



Fostering Mathematics Teaching Competence Through STEM-Oriented Education for General School Teachers in The Era of Digital Transformation: Theoretical Foundations and Framework Proposal

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ABSTRACT

STEM-oriented instruction has become a core mandate for school teachers, especially mathematics teachers, whose subject plays a foundational role in developing students' logical reasoning and problem-solving capacity. This paper examines the theoretical foundations of STEM-based mathematics teaching competence among school teachers in the digital era and proposes a conceptual framework for mathematics teacher professional development aligned with current educational reform trends. By synthesizing and analyzing contemporary theoretical approaches such as the Technological Pedagogical and Content Knowledge (TPACK) framework, Professional Learning Communities (PLC), and the Digital Competence Framework for Educators (DigCompEdu) proposed by Redecker (2017) this study develops a professional development model for mathematics teachers comprising: (1) core competencies integrating disciplinary knowledge, pedagogy, and technology; (2) experiential, collaborative, and practice-oriented learning processes; and (3) supportive conditions shaped by digital transformation and school learning cultures. In the proposed framework, TPACK is used to describe the knowledge base that mathematics teachers need for STEM-oriented teaching. DigCompEdu further clarifies how digital competence is involved in designing, organizing, and assessing learning activities. PLC provides the professional setting in which teachers collaboratively plan lessons, examine classroom evidence, receive feedback, and adjust their teaching practices. The proposed framework clarifies the relationship between teachers' STEM-teaching competence and their digital competence, while suggesting a development pathway that integrates pedagogical innovation grounded in STEM, TPACK, and PLC approaches with digitally enhanced instructional practices. The findings offer both theoretical and practical implications for improving professional development, strengthening mathematics teachers' competencies, and fostering a digitally responsive STEM education ecosystem.

1. INTRODUCTION

In the context of globalization and the rapid development of the Fourth Industrial Revolution, STEM education (Science, Technology, Engineering, and Mathematics) has increasingly been regarded as an important orientation for developing learners' competencies. STEM education enables students to connect scientific, technological, engineering, and mathematical knowledge in order to identify problems, analyse situations, and propose well-

grounded solutions. UNESCO (2021) emphasizes that education should prepare learners to adapt to social, technological, and environmental changes. OECD (2019) also argues that education systems need to develop the knowledge, skills, attitudes, and values that enable learners to participate effectively in learning, work, and social life in the future. Regarding labour and skills, the World Economic Forum (2025) projects that by 2030, labour-market transformation will affect about 22% of current jobs, while 39% of workers' core skills are expected to change. In Vietnam, the Ministry of Education and Training's digital transformation agenda (Prime Minister of Vietnam, 2022) requires general school teachers to gradually strengthen their digital competence and use technology appropriately in teaching, assessment, and professional development.

In STEM education, mathematics school teachers play an important role because mathematics provides tools for modelling, logical reasoning, data analysis, prediction, and optimization. These forms of thinking are frequently required in learning tasks related to science, technology, and engineering. Mathematics teachers therefore need to guide students in using mathematical knowledge to analyse real-life situations, construct models, test possible solutions, and explain results in interdisciplinary contexts. Tuong et al. (2023) found that Vietnamese teachers recognize STEM education as an important approach in mathematics instruction. Their study further demonstrated that STEM-based learning activities can enhance students' real-world problem-solving competence and foster key twenty-first-century skills, including critical thinking, collaboration, communication, and creativity. The World Bank (2021) also identifies limited interdisciplinary integration capacity and insufficient digital competence as notable barriers to STEM implementation in Southeast Asia.

These issues suggest that the development of mathematics teachers' STEM-oriented teaching competence should be considered together with their digital competence and professional learning. Over the past decade, teacher professional development and STEM education have been widely discussed, but often as relatively separate lines of research (Desimone, 2009; Bybee, 2013). Studies on TPACK have clarified the role of integrating content knowledge, pedagogical knowledge, and technological knowledge in teaching (Mishra & Koehler, 2006). Research on professional learning communities has also emphasized collaboration among teachers, attention to student learning, and the improvement of classroom practice (DuFour, 2004). Meanwhile, DigCompEdu provides a reference framework for educators' digital competence in the use of digital resources, teaching and learning, assessment, and learner support (Redecker, 2017).

Nevertheless, these perspectives have not always been brought together in a common analytical framework to explain how mathematics teachers develop STEM-oriented teaching competence in the context of digital transformation. Some professional development programs continue to focus mainly on subject content or methods for organizing STEM lessons, while digital competence is often understood primarily as the ability to use technological tools. Such a separated approach does not fully explain how mathematics teachers combine disciplinary knowledge, pedagogy, digital tools, collegial collaboration, and reflection on practice to improve classroom teaching. This gap indicates the need for an integrated theoretical framework to guide the development of mathematics teachers' competence in ways that respond to STEM-oriented teaching and the demands of digital transformation.

