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Collaborative professional development for science, technology, and mathematics teachers in designing iPad-integrated lesson plans

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Abstract This study presents a teacher development program designed to enhance STEM teaching skills through the integration of iPad-based technology, emphasizing the advancement of Technological Pedagogical Content Knowledge (TPACK). The program utilizes a blended learning approach, combining online modules with hands-on, school-based sessions to develop teachers' expertise in content, pedagogy, and the effective application of digital tools. Structured into three phases—preparation, collaboration, and classroom implementation—the program supports teachers in creating and delivering interactive, inquiry-driven STEM lessons using iPad applications to boost student engagement and learning outcomes. A mixed-methods research design was employed to study and refine the program, involving 444 school teachers in ongoing collaborative work, with a focused analysis of 36 selected participants. Data was collected through teacher focus group interviews, classroom observations, TPACK surveys, and direct collaboration in classrooms. Analysis was conducted using both content analysis and statistical methods. The findings indicate that the blended professional development program offers teachers flexibility to participate and apply learned strategies in their classrooms during the research process. The involvement of school administrators and educational supervisors was crucial in fostering a Professional Learning Community (PLC), enabling continuous collaboration, reflective practices, and iterative lesson design through activities like lesson study, co-teaching, peer observations, and joint lesson planning. The study highlights the program's impact on teachers' instructional practices, their ability to integrate technology effectively, and student engagement in STEM learning. Collaboration among various stakeholders—teachers, school administrators, supervisors, and academics—emerged as a key factor for success. The findings suggest that this approach enhances teachers' digital and pedagogical skills while offering a scalable model for professional development in technology-rich educational environments. This model demonstrates the potential for sustained improvements in STEM education by bridging theory and practice through collaborative and flexible learning opportunities.

Keywords: teacher education, technological pedagogical content knowledge (TPACK), iPad based STEM, collaborative professional development program

1. Introduction

Developing human capital for the digital era aligns with Thailand's digital transformation strategy toward "Digital Thailand." Education that leads to change must be adapted to local contexts. Therefore, educational administration by school administrators, supervisory guidance by educational supervisors, instruction by teachers, and learning by students must be interconnected, aligned, and share the same goal to prepare for evolving situations. Enhancing teachers' ability to design learning that cultivates key 21st-century competencies in students is urgently needed. It is essential for students to gain these competencies, both as digital technology users in learning and innovators who can build upon existing technologies. Teaching that promotes 21st-century competencies is based on a new paradigm that focuses on student-driven knowledge construction. Every student has the potential for active learning, and learning should be more integrated rather than subject specific. This is practical, meaningful learning. The role of teachers has thus shifted to being facilitators, stimulating and guiding students' learning and potential. Additionally, learning must integrate digital technology, an essential tool for preparing Thai citizens for the 21st century, which aligns with government policy supporting the adoption of digital technology in education management. Today's educational trends require integration to connect real-world events, situations, and phenomena with lessons. This involves structuring learning experiences and categorizing them according to student-oriented goals and integrating subject matter, processes, and outcomes to form a holistic learning experience. Integrative learning design uses these elements to reach specific learning goals (Breiner, et al., 2012; Dejarnette, 2012). In today's rapidly changing global society, driven by technological and communicative advances, vast information sources exist everywhere, and competition for economic gains has intensified. Every country must increase its population quality to compete in the workforce. Therefore, curricula must be

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adapted by integrating science, mathematics, technology, and engineering processes to equip students with skills to solve real-world problems and pursue future careers. Both teachers and students must develop skills suitable for 21st-century education (Institute for the Promotion of Teaching Science and Technology, 2015, p.1). STEM education serves as an example of integrated learning across four disciplines: science, technology, engineering, and mathematics (Pitakkeukung, 2015, p.201--202). This approach combines the inquiry approach with engineering design to incorporate science, math, and technology learning aligned with Thailand's core curriculum. It links science and technology-related events or phenomena at local, national, or global levels, encouraging students to explore, assess, and design scientific inquiries. Students apply mathematical skills and technological knowledge to develop solutions or products in response to real-life scenarios.

