. Although the practical and collaborative approach was positive, continuous reflection and the adaptation of pedagogical and technological methods are still necessary.

A13 and T2 involved both initial and continuing teacher education and were developed within the Community of Practice for Mathematics Teacher Education (CoP-FoPMat)⁷. In A13, 12 in-service teachers and 9 pre-service teachers participated in 25 weekly meetings lasting 1 hour and 40 minutes each, focused on integrating GeoGebra and articulating TPACK knowledge. Positive aspects included collaboration, mutual learning, and professional growth. A13 presented mobilized knowledge such as the classification of quadrilaterals, properties of triangles, area

⁷A Community of Practice focused on training teachers who teach Mathematics, coordinated by Professor Dr. Márcia Cristina Costa Trindade Cyrino at the State University of Londrina (UEL).

and perimeter calculations, and the study of functions as CK; the appreciation of students' productions and articulated tasks as PK; and the use of GeoGebra for figure construction as TK.

The research reported in T2 involved 12 teachers and 9 pre-service teachers in 25 meetings using GeoGebra. It mobilized CK (the Pythagorean Theorem), PK (classroom management and challenging students), PCK (teaching the theorem through the integration of mathematical content), TK (constructing figures in GeoGebra), TCK (exploration of the software's properties and resources), TPK (teaching strategies using the software), and TPACK (effective strategies highlighting GeoGebra's potential). The software was praised for facilitating geometric visualization and the understanding of concepts. However, difficulties emerged, such as lack of equipment, scheduling problems, resistance, and absence of technical support in the computer laboratory.

Table 4 synthesizes the information extracted from D3, D5, D7, D8, T1, T3, T5, T6, and T11, providing an overview of continuing teacher education in postgraduate contexts, described in terms of organization, participants, duration, articulated TPACK knowledge, and main challenges.

Table 4

Summary of Continuing Teacher Education Programs Reported in Dissertations and Theses

Pub.	Focus of the Training Program	Participants/ Duration	TPACK Knowledge Mobilized	Main Challenges
D3	GeoGebra on mobile devices — functions	18 teachers / 6 sessions (4 h)	TCK (GeoGebra used to explain content)	Resistance to change; lack of infrastructure
D5	GeoGebra in Secondary Education — quadratic functions	6 teachers / 6 sessions (5 h) + distance activities (30 h)	CK (canonical form ⁸); PCK (relevance of teaching the content); TCK (concepts explored through the software)	Additional time required; challenging GeoGebra constructions
D7	Collaborative lesson planning with Learning Objects (LOs) for fractions — OBAMA platform ⁹	3 teachers / weekly meetings (2 months)	CK, PK, and TK (LOs for fractions, objectives, and pedagogical strategies)	Lack of internet access; heavy workload; insecurity regarding CK
D8	TPACK-based professional development practices — Science and Mathematics	12 teachers / 5 face-to-face meetings + distance activities (20 h)	CK (perimeter, area, fractions); TPK (software para Ciências e Matemática)	Software unavailability; software; insecurity regarding CK

⁸ A simplified way of representing an equation or function.

⁹ Learning Objects for Mathematics.

T1	Geometric figures using <i>SketchUp</i> , Ruler, Compass, and Construíg3D	4 teachers / 18 face-to-face meetings	CK (Geometry); TK and TPK (teaching Geometry with TD); TCK (<i>software</i> para Geometry)	Non-linear progression; need for continuous professional development
T3	<i>Tablets</i> nos Anos Iniciais — <i>mentoring</i> as a strategy	9 teachers / 11 meetings (40 h)	CK (Geometry, fractions, operations); TK (<i>tablet</i> e computador)	Adapting to students' needs; classroom management
T5	Programming with <i>Scratch</i> — <i>construcionismo</i> ¹⁰ de Papert	10 teachers / 2 courses of 30 h each	CK (Mathematics and curriculum); TK (<i>Scratch</i>); PK (strategies and mediation); PCK (instructional materials)	Partial appropriation of CK; resistance to new representations
T6	<i>Tablets</i> and GeoGebra — first-degree polynomial functions	6 teachers / 5 face-to-face meetings	CK (functions); TK (<i>tablet</i> e <i>software</i>)	Insufficient time; lack of administrative support; distraction
T11	GeoGebra 3D — Polyhedra in Secondary Education (online)	30 professores / 6 meetings + distance activities (30 h)	TK (GeoGebra 3D); CK (Polyhedra); PK (new ways of teaching Geometry)	Professional isolation; colleagues' distrust