To address this gap, this article uses TPACK, PLC, and DigCompEdu as three theoretical bases for analysing the development of mathematics teachers' competence. TPACK helps identify the knowledge required when teachers design STEM-oriented mathematics instruction. DigCompEdu clarifies the digital competence needed for selecting resources, organizing learning activities, and conducting assessment. PLC explains how teachers learn from colleagues, try out lessons, receive feedback, and adjust their teaching practice.

On this basis, the article has three main aims: (1) to synthesize international and Vietnamese studies related to mathematics teacher professional development, STEM education, and digital competence in education; (2) to propose an integrated framework for developing STEM-oriented mathematics teaching competence among general school teachers in the context of digital transformation; and (3) to clarify how TPACK, PLC, and DigCompEdu can be connected to inform the design of teacher professional development programs aligned with general education reform in Vietnam.

The proposed framework may provide a conceptual basis for further research and practical implications for teacher education institutions, professional development providers, and educational administrators. It can be used to design, implement, and evaluate professional development programs that support mathematics teachers in connecting STEM lesson design, digital competence, professional learning communities, and classroom practice.

2. LITERATURE REVIEW

2.1. STEM-Oriented Mathematics Teaching Competence

STEM-oriented mathematics teaching competence refers to teachers' ability to design, organize, and assess learning activities that integrate mathematical knowledge with science, technology, and engineering. The very competence helps teachers to develop students' higher-order thinking, creativity, and real-world problem-solving abilities. Following UNESCO (2021) and Bybee (2013), this competence is not limited to mathematical proficiency, but also integrates the ability to apply STEM ideas appropriately in teaching. In mathematics teaching, this competence should be understood in relation to subject-specific practices such as modelling, reasoning, data analysis, prediction, optimization, and explanation of results.

At the center of STEM-oriented mathematics teaching competence are three important components: STEM literacy, mathematical modelling, and inquiry-based learning. STEM literacy refers to the ability to understand and apply STEM knowledge in practical contexts. Mathematical modelling is defined as the ability to use mathematical representations to analyse and solve problems. Inquiry-based learning can be characterized as the ability to organize learning through questioning, investigation, experimentation, and revision of solution strategies. These components signify the integral role of mathematics in STEM education and help avoid treating STEM merely as isolated experiential activities or a formal combination of content from different subjects.

Drawing on Mishra and Koehler's perspective (2006), STEM-oriented mathematics teaching competence can be analysed through three main domains of knowledge:

- Content Knowledge (CK): in-depth understanding of mathematical concepts, structures, and applications in interdisciplinary and real-world contexts;
- Pedagogical Knowledge (PK): the ability to select and use active, inquiry-based, project-based, modelling-oriented, and problem-solving teaching approaches;
- Technological Knowledge (TK): the ability to use digital tools, simulation software, online learning platforms, interactive boards, learning data, and teaching-support tools to design and organize learning activities.

These knowledge domains intersect within the TPACK framework, which substantiates how teachers integrate technology into the teaching of a specific subject. In STEM-oriented mathematics teaching, TPACK helps teachers understand the relationship between mathematical content, teaching methods, and digital tools in specific learning tasks. For example, when designing a modelling activity, teachers need to identify the relevant mathematical knowledge, choose how to organize student data analysis, and consider which digital tools can support representation and model testing. In this sense, technology is meaningful only when it is selected on the basis of mathematical objectives and the organization of learning activities.

2.2. Teacher Professional Development Models

Teacher professional development is conceptualised as a continuous process of professional learning, training, and self-improvement aimed at enhancing teachers' knowledge, pedagogical skills, teaching effectiveness, and professional competence. In the context of educational reform and digital transformation, professional development is not limited to updating subject knowledge. It also involves strengthening teachers' ability to design learning activities, use digital tools appropriately, analyse students' learning outcomes, and adjust instruction. According to Desimone (2009), an effective professional development program usually includes five features: content focus, active learning, collaboration, coherence, and sustained duration.

Content focus means that professional development should be connected to the subject that teachers specialise in. As for mathematics teachers, professional development content should be linked to mathematical topics that can be organized in STEM-oriented structures, such as modelling, statistics, functions, geometry, measurement, optimization, or data processing (Desimone, 2009; Desimone & Stuckey, 2014). Active learning requires teachers to participate in activities such as designing learning tasks, analysing students' work, trying out teaching tools, and reflecting on lessons after implementation. Collaboration enables teachers to exchange experiences, share resources, give feedback on lessons, and solve practical problems together. Coherence requires professional development to be aligned with the general education curriculum, student competency development goals, and assessment reform. Sustained duration allows teachers time to apply, adjust, and consolidate new practices.