STEM learning demonstrates the importance of science and math knowledge in the development of complex problem-solving skills. Teachers must plan to align in-course and final assessments, ensuring coherence in the learning process (Sarnsorpisut, 2015). Realizing comprehensive STEM education in schools requires school leaders' commitment to promote STEM awareness, understanding, and accurate knowledge among all involved teachers (Institute for the The theory that supports the concept of integrated STEM learning is constructivist theory). This theory emphasizes the student, positing that learners can construct their knowledge through active interactions with others and the environment. The framework of constructivist theory includes the following principles: 1) students are creators of their knowledge, with each student constructing knowledge in unique ways that may differ from the teacher's methods; 2) students' prior experiences are essential foundations for building new knowledge, and each student has different prior knowledge and experiences; 3) interactions with the environment, direct experiences, and exchanging opinions contribute to students' creation of new knowledge; and 4) teachers play a role in setting up the learning context, posing challenging questions, encouraging students to construct knowledge, and providing support in all aspects (Kamolchat Klom-im, 2013, p. 3). Such learning emphasizes active, hands-on participation by students, enabling them to create knowledge independently. This approach aligns with students' interests, aptitudes, and needs, enhancing their analytical thinking, life skills, empathy, teamwork, and joy in learning (Office of the Basic Education Commission, 2015, p.2). Similarly, integrated STEM learning promotes students' self-directed knowledge creation, analytical thinking, problem-solving skills, and teamwork. School leaders must support integrated work among teachers across 3-4 STEM-related subjects and encourage collaborative learning among teachers, forming a professional learning community. This community fosters teacher growth in adapting instruction and applying STEM learning.

Research shows that developing teachers' technological pedagogical content knowledge (TPACK) is crucial for enabling teachers to design technology-integrated lessons. Teachers must have a deep understanding of each knowledge component to integrate digital technology, pedagogy, and content effectively into their teaching. Teachers need experience in harmonizing these three elements in specific teaching contexts (Rosenblatt, 1978; Mishra & Koehler, 2006). Modern digital technology alone cannot ensure student learning; therefore, it is necessary to develop teachers' knowledge to connect with the potential and limitations of digital technology. This requires instructional design tailored to content, either to fill in gaps left by digital technology or to enhance it through suitable instructional strategies. This study underscores the importance of a context-based professional development model designed to increase teachers' knowledge of content, pedagogy, and technology for implementing STEM-based learning via iPads to create competency-based classrooms. Teachers function as facilitators and are responsible for planning learning units and selecting content that aligns with students' natural learning styles, interests, and abilities while addressing individual differences. The instructional approach embodies the principles of science, mathematics, technology, and engineering through inquiry-driven activities, active student engagement, problem-solving, and hands-on experiences. These activities promote interaction and collaboration, allowing students to learn collectively and assess their progress in authentic, real-world contexts. This ongoing support involves school administrators, educational supervisors, and academic teams who are researchers. Through a whole school approach (WSA), the goal is to achieve the expected outcomes in alignment with the school's objectives. This approach integrates all school components and engages all stakeholders, providing a model for schools under the Office of the Basic Education Commission to manage and support integrated STEM learning, as well as developing school curricula using digital technology (Henderson & Tilbury, 2004). Promotion of Teaching Science and Technology, 2015).

1.1. Research questions

1. How do the content knowledge, pedagogical methods, and technology skills of Thai teachers for STEM-based learning via iPads develop before, during, and after they participate in professional development programs for teachers?
2. How do Thai teachers' perceptions and understanding of the use of digital technology tools for STEM-based learning improve, and in what ways?
3. What are the characteristics of STEM-based learning via digital technology tools and iPads?
4. What is the structure of the teacher professional development program delivered through a blended learning platform?

This article focuses on the design of a teacher professional development program delivered through a blended learning platform structured according to the concept of the whole-school approach.

2. Literature Review

2.1. Digital technology

Access to computers, software, and technical support are recognized as critical factors that influence teachers' willingness to adopt ICT tools (Ertmer, 2005; Eteokleous, 2008; Guzey & Roehrig, 2009; Hew & Brush, 2007). A path model analysis by Inan and Lowther (2010) revealed that the perceived availability of computer resources significantly impacts teachers' frequency of technology integration in K–12 classrooms. Barriers to access often lead teachers to avoid ICT tools (Mouza & Karchmer-Klein, 2013; Niess, 2013), thereby limiting their TPACK development to the tools they can access. However, studies indicate that strong motivation to use technology can drive teachers to overcome access barriers (Drent & Meelissen, 2008; Ward & Parr, 2010). In such cases, teachers develop the TPACK needed to address contextual barriers (Porras-Hernández & Salinas-Amescua, 2013).