Note. Prepared by the authors (2025).

The results reveal how TPACK was developed throughout the educational processes through the articulation of different forms of knowledge. CK appears in D5 (definition of canonical form), D8 (perimeter, area, fractions, numbers, and operations), and T1 (geometry). Experiencing TD is evidenced in D3 (selection of GeoGebra), T1 (reflections on integrating TD into geometry teaching), and T5 (Scratch). PK emerges in D7 (which Learning Objects to use) and in T5 (learning strategies and mediation through software). The combination of knowledge occurs in D5 (PCK when discussing the relevance of teaching canonical form and TCK when applying concepts within the software), in D8 (TPK when using software for Science and Mathematics), and in T1 (TCK when employing software for geometry teaching).

It is observed that teachers often did not explicitly state the specific forms of knowledge addressed during the educational processes aimed at developing TPACK. AE4, AE6, A7, A31, and A32 detailed structure and objectives, but did not describe how the meetings were conducted or which forms of knowledge were mobilized. This silence contrasts with what Niess (2005) and Palis (2010) proposed: the development of Mathematics TPACK is progressive rather than spontaneous and depends on educational processes that explicitly articulate CK, PK, and TK. The absence of a shared knowledge base hinders the continuity of achieved advances

¹⁰ Constructionism is a theory proposed by Seymour Papert, based on Piagetian constructivism, according to which learning occurs when the student builds something concrete and shareable, learning through action and creation (Papert, 1994).

(Hiebert & Morris, 2003) and indicates the need for future research to provide detailed evidence regarding these forms of knowledge.

Among the positive aspects, the following stand out: teachers' interest and engagement (D3, D5, T3); development of knowledge and skills (D7, D8, T1, T4); collaboration (D7, T4, T11); autonomy and motivation (D8, T3, T6); and experience with TD (T4, T5, T6). Among the negative aspects, technical problems and lack of infrastructure stand out (AE05, D3, D7, D8, T4), as well as lack of time combined with excessive workload (D3, D7, T6, T8, T9). Difficulties in integrating TD (D5, D8, T5, T6), resistance to change (A51, D3, T5), and the absence of longitudinal education or continuous support (T1, T11) were also reported.

In A36, teachers did not have opportunities to implement classes with TD in real contexts, while in T12 there were difficulties in planning technology-based lessons, which demands more detailed planning. In A12, teachers demonstrated CK and TK, but faced difficulties integrating PK, especially in tasks combining all forms of knowledge. The results reinforce the importance of continuing teacher education in addressing these gaps.

The integration of TD into Mathematics classes often encounters resistance from teachers, which cannot be attributed to a single factor. Among the external barriers are time limitations, lack of institutional support, and precarious school infrastructure — factors that, when combined, tend to reinforce resistant attitudes. Internal barriers include consolidated beliefs about teaching with TD and fear of technical failures, which, according to Bueno et al. (2023), keep many teachers at an initial stage of acceptance without advancing toward intentional and contextualized pedagogical integration.