In STEM teaching, professional development needs to be connected to teachers' specific professional tasks, such as designing learning topics, developing guiding questions, selecting supporting tools, organizing group activities, assessing learning products, and revising lessons after implementation. Teachers are unlikely to develop STEM teaching competence through short-term training sessions or general guidelines alone (Darling-Hammond et al., 2017). Professional learning needs to take place through practice, feedback, and lesson improvement.

Professional learning communities, as discussed by DuFour (2004), emphasize teacher collaboration, a focus on student learning, and the use of evidence to improve teaching. In the context of STEM-oriented mathematics teaching, PLCs enable teachers to jointly design lessons, discuss students' difficulties, analyse learning products, test teaching tools, and adjust teaching activities. Thus, PLC is not merely a form of professional meeting, but a way of organizing professional learning that helps teachers bring theoretical ideas into classroom practice.

2.3. Digital Transformation in Education

2.3.1. Concept and Implications for the Teaching Profession

Digital transformation in education signifies the use of digital technology, data, and artificial intelligence to renovate teaching, learning, assessment, and educational management. This process is not limited to digitizing materials or bringing digital devices into classrooms. What matters more is teachers' ability to select and use digital tools to fulfil teaching objectives, enhance students' opportunities for interaction, monitor learning progress, and adjust learning activities when necessary (Redecker, 2017; UNESCO, 2018).

As regards the teaching profession, digital transformation alters several professional tasks of teachers. Teachers not only prepare lesson content, but also design learning tasks that can exploit digital resources, organize learning activities across different environments, utilise learning data to identify students' difficulties, and provide timely feedback. In mathematics teaching, digital tools can facilitate concept visualization, simulation, data processing, graph representation, hypothesis testing, and presentation of results.

However, the use of technology does not automatically make teaching more effective. Technology is valuable only when it is selected in alignment with teaching objectives, mathematical content, student characteristics, and the organization of learning activities. Therefore, in this study, digital transformation is viewed as a discourse that creates new requirements for teachers' professional competence, especially the competence to select, utilise, and evaluate digital tools in teaching.

2.3.2. Educators' Digital Competence According to DigCompEdu

Redecker's (2017) DigCompEdu framework is an important reference for educators' digital competence. The framework describes teachers' digital competence through areas such as professional engagement in digital environments, selection and management of digital resources, teaching and learning, assessment, learner support, and the development of students' digital competence. DigCompEdu does not refer merely to the operation of devices or software; it emphasizes how teachers use technology in specific professional activities.

As for mathematics teachers, DigCompEdu clarifies specific requirements in technology-supported teaching. Teachers need to select digital resources appropriate to mathematical content, design learning tasks using software or data, use assessment tools to collect learning evidence, provide feedback, and support students in using technology responsibly. In STEM teaching, these requirements become more visible because students often need to observe, measure, process data, model situations, and present results in different forms (Redecker, 2017).

Therefore, digital competence is treated in this study as part of teachers' professional competence. It is not separate from pedagogical knowledge and content knowledge. Rather, it extends the ways teachers design, organize, and assess learning activities, especially in STEM tasks involving data, simulation, learning platforms, or feedback tools.

2.3.3. Roles of Artificial Intelligence, Learning Analytics, and Smart Classrooms in Pedagogical Innovation

The development of artificial intelligence, learning analytics, and technology-supported learning environments is providing teachers with additional tools for designing and assessing teaching activities (OECD, 2021; UNESCO, 2023). Artificial intelligence can support teachers in tasks such as suggesting learning resources, generating questions, creating differentiated tasks, analysing students' responses, or assisting in the assessment of certain types of work. Learning analytics can help teachers monitor learning progress, identify groups of students experiencing difficulties, and adjust teaching activities based on evidence.

In STEM-oriented mathematics teaching, tools such as simulation software, spreadsheets, learning management systems, online survey tools, or platforms for submitting learning products can support students in observing phenomena, processing data, testing models, and presenting results. These tools also help teachers collect information about students' learning processes and provide more specific feedback.

Nevertheless, teachers' professional role remains central. Teachers are responsible for defining lesson objectives, selecting mathematical content, organizing learning activities, assessing students' understanding, and deciding how teaching should be adjusted. Therefore, artificial intelligence, learning analytics, and other digital tools should be viewed as professional supports, not as replacements for teachers' professional judgement.

2.4. Integrated Theoretical Basis

In this study, TPACK, PLC, and DigCompEdu are used to analyse three different aspects of the development of STEM-oriented mathematics teaching competence.

