



STEM-BASED PROFESSIONAL DEVELOPMENT MODEL TO IMPROVE TEACHERS' PERCEPTIONS AND STUDENTS' STEM LITERACY: A MIXED RESEARCH APPROACH

D. Ardianto*¹, T. Windiyani¹, A. Puteri¹, H. Aziz¹, I. R. Suwarma², S. R. Yunus³

¹Graduate School, Universitas Pakuan, Bogor, Indonesia

²Department of Physics Education, Universitas Pendidikan Indonesia, Bandung, Indonesia

³Higher Degree Research, School of Education. The University of Queensland, Australia

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ABSTRACT

This study examines the effect of a structured professional development model on enhancing primary teachers' understanding and their capacity to promote students' STEM literacy. A mixed-methods design was employed to capture both quantitative outcomes and qualitative insights. Pre-test and post-test intervention surveys were used to measure shifts in teachers' perceptions, while students' literacy was assessed through structured essay tasks. Complementing this, open-ended questionnaires and interviews with selected teachers and students were conducted to explore their experiences and the perceived impact of the programme. The results demonstrate significant improvements in teachers' perceptions of STEM education and students' STEM literacy following the program's implementation. Quantitative findings indicate a substantial increase in teachers' self-efficacy and confidence in implementing STEM-based instruction, accompanied by measurable gains in students' STEM literacy across participating schools. These improvements are further explained and supported by qualitative findings, which reveal that teachers perceived the program as effective in strengthening their STEM content knowledge, pedagogical competence, and instructional confidence through hands-on learning activities, collaborative practices, and sustained professional support. In addition, qualitative evidence highlights contextual challenges, including limited instructional time and insufficient resources, which help explain variations in implementation effectiveness among schools. Overall, the findings suggest that a well-designed, contextually responsive STEM professional development model can enhance teacher capacity and meaningfully improve student STEM literacy in primary education, while underscoring the importance of ongoing support for sustainable implementation.

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Keywords: STEM literacy; teacher perceptions; teacher professional development

INTRODUCTION

STEM literacy is a key goal of STEM education, encompassing knowledge, skills, and dispositions across science, technology, engineering, and mathematics disciplines (Brand, 2020; Asrizal et al., 2023). It involves not only mastery of content but also the ability to apply STEM concepts and practices to real-world contexts (Nhung & Hanh, 2021; Liu, 2023) In the broader global

context, the development of STEM literacy directly supports the United Nations Sustainable Development Goals (SDGs), particularly SDG 4: Quality Education, which emphasizes the need to ensure inclusive and equitable education and promote lifelong learning opportunities for all. Strengthening STEM education equips learners with essential 21st-century competencies—such as problem-solving, creativity, and innovation—that contribute to SDG 9: Industry, Innovation, and Infrastructure, preparing future generations to address global challenges and sustainable development.

*Correspondence Address

E-mail: diditardianto@unpak.ac.id

The 2022 PISA survey results showed that Indonesian students' average scores in science, mathematics, and language literacy were unsatisfactory (OECD, 2023). This data indicates that students' literacy remains below the average score of all participating countries. The 2021 Minimum Competency Assessment results, as reported by the Ministry of Education, Culture, Research, and Technology, also support this finding, indicating that more than 60% of elementary and junior high school students were at or below the basic competency level in numeracy and reading literacy (Pusat Asesmen Pendidikan, 2022).

Specifically in the local context, the survey results are not significantly different from the STEM literacy of students in Bogor City and Cianjur Regency. Students' STEM literacy still needs improvement (Ardianto & Rubini, 2021). Data on students' STEM literacy achievement remain quite low, averaging 2% across all domains (Ardianto & Rubini, 2021). Furthermore, the research results also indicate that student interest in STEM remains low. Students' low interest in and limited literacy in STEM are due to the limited implementation of STEM education in schools and the infrequent use of scientific and engineering concepts in classroom instruction (Ardianto et al., 2024).

Teachers receive insufficient external support and coaching in STEM education (Ardianto et al., 2024). However, teacher professional development programs play a crucial role in equipping them with the knowledge and skills necessary for STEM education (Affouneh et al., 2020; Surahman & Wang, 2023; Şahin et al., 2024a). Numerous studies have demonstrated the importance of effective STEM teacher professional development in improving teachers' perceptions and instructional skills, as well as student engagement in STEM fields (Han et al., 2021; Wahono et al., 2021).

