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Research Article

# Enhancing STEM Competence among In-Service Teachers through School Partnership-Based Professional Development: A Mixed Methods Study

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## Abstract

This study examined the impact of a STEM professional development (PD) program on 30 in-service teachers working in a school partnership. The study aimed to: (1) examine teachers' baseline STEM competencies, (2) develop a PD program integrating technology for STEM education, and (3) enhance teachers' competencies in STEM instruction. A convergent mixed-methods design was employed. Thirty teachers participated in the STEM PD program, and three were purposively selected for in-depth case studies representing different competency levels. Findings revealed substantial improvements in teachers' STEM instructional competencies, particularly in applying the engineering design process, formulating driving questions, and integrating STEM disciplines into classroom practice. Cross-case analysis further revealed that competency development occurred through multiple pathways: context-based integration (T1), engineering design-oriented learning (T2), and cognitively demanding instruction and assessment (T3). These patterns suggest that STEM competency is multidimensional and enacted differently across instructional contexts.

The technology-integrated teacher PD program elevated teachers' competencies from the basic level to the proficient and advanced levels across conceptual understanding, process knowledge, and STEM-based learning activity design. However, continuous development remains necessary, particularly in STEM learning assessment, to ensure comprehensive competency growth across all dimensions.

**Keywords:** Teacher competency, Professional development, STEM education

## Introduction

In today's world, characterized by rapid social, economic, scientific, and technological change, competition has intensified across all dimensions. In this context, countries around the world are fostering human capital development to remain competitive in the contemporary global landscape. Scholars have identified three important competency domains: core subject knowledge and general literacy, life and career skills, and learning and innovation skills. These competencies are closely associated with the 4Cs: communication, collaboration, creativity, and critical thinking, which are widely recognized as fundamental capacities for individuals in the modern era (Bybee & Fuchs, 2006; Trilling & Fadel, 2009).

In Thailand, the government has prioritized science, technology, and innovation as key drivers of national development, with the primary goals of enhancing competitiveness, building an innovation-based economy, and fostering sustainable social development (Ministry of Higher Education, Science, Research and Innovation, 2021). This vision is consistent with the National Education Plan (2017–2036), which states that "all Thai people will receive quality lifelong education, live happily, and adapt to changes in the 21st century based on the philosophy of sufficiency economy." However, creating innovation requires human resources with high-level competencies, a quality Thailand still lacks.

Thai youth, in particular, must be equipped with the competencies necessary to thrive in a rapidly changing world and to contribute as future innovators. However, evidence from both international and national assessments suggests that the current educational system has yet to achieve this goal. The 2022 Program for International Student Assessment (PISA) revealed a decline in Thailand's performance across all domains compared to 2018, with science scores falling from 426 to 409 and remaining below the OECD average (IPST, 2023). At the local level, data from Phetchaburi Province paint an equally concerning picture. The 2020 Ordinary National Educational Test (O-NET) results showed that lower secondary students achieved an average of only 25.46% in mathematics and 29.89% in science. Upper secondary students performed slightly better, scoring 26.04% in mathematics and 35.93% in science, but these figures remain critically low (Phetchaburi Provincial Education Office, 2021). Taken together, these findings underscore the urgency of improving science teaching quality by systematically strengthening the professional competencies of science teachers.

Teacher competency encompasses the knowledge, skills, attitudes, and expertise that enable teachers to perform their professional duties effectively and to adapt to new and challenging educational demands (Dechakupt et al., 2023). Within the context of Thailand 4.0, teachers occupy a central role in realizing the national vision of producing lifelong learners, innovative creators, and responsible citizens. To fulfill this role, teachers must develop high-level competencies in Active Learning STEM, an instructional approach that integrates science, technology, engineering, and

mathematics through problem-solving and innovation (Chamrat, 2017; Kelley & Knowles, 2016). Active learning, in this context, emphasizes learner engagement through collaboration, inquiry, and hands-on practice, enabling students to construct new knowledge and gain authentic experiences (Dechakupt et al., 2023). Therefore, teacher PD programs must be thoughtfully designed to bridge the gap between theory and practice, helping teachers translate their pedagogical knowledge into real classroom strategies that genuinely improve student learning.