Digital Technologies Experienced in Mathematics TPACK

This section addresses the research question: Which TD are being experienced in Mathematics TPACK studies, and how are they being experienced? Among the publications in the corpus, which encompass studies in Mathematics Education and related areas, several TD were identified and distributed into three categories. Among the software programs, the most prominent are GeoGebra, The Geometer's Sketchpad, Winplot, Scratch, Graphmatica, Desmos, Derivative Calculator, PhotoMath, Mathway, Cabri-Géomètre, among others. As digital platforms, the studies mention Moodle, Google Classroom, Google Drive, Kahoot!, WebLEM, Plataforma Obama, and Open Roberta. Among applications and digital

resources, the studies cite tablets, the interactive whiteboard (IWB), graphing calculators, Microsoft PowerPoint, Canvas, Poli, Python, MATLAB, Scratch, Raptor, and TinkerPlots.

This variety of TD was cited by the authors of the analyzed studies in teaching contexts and in initial and continuing education for teachers who teach Mathematics. Their mention indicates familiarity with these technologies but does not necessarily imply that they were experienced in the classroom in an intentional and articulated manner connected to mathematical content. GeoGebra stands out as the predominant software, being cited in 62 publications. Some studies merely mention it as a complementary resource for Mathematics teaching and learning, whereas others explore specific applications and demonstrate their effective uses.

Among the 31 publications on initial and continuing teacher education that integrated TD, GeoGebra was the predominant technology, employed in content areas such as Geometry (A31, A32), geometric figures (A13, A24), Linear Algebra (AE6), quadratic functions (D5), fractions (D7), polynomial functions (T6), and polyhedra (T11). Other TD were also explored: tablets (T3, T6), Open Roberta (A50, A51), PhET Colorado (D8), OBAMA (D7), Moodle (T9), SketchUp, ruler, compass, and Construfig3D (T1), Poli (A32), Winplot and Excel (T4, T9), and Grapher (T6). T5 and A15 developed practical programming activities with Scratch.

The contents identified in the corpus were organized according to the five thematic units of the Base Nacional Comum Curricular (BNCC, Brazil, 2018), presented in Table 5. Geometry and Algebra stand out due to their applicability, mainly because of the recurrent use of GeoGebra; the remaining contents appear in conversations among teachers, lesson plans, or theoretical discussions, without necessarily indicating classroom implementation.

Table 5

Mathematical Content Organized According to the BNCC Thematic Units

Thematic Unit	Mathematical Content
Numbers	- Fractions (D7) - Mean, median, and mode (T13)
Algebra	- Construction and analysis of mathematical functions (D3) - Identification of roots, maximum points, and minimum points in graphs (D3) - Quadratic functions (D5, T8, T10, T12) - Linear functions (D9, T10, T12) - First-degree polynomial functions (T6) - Trigonometric functions (D9) - Matrices and determinants (T7)
Geometry	- Construction and manipulation of geometric figures (T1, T2) - Pythagorean Theorem (T2) - Construction of geometric solids (T3) - Geometry plana (T7)

		- Perimeter and area (D8, T17)
		- Polygon diagonals (D9)
		- Angles and their measures, geometric constructions, and arc studies (T16)
		- Geometric properties of circles and triangles (T2)
		- Algebraic, numerical, and geometric mathematical representations (T9)
Quantities	and	- Relationship between degrees and radians (T9)
Measures		- Measurement of lengths and areas in a polygon (T12)
Probability	and	- Probability (D4, T7)
Statistics		

Note. Prepared by the authors (2025).

In addition to mathematical content, publications A15, A47, A50, A51, D4, and T5 address topics such as Robotics, programming with Scratch, and Financial and Tax Education. For example, D4 focuses on the development of an educational product on Robotics, with activities also related to probability.

AE5 carried out 36 projects using Applet, GeoGebra, Superlogo, Logo, Draw Function, and Microsoft Excel to address mathematical content in Elementary and Secondary Education. A32 employed Poli, GeoGebra, and educational games following the f@r¹¹ model. The educational process emphasized collaboration and a discussion-oriented environment.