2.2. Peer and coaching

Peer support through sharing ideas, coaching, and collaborative problem solving is essential in supporting teachers' ICT integration efforts (Galanouli, Murphy, & Gardner, 2004). Teachers often cite time constraints as a barrier to innovative ICT integration (Hew & Brush, 2007), but collaboration with colleagues can help mitigate this barrier (Guzey & Roehrig, 2009). Collaborative design, as Levin and Wadmany (2008) suggest, enriches teachers' TPACK development through dialogical learning.

2.3. TPACK-in-action

Building on previous research, the context surrounding teachers comprises four interdependent dimensions: intrapersonal, interpersonal, cultural/institutional, and physical/technological (Chai, Koh, et al., 2013). To analyze school-based and technological factors, Ertmer's (1999) framework divides first-order barriers into two dimensions: physical/technological and cultural/institutional. The physical/technological dimension addresses resource availability and effectiveness, including hardware, software, and tech support. Cultural/institutional factors involve the influences of societal and educational policies, school leadership, policies, and curricula on teaching practices. Following Ertmer's (1999) second-order barriers, the Intrapersonal dimension includes teachers' beliefs that impact ICT integration. Tsai and Chai (2012) suggested that teachers' design thinking could serve as a third-order barrier to ICT integration and TPACK development. While Ertmer (1999) considered these dimensions as barriers, the TPACK-in-Action framework views them as contextual variables that teachers manage while enacting TPACK in ICT lesson design. Teachers' design capacity affects their TPACK navigation within contextual tensions and opportunities. The interpersonal dimension addresses collaborative problem solving and innovation, acknowledging the essential role of human relationships in ICT lesson design teams, which often involve teachers and technologists (Koehler et al., 2007).

3. Materials and Methods

This research aims to develop content knowledge, pedagogical methods, and technology skills for teachers in Thailand through a collaborative teacher professional development program delivered on a blended learning platform. The program brings together teachers, school administrators, and educational supervisors to support STEM-based learning with iPads via a blended learning approach. This research employs a mixed-methods research design that integrates both quantitative and qualitative approaches. The study is conducted in two phases, involving data collection, data analysis, and interpretation, to achieve comprehensive, in depth, and clear answers to the research questions. The first phase focuses on developing Thai teachers' content knowledge combined with pedagogy and technology for STEM education via iPads. The second phase examines the outcomes of STEM learning facilitated by iPads within the classroom, as well as teachers' instructional practices. School administrators and educational supervisors act as coaches, providing support and guidance in their roles. The research design follows the model outlined in Figure 1.

3.1. Research participants

The main target group includes three science, technology, and mathematics teachers per school from 148 schools, totaling 444 participants. These schools fall under the Office of the Basic Education Commission and receive support for digital technology equipment for teaching and learning. The schools span six regions: northern, northeastern, central, southern, eastern, and western Thailand. The selection criteria specify that the participating schools must be part of the Quality School Project, voluntarily participate in the project, and have continuous support teams that include school administrators, educational supervisors, and technology specialists. The focus is on implementing STEM-based learning via digital tools and iPads. This developmental research focuses on collecting and analyzing data during the research process to gain in-depth insights and refine the model for science teachers' professional development. The research was conducted over a period of one year, from November 2021 to October 2022.