Effective professional development strategies include planning, action, and reflection cycles (Hamontree, 2015); micro-teaching, workshops, coaching and mentoring, case discussions, study groups, and supervision during teaching practice (Loucks-Horsley et al., 1998). These strategies provide structured opportunities for teachers to enhance their professional knowledge and teaching practices. Despite the importance of STEM education and continuous PD efforts in Thailand, there remains a lack of research on developing science teachers into high-competency STEM education practitioners within school partnerships and Rajabhat University contexts. Furthermore, most existing studies do not sufficiently integrate digital technologies into PD strategies that incorporate mentoring or coaching systems**,** even though such integration is essential to create transformative impacts on teachers' instructional practices and students' learning outcomes. Therefore, this study aims to develop science teachers in the Phetchaburi Rajabhat University school partnership to achieve high competency in STEM instruction through a professional development approach that emphasizes authentic practice, digital technology integration, and coaching support. This study also aims to explore how STEM instructional competencies are enacted differently across classroom contexts through case-based analysis. The following research questions were formulated:

(1) How can a technology-integrated teacher PD program enhance the competency of in-service teachers in partnership schools to achieve high competency in STEM instruction?

(2) What is the level of in-service teachers' competency in STEM education instruction after participating in the PD program?

**Research Objectives**

1. To examine the baseline competency of in-service teachers in STEM instruction within school partnerships.
2. To design a technology-integrated professional development program for STEM education instruction.
3. To strengthen the competencies of in-service teachers in partnership schools to a high level in STEM instruction.

## Research Framework

*STEM Professional Development (STEM PD)*

Professional development in STEM education is a structured, sustained process through which teachers deepen their subject matter knowledge, refine their pedagogical skills, and strengthen their competency to deliver effective STEM instruction. Unlike traditional training models that rely on isolated workshops or one-time seminars, STEM PD emphasizes continuity, collaboration, and direct application within authentic classroom contexts (Darling-Hammond et al., 2017; Desimone, 2009). A well-designed STEM PD framework is grounded in several core principles. First, it must be content-focused, ensuring that teachers develop a deep conceptual understanding of science, technology, engineering, and mathematics as integrated disciplines rather than as separate subjects. Second, it must incorporate active learning strategies that allow teachers to experience inquiry-based and problem-solving approaches firsthand, enabling them to transfer these methods to their own instructional practice. Third, effective STEM PD must be collaborative, fostering professional learning communities in which teachers share experiences, examine student work, and collectively reflect on their teaching (Loucks-Horsley et al., 2010).

In the 21st century, STEM PD has increasingly integrated digital technologies as both a medium and a tool for teacher learning. Digital platforms support coaching, peer observation, and reflective practice across geographic boundaries, expanding the reach and sustainability of professional development programs. Furthermore, the incorporation of mentoring and coaching systems within STEM PD has been shown to produce more transformative and lasting changes in teachers' instructional behavior, as these mechanisms provide personalized, ongoing support that bridges the gap between theory and classroom practice (Kraft et al., 2018).

Research consistently demonstrates that high-quality STEM PD produces measurable improvements not only in teacher competency but also in student learning outcomes, particularly in science and mathematics achievement. For this reason, STEM PD serves as a foundational mechanism through which educational systems can respond to the growing demand for scientifically literate and innovation-capable graduates.