Several studies have also demonstrated that STEM professional development programs, which provide teachers with opportunities to learn STEM concepts and effective teaching strategies, can improve students' STEM literacy (Affouneh et al., 2020; Saat et al., 2021; Hasim et al., 2022). Furthermore, programs that include workshops and peer discussions to address classroom learning challenges can enhance teachers' skills in managing STEM learning and student engagement (Affouneh et al., 2020; Boice et al., 2021; Rusydiyah et al., 2021). The success of a coaching program is related to the content, curriculum, the appropriateness of the coaching, and support for teachers (Blazar, 2020). Professional

development programs for STEM teachers that involve comprehensive, constructivist-oriented, and ongoing learning processes can significantly improve students' inquiry-based learning experiences in science classrooms (Şahin et al., 2024).

STEM professional development programs are also significantly influenced by teacher perceptions (Affouneh et al., 2020; Hasanah & Permanasari, 2021). Teacher perceptions of STEM education can be influenced by various factors, including policy pressures, external support, and the school environment (Affouneh et al., 2020; Khuyen et al., 2020; Hurley et al., 2024). These factors can encourage or hinder teacher engagement and commitment to the development program (Hasanah & Permanasari, 2021). Previous studies have examined various approaches to STEM professional development, such as workshops (Hasim et al., 2022; So et al., 2021), reflections on STEM teaching practices, video-based reflections on STEM practices (ElSayary, 2021), and collaborative approaches (Berisha & Vula, 2021).

Although prior STEM professional development models have demonstrated effectiveness in improving teachers' knowledge and attitudes, several limitations have been identified. First, many models emphasize content transmission rather than integrating content knowledge with pedagogical application in real classroom contexts (Saat et al., 2021). Second, existing programs often lack sustained coaching and follow-up support, which reduces teachers' ability to implement STEM strategies consistently over time. Third, contextual factors such as school resources, time constraints, and institutional support are often underemphasized, leading to variability in implementation effectiveness (Setiawan & Sugiyanto, 2020; Saat et al., 2021). As a result, improvements in teacher competence do not always translate into meaningful and sustained gains in student STEM literacy.

These limitations highlight the need for a more comprehensive, context-sensitive professional development model that integrates STEM content mastery, pedagogical training, collaborative learning, and ongoing support, particularly for elementary school teachers operating in diverse school environments. These limitations suggest that existing professional development models may be insufficient to sustain instructional change and achieve consistent improvements in students' STEM literacy, particularly at the elementary level. However, most STEM development programs are conducted for secondary school teachers. STEM professional development

programs for elementary school teachers remain limited (Abd Ghani et al., 2023; Surahman & Wang, 2023). The lack of adequate development is a significant factor in teachers' limited understanding of integrating interdisciplinary learning. Consequently, learning tends to be fragmented, decontextualized, and teacher-centered, contributing to students' weak STEM literacy (Margot & Kettler, 2019). In the Southeast Asian context, only one study has investigated STEM-based professional development (Ismail, 2022).

The results of the preliminary study show that elementary school teachers still rarely use inquiry, experimental, and problem-based learning, as well as flipped classroom learning, in teaching STEM content. In fact, STEM education demands learning through scientific practice, with engineering as its main focus. The study also showed that 57% of teachers did not receive professional development support through training from external providers. In addition, more than 50% of teachers feel there is no support from external parties in teaching and research. The study also showed that 57% of teachers did not receive professional development support in the form of training from external providers. In addition, more than 50% of teachers feel there is no support from external parties in teaching and research.

Furthermore, almost 60% of teachers have not received guidance from external parties in their practice of professional development. The results of this survey show that elementary school teachers feel that support from external parties remains very limited, especially in training, re-

search, and teaching. Therefore, external roles, such as those of universities, education practitioners, and researchers, are urgently needed in the professional practice of elementary school teachers. Further analysis showed that the majority of elementary school teachers responded positively to their professional practices. They are aware that by developing professional practices, they can develop competencies in the pedagogic and scientific fields taught in the classroom, and they also have the opportunity to collaborate with their peers. In addition, they realize that to improve competence, they need a learning process, whether independent or through workshops.

The need for collaborative partnerships among schools, universities, and educational institutions also aligns with SDG 17: Partnerships for the Goals, which emphasizes multi-stakeholder cooperation to improve education quality and innovation capacity. Thus, building sustainable professional development networks is not only an educational priority but also a step toward achieving global development goals.