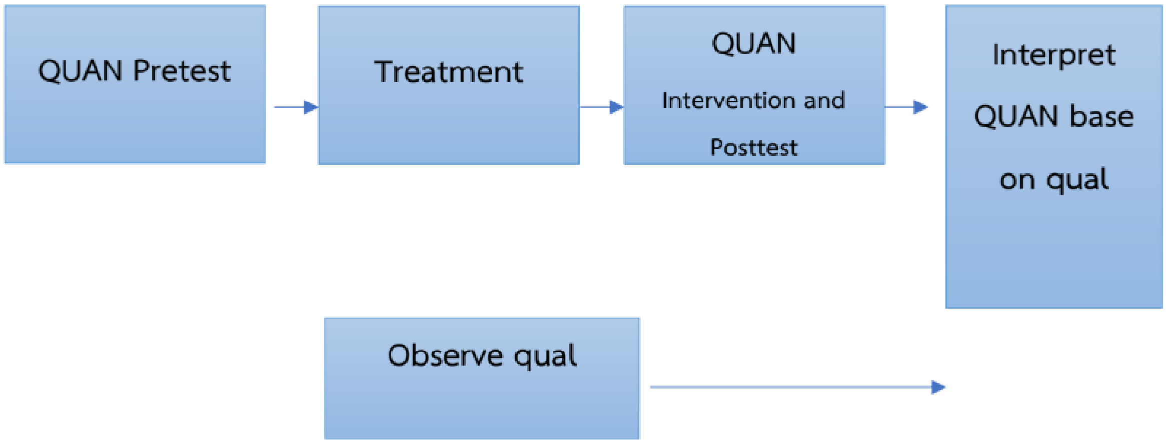

figure 1 Mixed method framework. *source:* creswell and plano clark (2007).

The primary research participants for this research, selected through purposive sampling, are as follows:

1) Schools under the Office of the Basic Education Commission that have received digital technology equipment for teaching and learning from six regions: northern, northeastern, central, southern, eastern, and western. The selection criteria specify that these schools must be part of the Quality Schools Project and must voluntarily participate in the program.
2) Science and Technology and Mathematics teachers, three per school, from 148 schools, totaling 444 teachers.
3) School administrators, one per school, totaling 148 individuals.
4) Educational supervisors, one per school, totaling 148 individuals.
5) Technologists, one per school, totaling 148 individuals.

The case study selection criteria included schools with teachers from three subject groups who could consistently implement the curriculum, leading to the creation of new learning activities. The teachers from these schools, totaling 12 schools with 36 volunteer teachers, were committed to ongoing participation in the research project, including open-class sessions. Each school joined a support team to implement STEM learning via digital technology tools, specifically iPads.

3.2. Developmental process of research instruments

The data collection instruments used in this research were developed according to the following research objectives:

1) The research team formulated a framework of questions on the basis of the research objectives, drawing from related literature. The instruments include the following: 1) self-assessment of content knowledge, pedagogy, and technology integration; 2) quality assessment of STEM learning plans; 3) assessment of digital tool awareness and usage; 4) STEM learning plan analysis; 5) semistructured interview guides; 6) instructional observation forms; and 7) group reflection and debriefing meeting logs.

2) Each tool underwent refinement and quality assurance processes. Both quantitative and qualitative instruments were validated for content accuracy, ensuring alignment with the research objectives. The experts were involved in checking content validity and evaluating each assessment item's ability to measure the intended objectives. The scoring criteria were as follows: +1 for definite alignment, 0 for uncertain alignment, and -1 for misalignment. Expert feedback was used to calculate the item-objective congruence (IOC) index for each item. All the instruments were reviewed for language appropriateness by three science education experts.

3) The researcher piloted the tools with a group similar to the actual study participants, making necessary adjustments before the full-scale application. Initial data collection began during this phase.

4. Results

The teacher professional development program, which follows a school-centered model to establish Area STEM partnership teams (see Figure 2), aims to enhance content knowledge, pedagogy, and technology integration. This blended program unfolds across three phases: 1) Teachers' preparation cycle: In this foundational phase, teachers in the research group are prepared and supported to deepen their knowledge and skills in content, pedagogy, and technology through an online platform. School administrators and educational supervisors join in regional onsite sessions to align program goals and provide targeted support. 2) Cooperating teacher cycle: This phase fosters collaboration between school administrators and teachers, building a supportive network that encourages the practical application and refinement of the knowledge and skills gained in the preparation phase. 3) Collaboration cycle: In the final phase, a teaching operations team works together directly in classrooms. This phase emphasizes hands-on, active learning approaches, promoting interactive and student-centered teaching practices aligned with the active instructional model Table 1.

Table 1 Types of research data collected from the instruments.