*STEM Teachers' Competency*

STEM teacher competency refers to the integrated set of knowledge, skills, attitudes, and professional dispositions that enable teachers to design, facilitate, and assess effective STEM learning experiences. Competency in this domain extends beyond disciplinary expertise to encompass a broad range of pedagogical, technological, and collaborative capacities that collectively define the quality of STEM instruction (Kelley & Knowles, 2016; Nadelson & Seifert, 2017). Scholars have proposed various frameworks for conceptualizing STEM teacher competency. Among the most widely cited is the Technological Pedagogical Content Knowledge (TPACK) framework, which

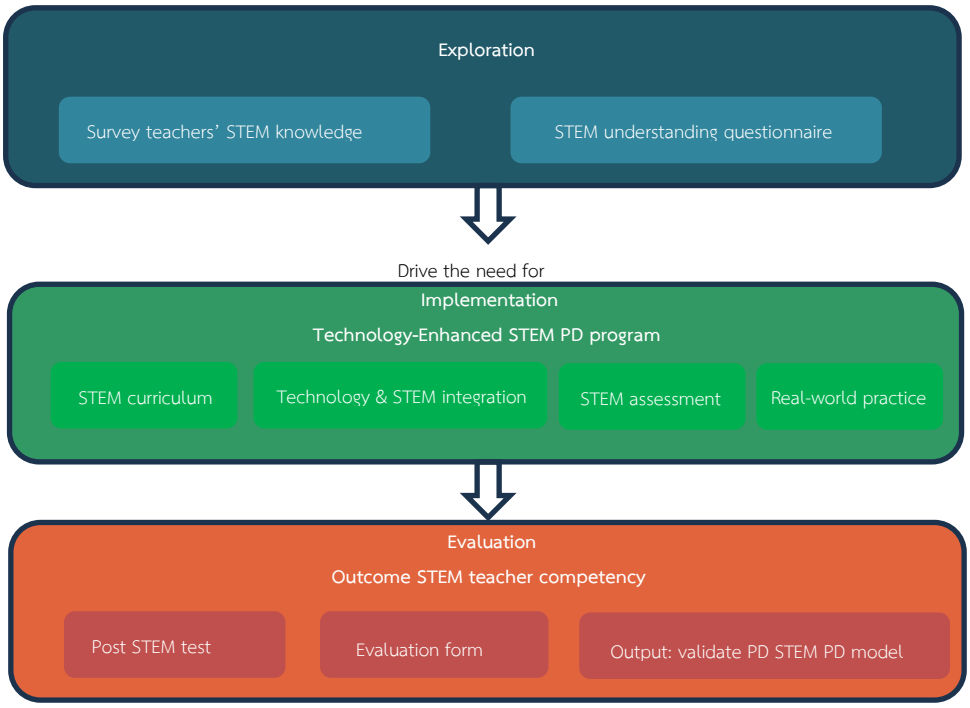
positions teacher competency at the intersection of content knowledge, pedagogical knowledge, and technological knowledge (Mishra & Koehler, 2006). Within STEM education specifically, this framework has been extended to incorporate engineering design thinking, critical thinking, and interdisciplinary problem-solving as additional dimensions of professional expertise. Teachers who demonstrate high-level STEM competency are therefore distinguished not only by their mastery of subject content but also by their ability to integrate multidisciplinary perspectives into coherent, meaningful learning experiences for students.

STEM teacher competency comprises four core domains: content knowledge, encompassing an integrated understanding of STEM concepts and their real-world applications; pedagogical competency, including the ability to design learning activities, facilitate inquiry-based and project-based instruction, and differentiate teaching to meet diverse learner needs; technological competency, involving the selection and integration of digital tools to enhance STEM learning; and professional competency, reflecting reflective practice, collaboration, and continuous self-improvement (Margot & Kettler, 2019; Ring et al., 2017). In the Thai educational context, STEM teacher competency development has become a policy priority in response to persistently low student achievement in science and mathematics. The shift toward Active Learning STEM requires teachers to move beyond content transmission and adopt student-centered, facilitative approaches — a transition that demands not only new pedagogical knowledge but also a redefined professional identity, from knowledge deliverer to learning designer (Dechakupt et al., 2023). Strengthening STEM teacher competency is therefore regarded as a critical lever for improving educational quality and preparing students for an innovation-driven society.