A50 and A51 used the Open Roberta platform to develop knowledge in Robotics and Mathematics based on Robotics and Pedagogical Mathematics Knowledge (RPAMK)¹², teaching block-based programming and constructing geometric figures. The contributions included knowledge in robotics, pedagogical strategies, teamwork collaboration, and platform accessibility. In A51, participants carried out specific tasks such as constructing equilateral triangles and pentagons through programming, applying concepts of internal and external angles.

Study A15 focused on Scratch to develop mathematical content by addressing Geometry and Trigonometry (movement on the Cartesian plane and figure construction), Algebra (patterns and numerical sequences), Arithmetic (mathematical operations), and Logic (logical operators and comparisons in problem-solving situations).

Thesis T5 explored the integration of programming into Mathematics teaching by using Scratch to develop mathematical concepts. It addressed Geometry (construction of geometric figures, visualization of angles and areas), Arithmetic

¹¹It is a training program built upon five stages, namely: vision, plan, practice, interaction, and reflection.

¹²RPAMK (Robotics and Pedagogical Awareness of Mathematics Knowledge) is an approach that articulates pedagogical knowledge, mathematical knowledge, and knowledge about Educational Robotics for the training of teachers who teach Mathematics.

(basic operations and fractions), and Algebra (manipulation of algebraic expressions and numerical patterns).

Various technologies and mathematical contents were mentioned, highlighting the diversity of TD addressed in the corpus. However, the variety of mentions does not necessarily imply intentional pedagogical integration. Harris, Mishra, and Koehler (2009) warn that many educational approaches are still restricted to technical exposure to TD, which is insufficient because learning about technology is not equivalent to experiencing it in a contextualized, pedagogical, and critical manner.

In this direction, Palis (2010) argues that integrating TD into Mathematics teaching does not correspond to the simple juxtaposition of digital resources onto an already established practice; rather, it implies their participation in conceptual and procedural development, problem-solving, and assessment — aspects that Mathematics TPACK translates into five progressive levels of teacher thinking and understanding.

To overcome these limitations, especially the dependence on GeoGebra and the scarcity of educational processes that articulate mathematical content and TD in a contextualized way, Mathematical Modeling (MM) integrated with TD emerges as a grounded possibility. This articulation is not arbitrary: MM mobilizes CK when interpreting real situations, TK when selecting the most appropriate TD for each context, and PK when organizing teaching strategies — which essentially constitutes the movement of TPACK construction proposed by Punya Mishra and Matthew J. Koehler (2006) and specified for Mathematics Education by Palis (2010). Thus, MM not only diversifies the repertoire of approaches beyond GeoGebra but also offers a methodological pathway through which teachers may experience the intentional integration among mathematical content, pedagogy, and TD.

CL1 addresses MM from different perspectives (realistic, contextual, educational, critical, epistemological, and cognitive), emphasizing the value of integrating TD into the teaching and learning of MM and exploring mathematical concepts through real problem situations. The need for teacher education that not only incorporates these technologies but also articulates MM and promotes practice in real contexts is highlighted. These authors propose a theoretical-methodological system combining the Onto-Semiotic Approach to Mathematical Knowledge and Instruction (EOS)¹³ with TPACK to support pedagogical practice.

¹³The EOS has been structured since the early 1990s, with Juan D. Godino as its mentor. This model aims at theoretical approaches that consider assumptions from pragmatism, anthropology, and semiotics to understand certain aspects of mathematical objects, their teaching, and their learning (Almeida; Silva, 2018).

The research described in A47 explores the integration of MM with TPACK in Financial and Tax Education, addressing the development of competencies established by the Base Nacional Comum Curricular (BNCC). The authors propose a theoretical-methodological approach combining the Anthropological Theory of the Didactic (TAD)¹⁴ with TPACK, applying praxeological models to analyze real situations involving public revenue collection and expenditures. The application involves solving problem situations related to Personal Income Tax (IRPF) calculations, encompassing Arithmetic content (income and deduction calculations) and Algebra (formulas for tax calculation), and emphasizes the relevance of teacher education in the context of curricular reforms.

