

Research paper**Exploring Pre-Service Teachers' STEM Readiness in Indonesia, Malaysia, and Thailand: Comparative Insights from Teacher Education Programs**

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Citation: Mahmudi, A., Tyas, R. A., Ariyanti, N. A., Borhan, M. T., Ismail, M. H., & Faikhamta, C. (2026). Exploring pre-service teachers' STEM readiness in Indonesia, Malaysia, and Thailand: Comparative insights from teacher education programs. *European Journal of STEM Education*. <https://doi.org/10.20897/ejsteme/19496>

Published: October 6, 2026

ABSTRACT

STEM education has become a central agenda for enhancing human resource quality and global competitiveness. This study explored pre-service teachers' readiness to implement STEM teaching in Indonesia, Malaysia, and Thailand, with particular attention to their conceptual understanding, implementation ability and experience, perceived barriers and institutional support, and attitudes toward STEM education. Using a qualitative descriptive multiple-case study design, the study involved 74 pre-service teachers from four universities, supported by data from 41 lecturers/supervisors. Data were collected through questionnaires, semi-structured interviews, microteaching observations, and document analysis. The findings indicate that pre-service teachers across the countries generally demonstrated positive attitudes and conceptual readiness, with questionnaire mean scores ranging from 3.43 to 4.17, while practical opportunities to implement integrated STEM teaching varied across national contexts. Malaysia demonstrated more structured opportunities for project development, engineering design, microteaching, and technology-supported STEM practice, while Thailand showed distinctive experiential opportunities involving coding, robotics, and sustainability-oriented STEM activities. Indonesia showed an emerging but more fragmented pattern of STEM implementation, indicating ongoing efforts to strengthen curriculum alignment, practical teaching experiences, mentoring, and institutional support. Interview and observation findings further indicate that collaborative curriculum design, interdisciplinary collaboration, mentoring, technological resources, and sustained professional development influence pre-service teachers' readiness to implement STEM teaching. The study concludes that STEM teaching readiness is a context-dependent and developmental process shaped not only by individual competence but also by the alignment of policy, curriculum, pedagogy, technology, and institutional support. Strengthening these conditions can support more coherent and sustainable STEM teacher education across Southeast Asia.

Keywords: STEM education, teacher readiness, pre-service teachers, comparative study, educational policy

STEM education (Science, Technology, Engineering, and Mathematics) has become a major focus in improving human resource quality and global competitiveness (Dare et al., 2021; Ichsan et al., 2023; Zheng, 2021). The

integration of STEM into national curricula is expected to produce graduates who are competent in addressing the challenges of the digital era and the Fourth Industrial Revolution (Ichsan et al., 2023; Isasi-Sánchez et al., 2023). Several countries, including Indonesia, Malaysia, and Thailand, have developed policies and programs to strengthen STEM learning. However, the readiness of pre-service teachers to implement this approach remains a crucial issue that requires deeper investigation (Berisha & Vula, 2021; Nugraha et al., 2023).

Indonesia continues to face significant challenges in STEM implementation. Data from the Higher Education Database show that there are only 1,595 researchers per one million people in Indonesia, including doctoral students, compared to Malaysia's 2,024 researchers per million. According to World Bank Data 2020, the number of STEM graduates in Indonesia reached 18.47 million, lagging Vietnam (23.38 million), Thailand (27.31 million), Malaysia (37.19 million), and Singapore (34.3 million). Another challenge is the limited laboratory infrastructure and insufficient training for pre-service teachers to adapt STEM-oriented learning approaches (Aslam et al., 2023; Reyes et al., 2024).

Malaysia, on the other hand, has positioned STEM education as a national priority, as reflected in the *Malaysia Education Blueprint 2013–2025* (Liew & Teoh, 2023). This policy encompasses a comprehensive STEM-based curriculum adaptation, specific budget allocation for laboratory enhancement, procurement of modern technological tools, and intensive teacher training (Ali et al., 2021). Support from industrial sectors also plays a key role in Malaysia's success in STEM implementation (Karpudewan et al., 2023; Marzuki et al., 2026). With systematic policies and a strong educational ecosystem, Malaysia demonstrates structured opportunities in developing its teacher readiness for STEM compared to Indonesia.

Thailand has also shown strong commitment to advancing STEM education through various initiatives and programs (Faikhamta & Lertdechapat, 2021). One of the notable efforts is the *Strengthening Teacher Education Programme (STEP Project)* launched in 2023 in collaboration with SEAMEO STEM-ED and supported by Chevron. The program aims to enhance the competencies of STEM educators and teachers in Indonesia, Kazakhstan, Malaysia, and Thailand. With a more structured and research-based training approach, Thailand is moving toward a more robust development of STEM teacher capacity (Chaisri Khureerung & Thao-Do, 2022).