Research Instruments		Qualitative Data	Qualitative Data
Self-Assessment of Knowledge	Evaluates knowledge in content, pedagogy, and technology integration.	/	
STEM Learning Plan Quality Assessment	Assesses the quality of STEM learning plans.	/	/
Digital Tool Awareness and Usage Assessment	Measures awareness and usage of digital technology tools.	/	
STEM Learning Plan Analysis	Analyzes the structure and content of STEM learning plans.	/	/
Semi-Structured Interview Guide	Facilitates semistructured interviews.		/
Instructional Observation Form	Observes and records teaching practices.		/
Group Reflection and Debriefing Meeting Log	Documents reflections and insights from group meetings and lesson debriefing sessions.		/

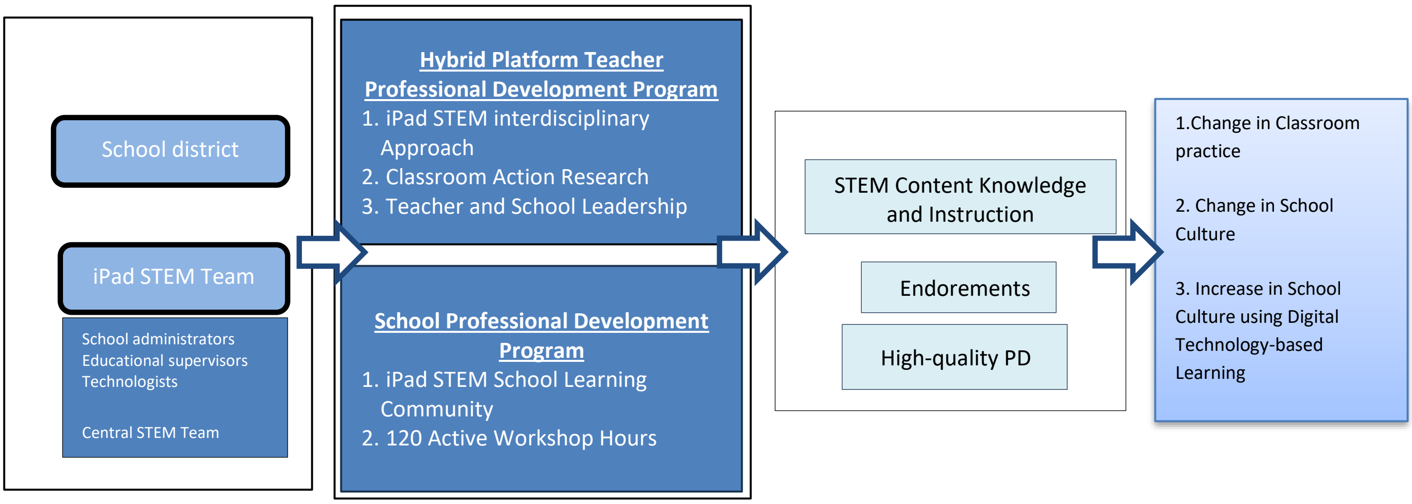

Figure 2 Area STEM partnership. *Source:* Creswell and Plano Clark (2007).

This program uses a hybrid approach to teacher professional development, combining online and in-person methods to enhance teachers' content knowledge, pedagogical skills, and technology integration in a school-centered setting. The program is structured in three progressive phases:

Phase 1: Teachers' Preparation Cycle

This initial phase prepares teachers by building foundational knowledge and skills in content, pedagogy, and technology integration. Teachers access an online platform for interactive modules, training resources, and tools to strengthen their instructional practices, whereas school administrators and educational supervisors participate in region specific, in-person sessions to align program goals and support strategies.

Phase 2: The Coaching Cycle and Lesson Study

In this phase, school administrators and supervisors offer ongoing support to teachers through structured coaching and active participation in professional learning communities (PLCs). Teachers work collaboratively in lesson planning, guided by STEM-focused engineering design principles that incorporate science, mathematics, and technology. This process involves identifying real-world challenges that shape learning objectives; gathering relevant information to facilitate problem solving; designing, planning, and developing effective solutions; testing and refining solutions for optimal learning outcomes; and presenting findings to promote reflection and further learning.

Through lesson study and model classroom debriefing, teachers continually refine their STEM lesson plans, creating richer learning experiences, as illustrated in Figure 3.