This study draws upon two interconnected theoretical pillars, STEM PD and STEM teacher competency, to construct a coherent research framework. The central argument is that a technology-enhanced PD program, when intentionally designed and sustained, is the primary mechanism by which science teachers can develop the integrated competencies required for effective STEM instruction. Rather than treating PD and teacher competency as separate concerns, this study positions them in a dynamic relationship: the PD program is the process, and the growth of teacher competency is the outcome. Digital technology functions not merely as a supplementary tool but as a structural component that enables coaching, collaborative reflection, and the transfer of pedagogical knowledge into real classroom practice. Ultimately, this framework is oriented toward a distal but critical goal of improving student learning outcomes in science within a school partnership context. The conceptual framework of this study is illustrated in Figure 1.

**Figure 1**

*Conceptual framework of the study comprising exploration, implementation, and evaluation.*




This framework highlights a systematic process that begins with exploration, proceeds through implementation, and concludes with evaluation, ensuring both the development and validation of a technology-integrated PD program for in-service teachers.

## Methodology

This study employed a convergent parallel mixed-methods design to investigate the competency of in-service teachers in STEM instruction. Quantitative and qualitative data were collected simultaneously, analyzed separately, and then integrated for interpretation (Creswell & Plano Clark, 2018). Triangulation was applied to enhance credibility and trustworthiness by using multiple data sources and methods, including surveys, competency assessments, evaluation forms, focus group discussions, classroom observations, and document analysis (Denzin, 1978; Lincoln & Guba, 1985; Patton, 1999). This approach ensured rigorous and valid conclusions regarding the development of teachers' STEM teaching competency.

The participants in this study consisted of 30 in-service teachers of science, mathematics, and technology from schools in partnership with a Rajabhat University in the western region of Thailand. Participants was selected through purposive sampling based on the following criteria: (1) being an in-service teacher who works in a partnership school, (2) having at least one year of teaching experience, (3) teaching in the subject areas of science, mathematics, or technology, and (4) voluntarily participating in the program on a full-time basis.

Three teachers were purposively selected as case study participants, representing varying levels of STEM instructional competency: basic, advanced, and high. All three consented voluntarily to classroom observations conducted in authentic teaching settings throughout the follow-up semester (May–July), immediately following the workshop program. Data were collected using four main instruments. (1) The STEM Teaching Understanding Questionnaire was used to examine participants' baseline understanding and perceptions of STEM education. It comprised three parts: (1) demographic information such as teaching experience and prior exposure to STEM teaching, (2) understanding of STEM teaching concepts, goals, assessment, and essential characteristics, and (3) perceptions toward STEM education policy and readiness for implementation. The questionnaire contained 16 items, validated by three experts with an Index of Item-Objective Congruence (IOC) ranging from 0.67 to 1.00 and an overall average of 0.95, exceeding the acceptable threshold of 0.50. (2) The Technology-Integrated Professional Development Program was designed through expert consultation using focus group discussions. (3) STEM Teaching Competency Assessment (Post-Program) was used, to assess teachers' competencies in designing and implementing STEM lessons after participating in the program. It included demographic data and open-ended questions focusing on lesson design, interdisciplinary integration, assessment strategies, goal setting, and the use of driving questions. The assessment comprised 20 items, validated by three experts, with IOC values ranging from 0.67 to 1.00, averaging 0.97. (4) A semi-structured Focus Group Interview Protocol, consisting of eight questions, was used to capture teachers' reflections, classroom practices, challenges, and suggestions after program participation. Content validity was confirmed by three experts, with IOC values ranging from 0.67 to 1.00 and an overall average of 0.96. Revisions were made based on expert recommendations to broaden the scope of specific questions, ensuring more diverse responses.

All instruments were administered directly by the researcher. Quantitative data were analyzed using descriptive statistics (percentages, means, and standard deviations) with computer software. Qualitative data from documents, observations, and open-ended responses were analyzed using content analysis and inductive interpretation to synthesize and explain the findings.