2.4.1. TPACK: Integrating Technological, Pedagogical, and Content Knowledge

In STEM-oriented mathematics teaching, TPACK helps identify the knowledge domains required of teachers and explains how mathematical knowledge, pedagogical approaches, and technology interact in the design of learning activities. Teachers are expected to transform mathematical content into meaningful learning tasks while selecting appropriate instructional strategies and technological tools based on specific learning objectives. In this regard, TPACK provides a theoretical foundation for understanding the knowledge base underpinning STEM-oriented mathematics teaching competence in the context of digital transformation.

2.4.2. Digital Competence Framework for Educators (DigCompEdu)

DigCompEdu provides a reference framework for specifying teachers' digital competence in professional activities (Redecker, 2017). In this study, DigCompEdu is used to specify the technological knowledge component of TPACK.

For mathematics teachers, DigCompEdu clarifies how digital tools are involved in the teaching process. Teachers may use simulation software to help students observe changes in a model, spreadsheets to process data, learning platforms to assign tasks and collect learning products, or online assessment tools to provide timely feedback. When connected with TPACK, DigCompEdu explains more specifically how digital competence supports teachers in designing, implementing, and assessing STEM lessons, instead of treating digital competence as a general technical requirement.

2.4.3. Professional Learning Communities Supporting Sustainable Development (PLC)

PLC is used in this study to explain how teachers develop professional competence in school practice. In a professional learning community, teachers can jointly design STEM lessons, discuss students' difficulties, analyse learning products, share teaching tools, and revise lessons after implementation. This form of organization helps teachers develop competence through concrete practice, rather than merely receiving theoretical knowledge or instructional materials.

PLC is especially important because STEM teaching often requires teachers to work with open-ended tasks, connect multiple fields, and respond to different solutions proposed by students. In this context, teachers cannot develop competence through self-study or short-term training alone (Darling-Hammond et al., 2017). Discussion with colleagues, observation of practice, feedback, and lesson revision help teachers bring TPACK knowledge and digital competence into specific teaching activities.

2.4.4. Integrated Basis of TPACK, PLC, and DigCompEdu

The integration of TPACK, PLC, and DigCompEdu is understood as the connection among teachers' professional knowledge, digital competence, and professional development. TPACK identifies the knowledge structure needed for teachers to design STEM-oriented mathematics instruction. DigCompEdu clarifies how digital competence is involved in selecting resources, organizing learning activities, assessing learning, and supporting students. PLC explains how teachers develop and adjust this competence through professional collaboration in schools.

The key point is that these three frameworks are not used as independent parts. DigCompEdu adds the digital competence dimension to TPACK, particularly in technological knowledge and technological pedagogical

knowledge. PLC helps bring professional knowledge and digital competence into practice through lesson design, trial implementation, feedback, and revision. Thus, STEM-oriented mathematics teaching competence is not only the result of individual understanding; it is developed through the appropriate use of digital tools and professional learning under specific school conditions (Table 1).

Table 1. Roles and Interconnections of TPACK, PLC, and DigCompEdu in Developing STEM-Oriented Mathematics Teaching Competence

Component	Role in developing STEM-oriented mathematics teaching competence	Interconnection in the integrated framework
TPACK	Identifies the professional knowledge structure teachers need when combining mathematical content, pedagogy, and technology in STEM teaching.	Clarifies how teachers connect mathematical concepts, teaching methods, digital tools, and real-life situations in the design of learning tasks.
PLC	Provides a professional learning setting in which teachers jointly design lessons, exchange feedback, analyse classroom practice, and revise lessons after implementation.	Helps teachers bring TPACK knowledge and digital competence into classroom practice through collegial collaboration, lesson trials, and reflection based on evidence of students' learning.
DigCompEdu	Specifies teachers' digital competence in selecting digital resources, organizing learning activities, assessing learning, and supporting students.	Adds the digital competence dimension to TPACK, especially in activities involving data, simulation software, learning platforms, and feedback tools

3. MATERIALS AND METHODS

3.1. Research Approach

This study adopts a conceptual framework development approach, drawing on the methodological orientations of Lynham (2002) and Jabareen (2009). The purpose of the study is to construct a theoretical framework for STEM-oriented mathematics teaching competence of general school teachers in the context of digital transformation. The framework was developed by synthesizing, analysing, and comparing published studies on STEM education, digital competence, and teacher professional development.

The study did not collect new survey data from teachers or students, nor did it examine the effects of a specific professional development program. The data used in this study consisted of scholarly works, international reports, policy documents, and academic materials related to the research topic. Qualitative content analysis was employed to identify key concepts, examine relationships among these concepts, and organize them into a shared analytical framework.

3.2. Research Design and Procedure

The research process was conducted in four steps.