Phase 3: Classroom Collaboration Cycle

The final phase implements collaborative teaching in the classroom. Teachers, alongside school administrators, supervisors, and expert mentors, apply their STEM lesson plans, using real-world applications to support student learning. Open-class sessions allow teachers to observe, practice, and refine their instructional techniques with guidance from supervising professors and colleagues. This collaboration is supported by a professional learning community (PLC), where continuous feedback and reflective practices drive improvements in teaching and learning.

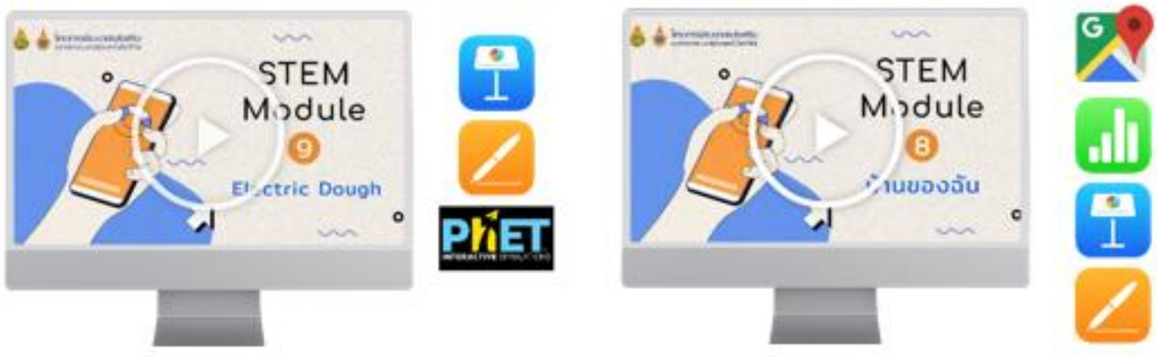

Figure 3 iPad STEM lesson design.

Over a year, this program has supported teachers in building sustainable instructional skills, encouraging a collaborative school environment focused on integrated, real-world learning. The implementation of content knowledge, pedagogy, and technology integration impacts teachers' STEM instruction through two case studies, as follows:

Case Study 1: STEM Learning Plan – "The Wonder of Leaf Colors"

Step 1: Problem identification

Activity 1: Adventure in Jungle: In this stage, the teacher uses a digital interactive worksheet with guided questions to prompt students to draw on their prior knowledge as they embark on "Adventure in Jungle." The following questions are asked:

What colors do you think leaves have?
Can you name some plants with yellow, red, and purple leaves?
What is the function of leaves in plants?
do green leaves contain only green pigments?
How could you determine if other colors are hidden in green leaves?

The teacher introduces an immersive "Adventure in the Jungle" scenario on the iPad, which is designed to help students identify and engage with the central problem, paving the way for data collection and concept exploration. In this context, students take on the role of candidates aspiring to become assistant researchers to Professor Beverley Glover, director of the Cambridge Botanic Garden, who is conducting research on Thailand's diverse plant life. The challenge is to design a portable, battery-free device capable of isolating plant components with precision for field identification. Using their Chromatography Test Kit (CTK), students must successfully distinguish between three mystery plant samples to secure the assistant position. The teacher encourages students to analyze the problem through 5W1H questions, such as the following:

Teacher: What is the main problem in this scenario?
Student 1: Designing a portable device to isolate plant components accurately for field use.
Teacher: What conditions are specified in the scenario?
Student 1: Small, portable device, no battery power, ability to isolate plant components accurately
Teacher: What device must students create, and for what purpose?
Student 2: A CTK designed to isolate plant components accurately, qualifying them as research assistants.

Step 2: Related Information Search

Activity 2: Magic of Leaf Colors

In Activity 2, the teacher facilitates teamwork by grouping students to explore leaf pigments. The activity comprises three parts:

Step 3: Solution Design

In this stage, the teacher acts as a coach, guiding students in designing their CTKs via the materials provided. This stage encourages creativity and practical application of prior knowledge.

Step 4: Planning and development

Students work in groups to construct their CTKs and practice scientific skills and group collaboration.

Step 5: Testing, evaluation, and design improvement

Students test their CTKs on the basis of the following criteria:

- Quick, efficient component isolation
- Complete isolation

- Portability
- Suitable material choice

The teacher encourages students to refine their designs on the basis of these tests.