Based on the identified problems, gaps, and needs, this study is guided by the following research questions: 1) How does a STEM-based professional development model influence elementary school teachers' perceptions of STEM education? 2) To what extent does the implementation of the STEM-based professional development model improve students' STEM literacy? 3) How do teachers perceive their experiences of participating in a STEM-based professional development program, and what factors facilitate or hinder its implementation in classroom practice?

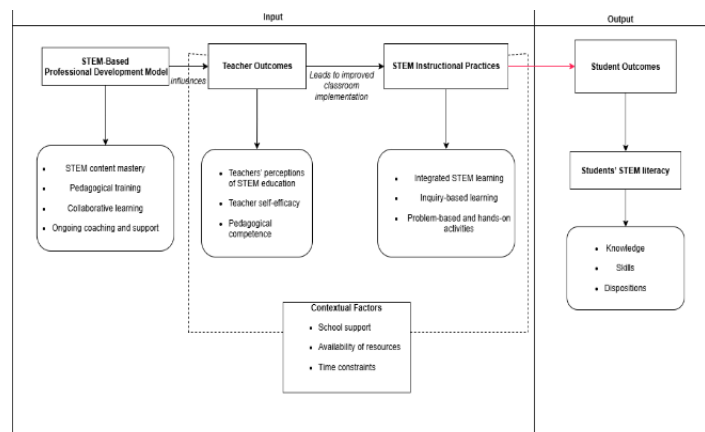


Figure 1. Conceptual Framework of STEM-based Professional Development

While previous studies confirm the positive impact of professional development on teachers' understanding of STEM education and integrative teaching strategies (Margot & Kettler, 2019;

Suebsing & Nuangchalerm, 2021), systematic, context-specific programs for elementary school teachers remain scarce and underdeveloped. Therefore, this study aims to develop and examine

a STEM-based professional development model designed to enhance elementary teachers' perceptions of STEM education and students' STEM literacy, in alignment with the broader objectives of SDG 4 (Quality Education) and SDG 9 (Innovation and Infrastructure), using a mixed-method research approach.

METHODS

This study employed a Sequential Exploratory Mixed Methods design, in which qualitative methods were used in the first phase to

explore contextual conditions and inform model development, followed by quantitative methods in the second phase to evaluate the effectiveness of the developed model. This design was selected to ensure that the professional development model and research instruments were grounded in empirical qualitative findings before being tested quantitatively.

The overall research procedure is illustrated in Figure 2, which presents the flow of the two research phases and the integration between qualitative and quantitative components.

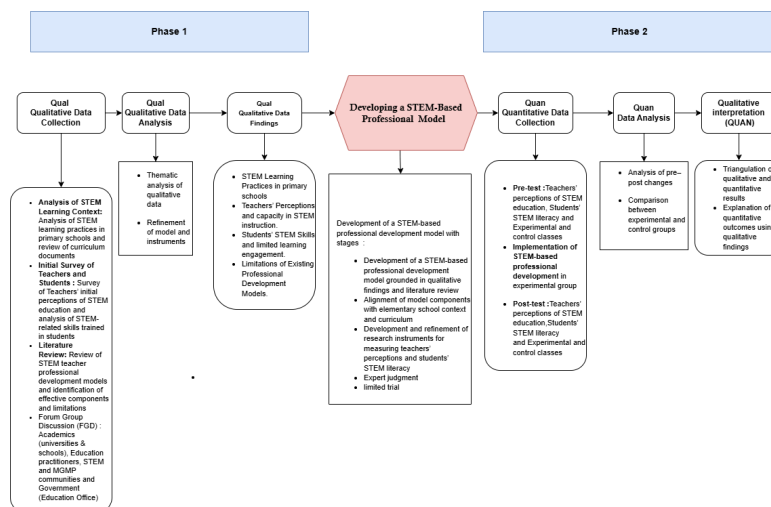


Figure 2. Sequential Exploratory Mixed-Methods Design for Developing aSTEM-Based Professional Development Model

Phase 1 Qualitative Phase (Exploration and Model Development)

The qualitative phase aimed to explore STEM learning practices, teacher capacity, and professional development needs in primary schools, and to develop a STEM-based professional development model and its assessment instruments. Qualitative data were collected through several activities: (1) analysis of STEM learning practices and curriculum documents in primary schools, (2) an initial survey of elementary school teachers' perceptions of STEM education and an analysis of STEM-related skills developed in students, (3) a literature review of existing STEM teacher professional development models, and (4) Focus Group Discussions (FGDs) involving academics, education practitioners, STEM and MGMP communities, and representatives from the Education Office.