First, the researcher identified the research problem and the scope of the literature review. The reviewed materials were organized around four themes: STEM education, mathematics teaching competence, teacher professional development, and digital competence in education. This step helped pinpoint the main research gap, namely that approaches to STEM education, digital competence, and teacher professional development are often presented separately, while their relationships in the development of mathematics teachers' competence have not been sufficiently clarified.

Second, the researcher searched and screened relevant literature. The search was conducted through Scopus, Web of Science, ERIC, Google Scholar, and sources from OECD, UNESCO, World Bank, and the World Economic Forum. Several Vietnamese publications related to STEM education, digital transformation, and teacher competence were also reviewed. The English search terms included "STEM education", "mathematics teaching competence", "mathematics teacher competence", "teacher professional development", "TPACK", "professional learning

community”, “PLC”, “digital competence”, “DigCompEdu”, and “digital transformation in education”. The Vietnamese search terms included “giáo dục STEM”, “năng lực dạy học Toán”, “năng lực giáo viên Toán”, “phát triển chuyên môn giáo viên”, “năng lực số của giáo viên”, and “chuyển đổi số trong giáo dục”.

A total of 64 documents were initially identified through academic databases, international organization reports, policy documents, and Vietnamese educational publications. After 14 duplicate or overlapping records were removed, 50 documents were screened by title and abstract. At this stage, 25 documents were excluded because they were not directly related to mathematics teachers, STEM education, teacher professional development, or digital competence in teaching. Twenty-five full-text documents were then reviewed. After full-text review, 12 documents were further excluded because they focused only on technology in general, lacked a clear theoretical basis, or did not contribute directly to the construction of the proposed framework. Finally, 18 key documents were included in the conceptual analysis, consisting of 16 international documents and 2 Vietnamese documents. After the screening process, 18 key documents were selected for the development of the theoretical framework and analysis. These documents included Bybee (2013), Darling-Hammond et al. (2017), Deming (1986), Desimone (2009), Desimone and Stuckey (2014), DuFour (2004), Holmes et al. (2019), Mishra and Koehler (2006), OECD (2019), OECD (2021), Prime Minister of Vietnam (2022), Redecker (2017), Tuong et al. (2023), UNESCO (2019), UNESCO (2021), Vescio et al. (2008), World Bank (2021), and World Economic Forum (2025). These documents were selected because they provide theoretical foundations and practical perspectives related to STEM education, mathematics teaching competence, digital competence, teacher professional development, educational transformation, and future-oriented skills.

Third, conceptual coding was conducted. Following the procedures of open, axial, and selective coding suggested by Strauss and Corbin (1998), the main ideas in the selected documents were recorded, compared, and grouped. In open coding, the initial codes included content knowledge, pedagogical knowledge, technological knowledge, digital competence, use of digital resources, digital assessment, teacher collaboration, professional feedback, reflection on practice, and school-level support. In axial coding, related codes were grouped into broader categories such as TPACK, DigCompEdu, professional learning communities, practice-based learning, and organizational conditions. In selective coding, these categories were organized into three main components of the proposed framework: Core, Process, and Context.

Fourth, the study integrated the concepts and constructed the proposed framework. TPACK was used to describe the professional knowledge teachers need when designing STEM-oriented mathematics instruction. DigCompEdu was used to clarify the digital competence required for selecting resources, organizing learning activities, and conducting assessment. PLC was used to explain how teachers learn from colleagues, try out lessons, receive feedback, and adjust their teaching practice. These concepts were organized into an integrated framework consisting of three components: Core, Process, and Context. This terminology is used consistently throughout the article.

3.3. Data Sources and Scope

The data sources of the study included journal articles, academic books, international reports, policy documents, and scholarly publications related to STEM education, teacher professional development, digital competence, and mathematics teaching. The review period was limited to 2013-2024. This period was selected because research on STEM education expanded noticeably after 2013 (Abdi et al., 2024). While digital competence frameworks and digital transformation in education have also become more widely used in educational research and policy.

The inclusion criteria were as follows: (1) the document was directly related to STEM education, mathematics teaching, teacher professional development, or digital competence; (2) the document had a clear theoretical basis, particularly in relation to TPACK, PLC, DigCompEdu, or teacher professional development; (3) the document was situated in general education or teacher education and professional development contexts; and (4) the document was published by a scholarly journal, academic publisher, international organization, or reputable educational authority.

The exclusion criteria were as follows: (1) documents not directly related to teachers or general education; (2) documents that addressed technology in general without a clear connection to teaching or professional development; (3) duplicate documents; (4) documents with unclear publication information; and (5) documents that were mainly informational, promotional, or opinion-based.