Step 6: Presentation

Students use Keynote to present their CTKs, summarizing their design process and evaluating device performance. This session fosters critical thinking and reflection on the science (e.g., natural color extraction through chromatography), technology (FizziQ and numbers applications), engineering (CTK design), and mathematics skills developed throughout the activity Table 2.

Table 2 Parts of the activity of leaf colors.

Part 1: A Colorful However, Dangerous World	Part 2: Hidden Colors in Leaves	Part 3: Mystery of Leaf Pigments
Students analyze articles on natural vs. synthetic colors, presenting information via the Numbers app to foster content understanding. Example questions include - Why do candies and snacks often have bright colors? Answer: Colors attract consumers by making products visually appealing. - How can contaminants from dyes in food affect the body? Answer: They can lead to health issues, including acute illness or even cancer	Students are then guided to raise community awareness of the hazards of synthetic colors through school broadcasts, promoting the use of natural colors instead. Students work in groups, collecting and analyzing two types of leaves with the FizziQ app, which records color data across stages (fresh, wilting, dry). Observing color changes in each stage, students explore chlorophyll degradation and pigment changes.	Using Chromatography Test Kits (CTK), students conduct chromatography on leaf samples, observing color separation and analyzing pigment concentration through a controlled experiment, concluding with key findings on chromatography effectiveness and pigment intensity across various solvents.

5. Discussion

This study analyzed teachers' discussions and practices during group-based lesson design sessions and identified several contextual factors influencing their TPACK development during collaborative work under the iPad STEM PD Program. These findings suggest that for effective TPACK coconstruction, teachers should prioritize pedagogical discussions. However, factors such as grade level and students' ICT competencies may also be required for designing training programs. Positive teachers' beliefs play a key role in stimulating TPACK-related discussions when articulated to support pedagogical action. This aligns with research indicating that teachers' beliefs impact ICT integration (Ertmer et al., 2012; Hermans et al., 2008; Sang et al., 2011). The research findings indicate that in developing technological pedagogical content knowledge (TPACK) for iPad-based STEM teaching, science teachers must seamlessly integrate digital technology with pedagogical methods while maintaining accurate content knowledge. TPACK serves as a framework that helps teachers understand subject-specific instructional methods using technology, focusing on balancing three core components: content, pedagogy, and technology. For effective STEM instruction, science teachers must build skills in each area and understand how these elements work together to enhance instructional quality and improve student learning outcomes.

The key components identified for designing effective STEM lessons include the following: 1) Integration of digital technology in STEM instruction: science teachers need skills in selecting and utilizing digital tools that enhance STEM learning. Beyond knowing how to use technology, teachers must understand how it aligns with pedagogy and content, such as using digital simulations or coding platforms to make complex concepts more accessible and to foster inquiry-based learning. Research indicates that professional development programs focused on TPACK benefit from providing hands-on learning experiences, encouraging reflection, and promoting collaborative lesson design involving technology. 2) Pedagogical knowledge within the STEM context: effective STEM instruction requires science teachers to employ specific pedagogical strategies, such as problem-based learning, inquiry-based learning, and collaborative work. Teachers should effectively integrate these strategies with digital technology, for example, by using virtual labs or collaborative platforms to create engaging, student-centered learning environments. Successful TPACK development involves continuous professional development where teachers experiment with technology integration and reflect on their instructional practices. 3) Content knowledge development: Strong content knowledge is crucial, as digital tools should support rather than overshadow the content. Teachers must align technology use with curriculum standards and learning goals, such as using graphing software in mathematics or 3D design tools in engineering, to focus on key concepts. Additionally, research shows that observing and learning from expert teachers can help less experienced teachers or trainees develop instructional skills (Cajkler & Wood, 2015; Dudley, 2015). Furthermore, experienced teachers can sometimes learn innovative STEM instructional designs from newer teachers, underscoring the importance of creating an environment that facilitates experience sharing among teachers, which can either foster or hinder their knowledge growth (Smith et al., 2018).