In T18, MM is mentioned as an emerging trend without focusing on practice. In D6, it is addressed implicitly through the articulation of knowledge. T9, in turn, explores how technologies may assist teachers in creating representations of situations within pedagogical practice.

These approaches highlight the continuing education of Mathematics teachers focused on experiencing MM integrated with TD, encompassing both technologies already available and those teachers still need to learn about. MM is understood as part of PK, fostering the understanding and articulation of mathematical concepts in real situations. Its integration with TD aims to build Mathematics TPACK in a practical and contextualized manner, aligned with international curricular guidelines and supported by nearly two decades of research.

Final Considerations

The study employed a Systematic Literature Review (SLR) to analyze 94 studies published in national and international contexts, based on five main research questions. The results revealed a gradual increase in references to TPACK, especially in Education, beginning in 2009. The geographical distribution highlighted Brazil, with 53 publications, followed by other countries, demonstrating a global concern with the integration of TPACK into Mathematics Education across varied approaches and contexts.

Most of the analyzed texts relied on the Venn Diagram to discuss the articulation of knowledge, whether in isolation, in pairs, or in an integrated manner

¹⁴ The Theory of Didactics (TAD), developed by Yves Chevallard (1998), aims to analyze how to organize a mathematical object of study and make it work in the classroom (Santos; Menezes, 2015, p. 649). Praxeological models are analytical structures of this theory used to understand and describe mathematical practices in educational contexts (Souza; Silva; Nunes, 2024).

within educational practice. This movement indicates a predominantly illustrative appropriation of the model, since, although the diagram was widely cited, it was rarely accompanied by an explanation of how the forms of knowledge were articulated within educational processes. Thus, it is observed that few studies truly advance in the empirical operationalization of TPACK, remaining largely at the level of describing the model's components without deepening the analysis of how these forms of knowledge are constituted in pedagogical practice.

The studies employed a variety of terms to refer to the integration of TD into pedagogical practices. The term “experiencing” emphasized not only the acquisition of knowledge about technologies but also the importance of living through and engaging with them in Mathematics teaching. The terminological variation reflected different approaches to the use of technologies, although some terms are now outdated.

The findings reveal an expanding field, with expressive growth in publications beginning in 2014 and a global presence, especially in Brazil. The educational processes analyzed, mostly empirical and qualitative, demonstrated advances in TPACK development, such as improvement in mathematical knowledge, collaboration among peers, and greater confidence in the use of TD. However, structural challenges persisted, including precarious infrastructure, excessive workload, and resistance to change, in addition to educational gaps, since only 18 publications focused on continuing teacher education, and few studies detailed the forms of knowledge effectively mobilized, limiting the replicability of the practices.

The review highlighted a diversity of TD mentioned in the studies, with GeoGebra standing out, appearing in 62 of the 94 analyzed publications. This concentration around a single TD reveals a recurring movement in the field: research on TPACK in Mathematics Education indicates a centrality of GeoGebra, which may be interpreted both as recognition of its potential in Mathematics teaching and as a limitation in the exploration of other digital technologies for this purpose. In this context, the relevance of studies aimed at expanding the technological repertoire is emphasized, considering the variety of TD currently available for Mathematics teaching.

Despite nearly two decades of research on TPACK, progressive and longitudinal studies are still needed to support and restructure future educational processes, both initial and continuing. Although many technologies are known by teachers, their integration into pedagogical practices remained limited by factors such as lack of specific knowledge, demotivation, resistance to change, lack of time,

access restrictions, precarious infrastructure, and absence of institutional support. Although the corpus presents relevant proposals, including projects, communities of practice, Mathematical Modeling (MM), the f@r model, Robotics, and Financial Education, few were implemented within continuing teacher education programs. It is recommended that future studies describe in detail the forms of knowledge mobilized at each educational stage and evaluate which approaches produce distinct results according to context, thereby facilitating the adaptation and replication of practices.

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