3.4. Analytical Strategy

The study employs qualitative content analysis to identify key concepts and relationships among concepts in the selected documents. The analysis was conducted by comparing different groups of literature in order to identify points of convergence and divergence among approaches to STEM, TPACK, PLC, DigCompEdu, and teacher professional development. The components of the proposed framework were determined based on three criteria: relevance to the research purpose, theoretical consistency, and applicability to the design of professional development programs for mathematics teachers.

The coding process is illustrated through a matrix linking ideas extracted from the literature with open codes, conceptual categories, and corresponding components of the proposed framework (Table 2).

Table 2. Illustration of the conceptual coding process

Ideas extracted from the literature	Open codes	Conceptual categories	Components in the proposed framework
Teachers need to integrate content knowledge, pedagogy, and technology in teaching	CK, PK, TK, TPACK	Teachers' professional knowledge	Core
Teachers use digital resources, assessment tools, and digital learning environments in teaching	Digital resources, digital assessment, learner support	Educators' digital competence	Core / Context
Teachers collaboratively design lessons, exchange feedback, and adjust their teaching	Collaboration, peer feedback, reflection on practice	Professional learning community	Process
Schools provide policies, time, resources, and professional culture to support instructional innovation	Policy, time, organizational support, professional culture	School-level organizational conditions	Context

The trustworthiness of the analysis was strengthened by iteratively comparing codes and conceptual categories across different groups of documents. Concepts that appeared only incidentally, were not directly related to STEM-oriented mathematics teaching competence, or did not contribute to the construction of the proposed framework were not included in the final analysis.

4. RESULTS AND DISCUSSION

4.1. Proposed Conceptual Framework

The conceptual framework proposed in this study aims to establish a foundational structure for developing STEM-oriented mathematics teaching competence among teachers in the context of digital transformation. Grounded in the integration of three major theoretical pillars TPACK (Mishra & Koehler, 2006), the Professional Learning Community (PLC) model (DuFour, 2004), and the Digital Competence Framework for Educators (UNESCO, 2019) the framework is organized into three interconnected layers: Core, Process, and Context.

4.1.1. Core: STEM-Oriented Mathematics Teaching Competence

STEM-oriented mathematics teaching competence should not be viewed simply as an extension of traditional mathematics teaching competence or as the addition of technology to classroom instruction. Instead, it is situated at the intersection of three key dimensions: the application of mathematics to real-world problem solving, the organization of learning through inquiry- and problem-solving-oriented approaches, and the purposeful use of technology to support learning. Accordingly, the "Core" component is defined as an integrated competence that requires teachers to mobilize content, pedagogical, and technological knowledge simultaneously in the design of STEM learning experiences.

4.1.2. Process: Professional Development and Competence Growth

Analysis of the selected documents revealed that the development of STEM-oriented mathematics teaching competence is typically characterized by a recurring cycle of professional activities. Across the dataset, the most prominent activities included lesson design, trial implementation, observation of practice, analysis of student learning evidence, feedback, and the continuous refinement of teaching practice.

This process includes three groups of activities. The first is practice-based learning, in which teachers develop STEM topics, design modelling tasks, select supporting tools, prepare assessment criteria, and analyse students' learning products. The second is collaborative professional learning, in which teachers work with colleagues to review lessons, share difficulties, discuss ways of organizing activities, and evaluate implementation results. The third is evidence-based reflection, in which teachers examine students' feedback, learning products, participation, and emerging difficulties in order to revise lessons.

Process can be organized through the Plan-Do-Check-Act (PDCA) cycle (Deming, 1986). In the Plan stage, teachers design the lesson and select supporting tools. In the Do stage, the lesson is implemented in a specific classroom. In the Check stage, teachers analyse students' learning products, classroom observations, and students' feedback. In the Act stage, teachers revise the learning task, teaching method, or use of digital tools for the next implementation. This organization connects professional development with the improvement of classroom practice, rather than restraining it to the reception of training content.

4.1.3. Context: School-Level and Policy Support Conditions

Context refers to the conditions that influence the formation and maintenance of teachers' STEM-oriented mathematics teaching competence. These conditions include technological conditions, professional culture within schools, and support from school management and policy.

First, technological conditions affect teachers' ability to use digital tools in teaching. Teachers may need simulation software, spreadsheets, learning platforms, or online assessment tools, but their actual use depends on devices, internet connectivity, teaching resources, and technical support. Therefore, digital transformation in this framework is understood as a condition that needs to be organized in line with teaching objectives, rather than as the formal addition of technology to lessons.

Second, professional culture within schools affects the operation of PLCs. A school that encourages lesson sharing, professional feedback, joint analysis of students' learning evidence, and pedagogical experimentation creates favourable conditions for teachers' competence development. By contrast, if teachers lack time, opportunities for collaboration, or if professional meetings are mainly administrative, it is difficult to sustain the development of STEM teaching competence.