The researcher strictly adhered to research ethics throughout all stages of the study, including topic selection, participant recruitment, research design, data collection, analysis, and reporting. Three main principles were emphasized: (1) Informed consent was obtained from all participants prior to observations, interviews, focus group discussions, and recordings, with clear explanations of the research objectives, confidentiality, potential risks, and the right to withdraw at any time; (2) Confidentiality was maintained by using pseudonyms (e.g., T1, T2, T3) and withholding institutional identities, with participants' personal information and images fully protected; and (3) Minimization of harm was ensured by avoiding additional workload or interference with teachers' regular

responsibilities and institutional structures. Cross-case analysis was employed to identify patterns and variations in the development of STEM instructional competencies across the three cases.

## Results

The researcher presents the results of data collection in four parts as follows: (1) Baseline understanding: prior to the workshop, in-service teachers demonstrated varied levels of understanding regarding STEM education. While many recognized the importance of STEM, misconceptions remained about its goals, integration methods, and assessment practices. Based on a pre-workshop survey of teachers' opinions, although most teachers agreed with the current STEM education policy (M = 4.13, SD = 0.80), misconceptions remained regarding STEM literacy. In particular, 50% of the teachers still perceived mathematics as being solely related to calculation. Furthermore, their overall readiness to implement STEM instruction was only moderate (M = 3.57, SD = 0.71), and they also expressed concerns about teaching STEM (M = 3.27, SD = 0.96). (2) The professional development program (PD) program: based on the analysis in Part (1), the researcher developed a technology-integrated teacher professional development program by synthesizing relevant documents, principles, and prior research. Once the program framework and activity procedures were established, the draft model was submitted to three experts for review and additional feedback through a focus group discussion. The experts also evaluated the program, and their suggestions were incorporated into revisions prior to implementation. The details are presented in Table 1.

**Table 1**

*Activity Plan of the Technology-Integrated Teacher Professional Development Program.*

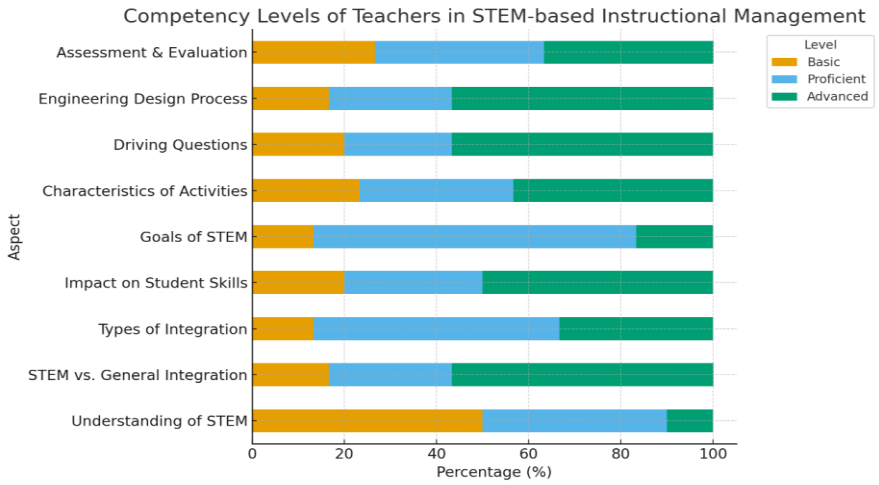
| Stage | Objective | Activity | Learning Materials |
|---|---|---|---|
| **Introduction (2 hrs.)** | To examine participants' prior knowledge and understanding of STEM concepts | Present STEM education concepts, introduce challenging issues, group discussion, and reflection on integration approaches and instructional goals | Canva slides, post-it notes |
| **Exploring Creativity (6 hrs.)** | To stimulate creative thinking, collaboration, and integration of digital technology | Team-based activities; teachers design models following the engineering design process; collaborative problem-solving | Canva slides, materials for constructing an earthquake model |
| **Presenting Explanations and Solutions (2 hrs.)** | To assess understanding of STEM instruction and encourage reflective practice | Teachers generate explanations, reflect on outcomes, and discuss case studies. | Canva slides, flip-chart paper, markers, and the Phyphox application |