Phase 2: Quantitative Phase (Implementation and Evaluation)

The quantitative phase focused on examining the effectiveness of the developed STEM-

based professional development model. Data collection began with a pre-test measuring teachers' perceptions of STEM education and students' STEM literacy in both experimental and control groups. The professional development program was then implemented in the experimental group, while the control group followed regular instructional practices. After the intervention, post-test data were collected using the same instruments.

Quantitative data were analyzed to examine pre-post changes and to compare outcomes between the experimental and control groups. This analysis provided empirical evidence regarding the impact of the professional development model on teacher perceptions and student STEM literacy.

Triangulation was conducted at the interpretation stage by integrating qualitative and quantitative findings. Quantitative results from the pre-test and post-test analyses were compared with qualitative findings from Phase 1 to explain patterns and variations in the outcomes. For example, qualitative themes related to teachers' perceptions, implementation challenges, and con-

textual factors were used to interpret differences in the effectiveness of the professional development model across classrooms. This methodological triangulation enhanced the credibility and validity of the findings by ensuring consistency and complementarity between qualitative insights and quantitative results.

This study involved 20 elementary school teachers, comprising 23% private school teachers and 77% public school teachers in Bogor City. They comprised six males and 12 females, as detailed in Table 1. In addition, 72 elementary school students participated in the study.

Table 1. Teachers' Characteristics

Teaching Experience		Experience in STEM Professional Development	
		Never	At Least Once
Years of Experience	Number		
0-4	9	8	1
5-10	8	6	2
>10	3	1	2

The STEM professional development program for elementary school teachers is designed based on findings from the literature and includes several key components: STEM content instruction, pedagogical training, collaborative learning, and ongoing support. STEM content instruction offers teachers the opportunity to deepen their understanding of STEM content and its effective integration. In pedagogical training, teachers are provided with materials on packaging effective STEM teaching strategies, such as problem-based and project-based learning, as well as on technology integration. Teachers collaborate with colleagues to design, implement, and solve STEM learning challenges in the classroom. Professional development is provided over a long period as ongoing support, including coaching for teachers.

The quantitative data in this study include teacher perceptions and students' STEM literacy. Teacher perceptions were collected through questionnaires administered before (pre-test) and after (post-test) the participants completed the training program. This questionnaire measured teachers' confidence and self-efficacy in STEM content and teaching. Teacher perception data were collected using the T-STEM Survey adopted from the Friday Institute for Educational Innovation (2012). Meanwhile, students' STEM literacy was measured using a five-item essay test. This data was collected through pre-tests and post-tests. The STEM literacy domains measured included

their knowledge, skills, and dispositions in STEM disciplines. In addition to quantitative data, this study also qualitatively explored teachers' conceptions of STEM education. Data on teachers' conceptions were collected using an open-ended questionnaire. Furthermore, in-depth interviews were conducted with several teachers. These interviews aimed to gain a deeper understanding of their experiences and perceptions of STEM-based professional development programs.

This study employed two data analysis techniques, both quantitative and qualitative. Quantitative data analysis includes pre-test and post-test data on students' STEM literacy, as well as data from elementary school teachers. The following is a technical description of quantitative data analysis. The average scores of teacher perceptions and students' STEM literacy before and after treatment were calculated. Afterward, a prerequisite test was conducted to ensure whether the data met the normality assumption. The significance test used a paired t-test when the data met the normality assumption and the Wilcoxon test when they did not. Next, an effectiveness test was conducted using Effect Size (Cohen's d). This test aims to determine the impact of the treatment on changes in the research subjects' scores. The interpretation of the Cohen's d value is as follows: 0.2 indicates a small effect, 0.5 indicates a medium effect, and 0.8 indicates a large effect.