Third, support from school management and policy enables professional development activities to be maintained over time. Forms of support may include allocating time for professional meetings, recognizing teachers' participation in lesson design and trial implementation, providing teaching resources, organizing professional development according to teachers' needs, and encouraging collaboration among mathematics, science, and technology teachers.

In this sense, Context links the proposed framework with the actual conditions of schools. STEM-oriented mathematics teaching competence depends not only on teachers' individual knowledge, but also on time, resources, professional culture, support mechanisms, and policy directions. Attention to these conditions makes the proposed framework more useful for designing teacher professional development programs and organizing professional learning in general schools.

4.2. Discussion and Implications

4.2.1. The Role of the Proposed Framework in Developing Mathematics Teachers' Competence

The proposed framework helps clarify how STEM-oriented mathematics teaching competence can be developed among general school teachers in the context of digital transformation. Instead of focusing on teachers' competence as a set of separate skills, the framework organizes competence development into three components: Core, Process, and Context. Core identifies the competence that teachers need to develop; Process describes how this competence is formed and adjusted through professional activities; and Context indicates the school-level and policy conditions that influence this process.

The proposed framework clarifies the relationship among teachers' professional knowledge, digital competence, and professional learning. In the Core component, teachers are expected to connect mathematical content, teaching methods, and digital tools in designing STEM tasks. In the Process component, this competence is developed through lesson design, trial implementation, analysis of learning evidence, feedback, and revision. In the Context component, competence development depends on time, teaching resources, professional culture, and support mechanisms within schools.

Thus, the proposed framework does not only indicate what should be included in teacher professional development, but also suggests how such development should be organized. For mathematics teachers, developing STEM teaching competence should not stop at training on STEM concepts or introducing digital tools. Teachers need to engage in specific professional tasks, such as designing STEM topics, developing modelling situations, selecting data, using appropriate digital tools, analysing students' work, and revising lessons after implementation.

From a theoretical perspective, the framework helps explain more clearly the integration of TPACK, DigCompEdu, and PLC in teacher competence development. TPACK defines the structure of teachers' professional knowledge; DigCompEdu clarifies the expressions of digital competence in teaching; and PLC shows how teachers learn and improve their practice through professional collaboration. From a practical perspective, this framework can be used to design professional development programs for mathematics teachers, organize STEM-focused professional learning activities, and develop criteria for assessing STEM teaching competence in schools.

4.2.2. Implications for Designing Teacher Professional Development Programs

Based on the proposed framework, professional development programs for mathematics teachers should be designed in a way that connects STEM content, digital competence, and classroom practice. An adequate professional development program should not separate "STEM", "technology", and "teaching methods" into independent units. These elements should be organized around teachers' specific professional tasks, such as designing a modelling lesson, organizing students' data-processing activities, or assessing learning products in a STEM topic.

First, professional development modules should integrate TPACK, STEM, and digital competence. Each module should help teachers identify relevant mathematical content, select real-life situations, design learning activities, and decide which digital tools should be used. For a topic on optimization or statistics, for example, teachers may be guided to select data, develop learning tasks, use spreadsheets or simulation software, design guiding questions, and construct assessment criteria for students' products.

Second, professional development formats should combine face-to-face learning, online learning, and school-based practice. Online learning can be used to provide materials, instructional videos, discussion forums, and repositories of teaching resources. Face-to-face sessions should focus on lesson design, example analysis, tool practice, and feedback on teachers' products. The most important part is trial implementation in classrooms or professional groups, because this is where teachers can examine whether the lesson is suitable for their students and the actual conditions of their schools. This recommendation aligns with previous research highlighting that effective teacher professional development should be grounded in practice, foster collaboration, and be situated within authentic classroom contexts, allowing teachers to implement, evaluate, and continuously improve new instructional approaches (Desimone, 2009; Darling-Hammond et al., 2017; Vescio et al., 2008).

Third, PLCs should be developed in connection with STEM teaching. PLCs may be organized within subject departments, across school clusters, or in online formats. Their activities should focus on concrete professional tasks, such as co-designing topics, sharing teaching materials, discussing difficulties in organizing group work, analysing students' products, and revising lessons. If PLCs stop at sharing materials or reporting experiences, their impact on classroom practice will be limited. PLCs need to produce concrete professional outputs, such as lesson plans, question sets, assessment criteria, evidence of students' learning, and revised lesson versions after trial implementation.