A challenge in developing TPACK for STEM lies in the rapid pace of digital technology advancements, which require science teachers to stay current. This demands continuous support and professional development to build confidence and competence with new tools. Long-term engagement programs, such as mentoring, collaborative networks, and peer coaching, effectively support teachers' TPACK growth, contributing to schools becoming self-sustaining in professional development. School-based professional development (SBPD) has thus gained interest as an approach to produce and develop science teachers. This method emphasizes collaborative work among school leaders, supervisors, and academic teams, significantly impacting teachers' TPACK at all grade levels. The research supports the importance of continuous support systems for teachers to implement STEM teaching, revealing that research team members play a crucial role in facilitating digital technology integration with teaching. Teachers can design technology-integrated lessons that promote student learning, aligning with Angeli and Valanides' (2009) findings that content, pedagogy, and technology knowledge integration is essential for TPACK development. Research suggests that effective cross-disciplinary collaboration requires professional learning communities (PLCs), where teachers can exchange teaching experiences, codesign learning activities, analyze lessons, and observe classrooms. Collaborative work enables teachers to apply integrated knowledge effectively in classrooms.

Studies by Lomos et al. (2011) and Jones et al. (2013) confirm that PLCs significantly impact teachers' instructional and classroom management skills. The findings also highlight the importance of pedagogical knowledge as a critical factor in TPACK development. According to Tanak (2020), teachers with digital technology knowledge but lacking pedagogical skills may struggle to integrate these effectively, indicating that pedagogical skill development is essential for strengthening TPACK. School-based professional development programs with collaborative involvement from school administrators, supervisors, and academic teams, with a focus on students' core and discipline-specific competencies, are crucial for transforming instructional practices. This study emphasized that foundational TPACK knowledge and the ability to apply it in classroom lesson design are vital for change.

This research included preparing teachers, building support teams both within and beyond the school, and providing in-school assistance to establish ongoing learning cycles through lesson studies and PLCs. Key findings suggest that a sustainable teacher development program for TPACK growth in elementary schools requires support at two levels: operational (within the school) and administrative (from supervising authorities).

6. Final Considerations

This study tracked teachers' understanding and application of digital technology tools for instructional management alongside ongoing monitoring and support by educational supervisors and school administrators. Future research should investigate the factors, challenges, and obstacles in implementing sustained STEM instruction with these tools. Effective implementation requires area-based teams and coaching coordinated at the school level, tailored to the school's unique context. Additionally, developing a model for implementing STEM curricula in a sustainable, continuous manner within schools would provide valuable insights. Another area for future research is the collaborative creation of iPad-based lessons that address a comprehensive range of scientific competencies. This approach promotes interdisciplinary, continuous learning across grade levels, emphasizing assessments of scientific literacy, technology, and mathematics. Furthermore, competency-based assessment tools are needed to collect data at the initial, developmental, and postdevelopment stages, yielding a more detailed understanding of student progress. The findings from this research highlight the value of a participatory approach in developing in-service teachers.

Further exploration could focus on establishing a teacher preparation model in which schools serve as both classrooms and instructional labs. This model involves collaborative planning, implementation, and reflective practices by teams of school administrators, teachers, and educational supervisors. The incorporation of digital technology as ongoing support and the design of learning activities that foster creative competencies—particularly those aligned with the creative thinking skills outlined in the PISA's international assessment framework—could greatly enhance teacher training and instructional efficacy.

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Ethical Considerations

This study adhered to ethical research standards, with all participants providing written consent by signing a consent form. The following ethical principles were upheld throughout the research process:

1. Informed Consent: Participants were fully informed about the research objectives, procedures, potential risks, and their right to withdraw at any time without negative consequences. Written consent was obtained before participation.
2. Confidentiality and Anonymity: Personal information was kept confidential and used solely for research purposes. Data was anonymized to prevent any identifiable links to individual participants.
3. Voluntary Participation: Participation was entirely voluntary. Participants had the right to refuse or withdraw from the study at any stage without penalty.

4. Non-Maleficence: Every effort was made to minimize potential risks or discomforts. No harmful procedures or interventions were involved in the study.
5. Data Security: Collected data were securely stored and accessed only by authorized researchers. Data management followed relevant privacy and data protection regulations.
6. Transparency and Integrity: The research process and findings were reported transparently and honestly, ensuring accuracy and reliability in data presentation and interpretation.

These measures ensured that participants' rights, safety, and well-being were protected throughout the study.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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