In addition, the qualitative data from this study were analyzed using thematic analysis to identify key themes and insights regarding teachers' conceptions of STEM education. This study employed a constant comparative approach in analyzing data on teachers' perceptions of the STEM approach. The constant comparative method is a data analysis process that involves comparing different data units, categories, and concepts to develop and verify theories. The main purpose of this method is to understand patterns, relationships, and differences in the collected data, as well as to build a solid and relevant theory (Charmaz, 2006). There are two stages in the coding process: initial coding, also known as line-by-line coding, and focused coding, which follows verbatim coding (Charmaz, 2006). The stages of data analysis for teachers' perceptions of the definition of the STEM approach are as follows. The researcher conducted initial coding of the data on teachers' perceptions of the STEM approach. This stage aims to identify relevant data sections and label teachers' responses regarding their perceptions of the STEM approach. The second stage is focused coding. After initial coding, the researcher compared the newly dis-

covered codes and categories with the new incoming data. These comparisons are conducted continuously to evaluate similarities, differences, and relationships among various data elements. Based on these ongoing comparisons, researchers develop and refine categories and concepts that emerge from the data. Consistent or frequently occurring categories become the focus of further analysis, while less relevant categories can be eliminated or combined. Researchers constantly evaluate and compare categories to ensure that they accurately reflect the data and are relevant to the theory being developed.

RESULTS AND DISCUSSION

This study provides an overview of the influence of the STEM-based professional development model on elementary school teachers' perceptions (Table 2). The results showed that teachers' perceptions of STEM education improved after they participated in STEM professional development training. The results indicated that the STEM-based professional development model effectively improved teachers' attitudes and self-efficacy.

Table 2. Statistical Analysis of Teacher Perception Scores

Teacher Perception	Mean	SD	Shapiro-Wilk test	Levene's test	Paired t-test	Effect Size
Pre-test	2.76	0.48	0.35	0.26	0.000	1.89
Post-test	3.48	0.38	0.09			

Table 2 shows that teachers' perceptions increased in mean scores from 2.76 in the pre-test to 3.48 in the post-test. The t-test results indicated a significant difference in teachers' perception scores before and after receiving the training program. This finding aligns with previous research suggesting that a coaching model focused on STEM content and hands-on experience can enhance teachers' understanding and confidence in STEM education. Collaborative, ongoing support makes teachers feel better prepared to teach STEM disciplines effectively (Jones et al., 2017; Kelley et al., 2020).

The effectiveness of STEM learning was assessed by analyzing improvements in elementary school students' STEM literacy. The testing was conducted across three schools, with different

topics covered (waste management, environmental pollution, and microplastics). STEM learning in each target school was conducted twice. Before the lesson, students were asked to complete a STEM literacy pre-test consisting of a five-item essay. After the learning ended, they were asked to complete a post-test with the same questions as the pre-test. Trained teachers implemented STEM learning in each school. The analysis results indicate an overall increase in students' STEM literacy following STEM instruction. Table 3 shows that STEM learning effectiveness had a very significant impact on improving students' STEM literacy in Schools I and II. In School III, the increase in students' STEM literacy was moderate.

Table 3. Statistics of STEM Literacy

Data	School I		School II		School III	
	Pre test	Post test	Pre test	Post test	Pre test	Post test
Mean	0.86	1.93	1.17	1.88	1.46	1.61
Shapiro-Wilk Normality Test	0.11	0.51	0.13	0.06	0.63	0.42
Levene's Test	0.51		0.70		0.90	
Paired t-test	0.00		0.00		0.00	
Effect Size	1.71		1.56		0.42	

Table 3 shows the increase in students' STEM literacy scores across schools following STEM-based learning by teachers who participated in STEM professional development. This increase reflects the successful strengthening of students' ability to understand and apply science, technology, engineering, and mathematics concepts in meaningful contexts. Differences in the level of improvement across schools also indicate

variations in implementation effectiveness, which is likely influenced by internal factors such as teacher preparedness, school support, and student characteristics. These findings generally confirm that the STEM learning approach has significant potential to improve student literacy when supported by appropriately and contextually implemented instruction.

Table 4. Statistical Analysis of Teacher Perception Scores

Teacher Perception	Mean	SD	Shapiro-Wilk test	Levene's test	Paired t-test	Effect Size
Pre-test	2.76	0.48	0.35	0.26	0.000	1.89
Post-test	3.48	0.38	0.09			

Table 4 shows that teachers' perceptions increased in mean scores from 2.76 in the pre-test to 3.48 in the post-test. The t-test results indicated a significant difference in teachers' perception scores before and after receiving the training program. This finding aligns with previous research suggesting that a coaching model focused on STEM content and hands-on experience can enhance teachers' understanding and confidence in STEM education. Collaborative, ongoing support makes teachers feel better prepared to teach STEM disciplines effectively (Jones et al., 2017; Kelley et al., 2020).