| Stage | Objective | Activity | Learning Materials |
|---|---|---|---|
| **Implementation (2 hrs.)** | To strengthen understanding and assess competency in applying knowledge | Teachers present and apply ideas in new contexts; performance-based assessment; follow-up in classrooms via lesson plan evaluation and focus group discussion | Competency assessment forms, Google Meet |

The table presents the stages of the process for developing competencies in STEM-based instructional management among in-service teachers. Prior to implementing the activities, the researcher conducted a briefing session to clarify procedures, including the use of assessment tools, ensuring a shared understanding. The session also covered the follow-up process to be conducted after the workshop, which involves case-based monitoring according to specified criteria. The evaluation methods included assessing teachers' lesson plans and engaging in focus group discussions via Google Meet. (3) Competency in STEM-based teaching after participation in the PD program: once the technology-integrated teacher PD program had been designed, the next step was its implementation. The program was applied through a workshop conducted in stages, as presented in Table 1, with 30 in-service teachers selected through purposive sampling. The outcomes of the implementation of the technology-integrated teacher professional development program were assessed using three methods: (1) an open-ended questionnaire measuring competencies in STEM-based instructional management, (2) an evaluation of the lesson plans designed and implemented in authentic classroom contexts, and (3) a focus group discussion. The results are presented in Figure 2.

**Figure 2**

*Teachers' competency levels after participating in the professional development program.*



The analysis of teachers' competency levels after participating in the PD program revealed that teachers demonstrated varied levels of STEM-based teaching competencies. Most teachers reached the proficient or advanced levels in several areas. For example, more than half of the participants achieved an advanced level in distinguishing STEM from general integration (56.67%), applying driving questions in STEM instruction (56.67%), and employing the engineering design process (56.67%). Similarly, half of the teachers (50.00%) reached the advanced level in demonstrating the impact of teaching on student skills. In contrast, competencies such as understanding the basic meaning of STEM were mainly at the basic level (50.00%), while competencies related to assessment and evaluation of STEM learning showed a more balanced distribution across the three levels. The highest proportion at the proficient level was observed in defining STEM goals (70.00%), followed by identifying types of integration (53.33%). Overall, the results indicated that teachers demonstrated substantial growth in competencies related to applying STEM pedagogy in practice, particularly in integration, use of driving questions, and implementation of the engineering design process. However, further support is needed to strengthen foundational STEM understanding and to enhance teachers' competencies in assessment and evaluation practices.

(4) STEM Instructional Competencies from Three Case Studies. The cross-case analysis of the three teachers (T1–T3) revealed distinct yet complementary patterns in the development of STEM instructional competencies. Rather than representing isolated practices, each case illustrates a different pathway through which teachers operationalized STEM pedagogy in authentic classroom contexts.

(A) Integration of Disciplines through Local Context (T1)

T1 demonstrated competency in integrating STEM disciplines through a context-based approach grounded in local agricultural practices. The lesson was designed around a real-world problem: designing a low-cost yet effective greenhouse for plant growth. The teacher initiated the lesson by activating students' prior knowledge using real plant materials and guiding them to explore plant-growing environments through field observations and multimedia resources.

During classroom implementation, students worked collaboratively to analyze environmental factors affecting plant growth and to propose design solutions under practical constraints such as cost and efficiency. The teacher adopted a facilitative role, using guiding questions to prompt students' reasoning and discussion rather than providing direct instruction. Evidence from classroom observation and student artifacts indicated that learners were able to connect scientific concepts (e.g., light, water, temperature) with engineering design decisions. This case highlights how contextualized STEM integration can enhance relevance and support meaningful learning by linking academic content to students' lived experiences.