Fourth, the use of AI and digital tools in teacher professional development should be placed within appropriate limits. AI can support resource suggestions, question generation, learning situation design, feedback analysis, or the assessment of some learning products. However, professional development programs need to emphasize teachers' decisive role in selecting content, checking the accuracy of resources, adapting learning tasks, and ensuring alignment with mathematical objectives. AI should not be treated as a replacement for teachers' pedagogical competence. This recommendation is consistent with UNESCO's (2023) guidance on generative AI in education, which emphasizes

that teachers should retain responsibility for evaluating, adapting, and making pedagogical decisions regarding AI-generated content. Similarly, Holmes, W., Bialik, M., & Fadel, C. (2019) argue that AI is most effective when used to support, rather than replace, teachers' professional expertise and judgement.

For schools with limited devices or unstable internet connectivity, professional development programs should include resource-efficient STEM options. Teachers can use available materials, data collected from local contexts, simple spreadsheets, or direct measurement activities to organize learning tasks. This approach makes STEM teaching more feasible across different school conditions, rather than limiting it to schools with stronger technological conditions.

4.2.3. Policy and Educational Management Implications

The proposed framework also suggests several implications for educational policy and management. These implications need to be considered in relation to the actual conditions of teachers and schools, especially teachers' time pressure, differences in technological conditions, and mechanisms for professional coordination.

First, schools need practical mechanisms to support PLCs. Mathematics teachers often have to handle a great amount of workload including teaching, assessment, documentation, and administrative tasks. If PLC participation is treated as an additional requirement, teachers may not have enough time or motivation to participate deeply. Therefore, schools need mechanisms for allocating time for professional meetings, converting participation in STEM lesson design and trial implementation into recognized working hours, or acknowledging teachers' professional products in the evaluation of their work.

Second, policies on teachers' digital competence need to be connected to specific teaching tasks. Digital competence standards should not be limited to criteria about technical operations. For mathematics teachers, digital competence should be reflected in their ability to select tools appropriate to mathematical content, organize students' work with data, use representation or simulation tools, design assessment, and provide feedback. This approach brings digital competence standards closer to teaching practice.

Third, educational management should take into account differences across regions and school types. Not all schools have sufficient digital resources, stable internet connectivity, or technical support staff. Therefore, teacher professional development policies should include different levels of implementation: a basic level with resource-efficient STEM activities; an intermediate level with common digital tools such as spreadsheets, simple simulation software, and learning platforms; and an advanced level with learning analytics, AI, or assessment-support systems.

Fourth, teacher education institutions need to strengthen coordination among academic units. Professional development for mathematics teachers in STEM and digital competence is unlikely to be effective if it is handled by only one faculty or one group of specialists. Collaboration is needed among lecturers in mathematics, mathematics education, information technology, and educational sciences in order to design professional development modules. Such coordination helps ensure that the content is mathematically accurate, pedagogically appropriate, and aligned with the requirements of digital tool use.

Fifth, future studies should validate the proposed framework in practice. Validation may be conducted in several ways: surveying mathematics teachers' STEM teaching competence, TPACK, and digital competence across different school contexts; analysing the relationships among professional development, PLC participation, digital competence, and STEM teaching competence; interviewing teachers and school administrators to clarify implementation difficulties; and conducting case studies in schools where STEM teaching has been implemented relatively consistently. These studies would help determine the suitability of the proposed framework and identify the adjustments needed when applying it in different school conditions.

5. CONCLUSION

This study proposed an integrated conceptual framework for developing STEM-oriented mathematics teaching competence among general school teachers in the context of digital transformation. The framework was developed by connecting three theoretical foundations: TPACK, PLC, and DigCompEdu. TPACK clarifies the professional knowledge teachers need when combining mathematical content, pedagogy, and technology. DigCompEdu specifies the digital competence required for selecting resources, organizing learning activities, assessing learning, and supporting students. PLC explains how teachers develop and refine their competence through collaboration, feedback, and reflection on classroom practice.

The proposed framework consists of three components: Core, Process, and Context. Core represents the competence teachers need in order to design and organize STEM-oriented mathematics learning tasks. Process describes the professional learning activities through which this competence is developed, including lesson design, trial implementation, analysis of learning evidence, feedback, and revision. Context identifies the school-level and policy conditions that influence competence development, such as technological conditions, professional culture, time allocation, resource support, and collaboration among teachers and teacher educators.

The main contribution of this study is that it does not treat STEM teaching competence, digital competence, and professional development as separate issues. Instead, it explains how these elements can be connected in a common framework for mathematics teacher development. The framework may support teacher education institutions, professional development providers, and school leaders in designing programs that are more closely connected to teachers' classroom practice and actual school conditions.

Future research should empirically validate the proposed framework in different school contexts. Possible directions include surveying mathematics teachers' STEM teaching competence, TPACK, and digital competence; examining the role of PLC participation in teacher development; analysing barriers to STEM-oriented and digitally supported mathematics teaching; and developing assessment tools for measuring integrated mathematics teaching competence in the context of digital transformation.

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