These findings align with previous research showing that well-designed STEM professional development programs for teachers can enhance teachers' skills, ultimately leading to improved student STEM literacy (Dare et al., 2021; Asrizal et al., 2023; Şahin et al., 2024). By providing teachers with opportunities to deepen their understanding of content, improve their pedagogical practices, and collaborate with peers, these programs equip them to create engaging, student-centered learning environments.

This study also explored teachers' conceptions of STEM education. The coding results revealed that teachers' understanding of STEM education's characteristics was categorized into 10 distinct areas. These categories represent various perceptions of the STEM approach held by teachers participating in STEM-based professional development programs. The themes that emerged from teachers' responses about the STEM approach are as follows: (a) Learning Experience, (b) Learning Process, (c) Real Problems, (d) Focus on Cognitive, (e) Focus on Thinking Skills, (f) Integration, (g) Technology as Context, (h) Resources, (i) Mathematics as Context, and (j) Others.

The professional development program also provided a new understanding that mathematics can be used as a context for STEM learning. These findings indicate that teachers' perceptions of the STEM approach have evolved to be more comprehensive, understanding STEM beyond science and engineering, and embracing mathematics as a crucial contextual and applied element in learning. Mathematics is a crucial context for STEM learning, providing a language and thinking tool that strengthens students' problem-solving and analytical skills.

Additionally, to strengthen the research findings, semi-structured interviews were conducted with 10 teachers. Qualitative data from the interviews aimed to provide information on factors that may facilitate or hinder the success of the professional development program, as well as teachers' perspectives on the challenges and opportunities associated with implementing STEM learning in the classroom.

Qualitative findings revealed that teachers had varying perceptions of the STEM-based professional development program, based on their prior experiences, knowledge, and skills. Several teachers stated that the program was very beneficial, as it helped them deepen their content knowledge, enhance their pedagogical knowledge, and increase their confidence in teaching STEM. The following are excerpts from interviews with teachers:

"This STEM training program is very important. I feel I have a better understanding of the key concepts and principles in STEM fields. I feel more confident teaching STEM subjects in the classroom."

"This program gave me practical, hands-on experience that I can apply in the classroom. The STEM Practical activities during the training gave me experience in integrating STEM concepts into classroom learning."

Several teachers also expressed challenges with the program, including a lack of time for lesson planning and reflection, as well as limited supporting resources for implementing STEM learning in the classroom. Teachers struggled to consistently implement new strategies in their classrooms due to a lack of ongoing support and coaching, as seen in the following example:

"Although the initial sessions were quite informative, I found it difficult to consistently implement the STEM approach without guidance and supporting resources during implementation."

Qualitative data also revealed that teachers' perceptions of the program's effectiveness were influenced by factors such as administrative support, access to necessary materials and technology, and the school's culture and STEM education infrastructure. One teacher stated:

"The lack of funding and resources in our school makes it difficult for us to fully implement

the STEM activities and lessons we learn in the professional development program.”

The research findings indicate several challenges associated with STEM-based teacher professional development programs. Overall, qualitative findings indicate that STEM professional development programs are largely successful in improving teachers' perceptions and self-efficacy in STEM teaching. The findings of this study have important implications for improving the quality of STEM education across academic research and professional practice. The results reveal that professionally designed, systematically structured, and contextually designed professional development programs have a positive impact on teachers' perceptions and students' STEM literacy (Affouneh et al., 2020; Rusydiyah et al., 2021; Surahman, 2024). This alignment reinforces previous findings regarding the elements that support effective teacher professional development. Some key components found include content-based teaching (Arifin et al., 2020; Hubers et al., 2022), strengthening pedagogical materials regarding the STEM approach (Rusydiyah et al., 2021; Nurwidodo et al., 2022; Efwinda et al., 2024), collaborative learning (Keshmiri et al., 2023; Parsons et al., 2020), and ongoing professional support (Murphy et al., 2020; Puspitasari et al., 2021).