(B) Hands-on Learning and Engineering Design (T2)

T2 exhibited strong competency in implementing STEM instruction through hands-on, design-based learning. The lesson focused on constructing a sailboat that could float and move effectively, requiring students to engage in the full cycle of the Engineering Design Process (EDP). Students worked in teams to analyze the problem, generate hypotheses, design prototypes, test their models, and iteratively refine their solutions. The classroom environment was characterized by active experimentation, peer discussion, and continuous improvement of student work. Observation data showed that students demonstrated high levels of engagement, particularly in the testing and redesign phases, where they evaluated the performance of their designs and made evidence-based adjustments. The activity fostered critical thinking, creativity, and collaboration, as students negotiated ideas and justified their design choices.

This case illustrates how structured engagement in the engineering design process can promote deeper learning and support the development of 21st-century competencies through experiential and iterative learning.

(C) Higher-Order Thinking through Questioning and Assessment (T3)

T3 demonstrated competency in promoting higher-order thinking through the use of open-ended questioning and authentic assessment. The lesson involved a design-based task (e.g., a fly-trap project), in which students were required to apply scientific concepts to solve a practical problem while explaining and justifying their design decisions. The teacher emphasized analytical thinking by posing open-ended questions that required students to reason, predict outcomes, and evaluate alternative solutions. In addition, authentic assessment strategies were employed, focusing not only on final products but also on students' reasoning processes and reflections. Classroom observations indicated that students engaged in deeper cognitive processes, including analysis, evaluation, and justification. Students were encouraged to articulate their thinking and to reflect on both the strengths and limitations of their designs. This case highlights the importance of questioning and assessment as pedagogical tools for shifting STEM instruction from content acquisition toward competency-based learning.

(D) Cross-case Interpretation

Taken together, the three cases demonstrate that STEM instructional competency is not a singular construct but a multidimensional capacity that can be enacted in different ways depending on context and instructional focus. T1 emphasizes contextual integration and relevance, T2 emphasizes process-oriented design and innovation, and T3 emphasizes cognitive complexity and assessment-driven learning. These findings suggest that effective STEM instruction emerges from the interplay between real-world context, active learning processes, and cognitively demanding tasks. Moreover, the variation across cases reflects teachers' adaptive expertise in applying STEM pedagogy

in ways that align with their classroom contexts and professional strengths. To further illustrate the differences and similarities across the three cases, a cross-case analysis was conducted, as presented in Table 2.

**Table 2**

*Cross-Case Analysis of STEM Instructional Competencies (T1–T3)*

| Case | Instructional Focus | Key Teaching Practices | STEM Integration Pattern | Student Learning Outcomes | STEM Competency Dimension |
|---|---|---|---|---|---|
| **T1** | Context-based learning through a local problem (greenhouse design) | Use of real materials (plants), field-based exploration, guided questioning, and group discussion | Contextual integration of science, mathematics, technology, and engineering grounded in local agricultural practices | Students connected scientific concepts to real-life situations, applied knowledge to solve practical problems, and demonstrated collaborative reasoning | **STEM Awareness & Integration** (relevance, real-world connection) |
| **T2** | Hands-on engineering design and innovation (sailboat project) | Implementation of Engineering Design Process (EDP): problem identification, prototyping, testing, redesign; teamwork and experimentation | Process-driven integration emphasizing engineering design and iterative problem-solving | Students developed critical thinking, creativity, collaboration, and problem-solving skills; demonstrated the ability to refine solutions based on evidence | **STEM Practices** (design thinking, iteration, collaboration) |
| **T3** | Higher-order thinking through questioning and authentic assessment (design-based task) | Use of open-ended questions, design challenges, and authentic assessment focusing on reasoning and reflection | Concept-driven integration linking scientific principles with design and evaluation | Students demonstrated analytical thinking, justification of ideas, and reflective reasoning; they engaged in evaluating the strengths and limitations of solutions. | **STEM Concepts & Cognitive Skills** (analysis, evaluation, reasoning) |

The cross-case comparison highlights that STEM instructional competency is multidimensional, encompassing contextual relevance, design-based practices, and higher-order cognitive processes. Each case represents a distinct but complementary pathway in the development of STEM teaching competency.