Training that involves teachers in the development process, both as decision-makers and implementers, tends to be more successful. This creates a sense of ownership and facilitates more contextualized learning (Hurley et al., 2024). The contribution of such programs demonstrates the importance of designing teacher training that integrates content and pedagogical aspects (Kazempour, 2019). This emphasizes that professional development is not uniform but must be tailored to each teacher's context and needs. Therefore, active teacher engagement in practice-based and reflective programs is key to the success of STEM teaching transformation (Han et al., 2021).

Furthermore, this study confirms that teachers' perceptions, attitudes, and self-efficacy play a crucial role in determining the quality of STEM learning practices in the classroom (Affouneh et al., 2020). Teachers with high self-efficacy will be more confident in implementing inquiry-based and problem-solving learning approaches, which are key characteristics of STEM education (Margot & Kettler, 2019; Christian et al., 2021). This efficacy does not emerge instantly but is developed through training, experience, and ongoing support from a professional environment. Therefore, STEM professional develop-

ment programs must be designed as comprehensive, long-term processes that are responsive to classroom dynamics (Suebsing & Nuangchalerm, 2021b; Dökme et al., 2022). Teachers' needs extend beyond content understanding to include enhancing pedagogical skills, reflecting on their practice, and strengthening their internal motivation. These aspects can only develop if training programs are transformative and participatory, rather than merely instructional (Dong et al., 2020; Suebsing & Nuangchalerm, 2021; Hurley et al., 2024).

In this context, self-efficacy is a key indicator of the success of professional development interventions. When teachers feel capable and prepared, the impact is directly reflected in the quality of learning and student engagement in STEM activities (Keiler, 2018). Sustainable STEM professional development programs have been shown to improve teachers' competency and readiness to address the complexities of STEM teaching in the classroom (Akgunduz & Mesutoglu, 2021; Martínez-Borreguero et al., 2022; Şahin et al., 2024). These positive impacts demonstrate that such programs are not merely short-term or theory-based, but instead require a continuous cycle of improvement relevant to the local context. Strengthening teacher professionalism is also inseparable from the role of educational institutions and local government policies responsible for providing systemic support. In its implementation, challenges often arise from limited access to resources, socioeconomic disparities among students, and differences in learning cultures (Regu, 2019). Therefore, a collaborative approach among schools, policymakers, and communities is crucial to effectively address these barriers (Lim et al., 2020; Abror et al., 2024).

Successful interventions must identify gaps while offering solutions grounded in data and reflective practice (O'Brien et al., 2022). Teachers need to be encouraged to become agents of change, actively adapting their teaching strategies to students' needs and potential in their respective classrooms. This will create a more inclusive learning climate and be relevant to developments in science and technology (Jamilah, 2020; O'Leary et al., 2020). One strategic implication of these findings is the need for schools and policymakers to invest in long-term STEM professional development programs. These programs should integrate in-depth STEM content training with pedagogical strategies based on real-life classroom practices.

Furthermore, training needs to be designed to foster teachers' confidence and efficacy

in actively, creatively, and contextually teaching STEM. In addition to enhancing individual teacher skills, programs must also create a learning ecosystem that supports collaboration, reflection, and innovation. This approach strengthens teachers' resilience in facing the challenges of 21st-century learning, including curriculum changes and the development of digital technology. The success of such programs is reflected in the improved quality of teacher-student interactions in STEM learning, as well as in student interest and achievement in science and technology. With the right support, teachers can play a central role in shaping a generation that is critical, creative, and adaptable to rapid global change. Therefore, the sustainability and effectiveness of STEM professional development programs need to be prioritized on national and regional education policy agendas.

CONCLUSION

This study shows that a thoughtfully designed STEM-based professional development program can make a meaningful difference for both teachers and students. Teachers who participated in the program developed more positive views of STEM learning, felt more confident in their abilities, and were better prepared to apply STEM approaches in the classroom. These changes were closely connected to improvements in students' STEM literacy. By bringing together numerical data and teachers' lived experiences, the study highlights the value of professional learning that emphasizes active engagement, collaboration, and learning that is closely connected to real classroom contexts. At the same time, this study has some limitations that should be acknowledged. The research involved a small number of schools, so the findings may not fully reflect educational settings beyond them. The program was also implemented over a relatively short period, making it difficult to observe long-term changes in teaching practice or student learning. Future studies could build on this work by involving a broader range of school contexts and following teachers and students over longer periods to better understand how STEM-based professional development can be sustained and expanded.

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