## Discussion

The assessment of in-service teacher competencies across three levels demonstrated substantial gains in both understanding and application of STEM concepts. Many teachers progressed from basic to proficient and advanced levels in areas such as distinguishing STEM from general integration, formulating driving questions, and applying the engineering design process. These findings confirm the effectiveness of the professional development (PD) program in bridging theoretical knowledge with classroom practice, consistent with Tamang et al. (2024), Pitiporntapin et al. (2023), and Charnprasert (2014). Importantly, competency development was not solely driven by the PD program itself but was reinforced by collaborative learning and school-level support. Teachers engaged in reflective dialogue, peer coaching, and joint problem-solving, aligning with Loucks-Horsley et al. (1998), while administrative support (e.g., time, resources, and autonomy) enabled experimentation and sustained practice (Pitiporntapin et al., 2023). This suggests that competency growth resulted from the interaction between PD design and a supportive professional ecosystem rather than from the intervention alone.

However, not all competencies were developed equally. Most teachers remained at the interdisciplinary level, with only a small proportion reaching transdisciplinary integration. This may be because such integration requires deeper contextual adaptation and experience in connecting learning with community-based problems, which cannot be fully achieved within a short-term PD program. Similarly, some teachers continued to rely on content-based assessment, reflecting the complexity of designing competency-based and authentic assessment, which typically demands sustained practice and conceptual understanding. These findings align with Tamang et al. (2024) and Han et al. (2015), who emphasized that continuous support is necessary for developing advanced integration and multidimensional assessment practices.

The case studies further illustrate differentiated pathways of competency development. T1 demonstrated context-based integration through local problem-solving, reinforcing the role of authentic learning contexts (Tamang et al., 2024; Pitiporntapin et al., 2023). T2 emphasized hands-on design and iterative problem-solving, reflecting the centrality of engineering design in STEM learning (Williams, 2000). T3 highlighted higher-order thinking through questioning and authentic assessment, supporting the importance of cognitively demanding tasks and diverse evaluation approaches (Han et al., 2015; Pimthong & Williams, 2021). Together, these cases suggest that STEM

competency development is multidimensional and context-dependent, rather than uniform across teachers.

Although the PD program effectively enhanced teachers' competencies, gaps remain in advancing transdisciplinary integration and assessment literacy. Addressing these limitations requires sustained and iterative PD that extends beyond initial training, with greater emphasis on contextual application, reflective practice, and competency-based assessment design. Such efforts are essential for achieving long-term impact and aligning STEM education with 21st-century learning goals (Tamang et al., 2024; Pitiporntapin et al., 2023; Charnprasert, 2014). This study extends existing STEM PD research by demonstrating that competency development is not uniform but occurs through multiple instructional pathways shaped by context, practice, and assessment.

## Recommendations

### Practical Recommendations

1. Encourage teachers to move from interdisciplinary to transdisciplinary integration by using community and social contexts as the foundation for designing learning activities.
2. Support the continuous use of field-based learning resources to connect classroom instruction with students' real-life experiences.
3. Develop teachers' skills in designing and applying assessment tools that are appropriate and responsive to learner diversity.

### Recommendations for Future Research

1. Investigate the long-term effects of teacher development in order to evaluate the continuity and sustainability of outcomes from professional development programs.
2. Analyze personal factors of both teachers and students that may influence the success of STEM-based instructional practices.
3. Develop and test competency-based assessment models that align with international standards, such as PISA.
4. Apply the development model to university network groups and conduct comprehensive evaluations of its effectiveness.

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