As summarized in [Table 1](#), the three countries have developed distinct policy and institutional approaches to STEM education, with differences in curriculum structures, teacher development initiatives, technological resources, and opportunities for practical STEM implementation. These contextual differences provide an important basis for examining whether and how pre-service teachers' readiness to implement STEM teaching varies across the three national settings.

Table 1

Overview of STEM education initiatives and teacher preparation contexts in Indonesia, Malaysia, and Thailand

Country	Indonesia	Malaysia	Thailand
STEM policy/program context	National efforts to strengthen STEM education; growing policy attention	STEM prioritized through Malaysia Education Blueprint 2013–2025	National STEM initiatives and STEP Project
Curriculum & institutional support	Uneven infrastructure and limited access to STEM-oriented resources	Curriculum adaptation, laboratory enhancement, technological resources, teacher training, and industry involvement	Structured teacher development and collaboration with STEM organizations
Teacher preparation / implementation context	Need for stronger STEM-oriented training and practical experience	More structured opportunities for STEM-related teacher preparation	Emphasis on strengthening STEM educator competencies and research-based training
Key issue relevant to readiness	Developing implementation capacity and institutional support	Alignment between policy, curriculum, and implementation	Sustaining and expanding STEM teacher capacity

Pre-service teachers' readiness to implement STEM learning is a key determinant in the successful integration of STEM within educational systems (Chai et al., 2020). This readiness encompasses deep conceptual understanding of STEM, the ability to design and apply effective instructional strategies, and proficiency in utilizing relevant technologies and tools (Karpudewan et al., 2023). However, the level of readiness may vary among countries depending on their educational systems, government policies, and available training programs for pre-service teachers. Therefore, a comparative study of STEM teaching readiness among pre-service teachers in

Indonesia, Malaysia, and Thailand is essential to identify each country's readiness and to provide recommendations for improving STEM education quality in the region.

This study aims to (1) analyze the extent of pre-service teachers' readiness in Indonesia, Malaysia, and Thailand to implement STEM teaching in terms of pedagogical, conceptual, and technological areas; (2) identify key factors that hinder or support pre-service teachers' readiness across these three countries, including curriculum differences, education policies, and teaching practice experiences; and (3) compare pre-service teachers' readiness in planning, implementation, and evaluation of STEM learning across Indonesia, Malaysia, and Thailand, with particular attention to similarities and differences that may provide insights for strengthening STEM teacher education in Southeast Asia. The findings of this study are expected to contribute to the development of evidence-based recommendations for STEM education policy in Southeast Asia, supporting the cultivation of a more competent teaching workforce capable of meeting global challenges. Accordingly, this study addresses the following research questions:

1. What are the characteristics of pre-service teachers' readiness to implement STEM teaching in Indonesia, Malaysia, and Thailand?
2. What institutional, curricular, pedagogical, and contextual factors shape pre-service teachers' readiness to implement STEM teaching in Indonesia, Malaysia, and Thailand?
3. What similarities and differences characterize STEM teaching readiness and its supporting conditions across Indonesia, Malaysia, and Thailand?

THEORETICAL FRAMEWORK

Concept of STEM teaching implementation

The readiness of pre-service teachers to implement STEM teaching is conceptualized in this study as a multidimensional capacity to understand the relationships among STEM disciplines, design and enact pedagogically appropriate integrated learning experiences, and use relevant technological resources to support authentic problem solving. This conceptualization is grounded primarily in the literature on integrated STEM education, which emphasizes that STEM should not be understood merely as the parallel teaching of science, technology, engineering, and mathematics, but as the intentional connection of disciplinary content and practices through meaningful and authentic contexts (Kelley & Knowles, 2016; Roehrig et al., 2021). Accordingly, STEM readiness in this study is not equated with technology proficiency alone or with knowledge of individual STEM subjects. Rather, it refers to the capacity to connect disciplinary knowledge, STEM practices, and pedagogical strategies in the design and implementation of integrated learning experiences.

Three interrelated dimensions were used to operationalize STEM readiness: (1) conceptual understanding, (2) pedagogical and implementation competence, and (3) technological competence. These dimensions were selected because they represent complementary requirements for translating the principles of integrated STEM education into classroom practice. Conceptual understanding concerns pre-service teachers' understanding of the nature of STEM and the relationships among science, technology, engineering, and mathematics. In particular, it includes recognition of how scientific inquiry, engineering design, technological applications, and mathematical reasoning can be connected when addressing authentic problems. Thus, engineering and mathematics are not treated as absent or secondary components of STEM readiness; rather, their practices are embedded within the interdisciplinary understanding that underpins integrated STEM learning. Previous conceptual frameworks similarly emphasize the interconnected roles of scientific inquiry, technological literacy, engineering design, and mathematical thinking in integrated STEM education (Kelley & Knowles, 2016).

Pedagogical and implementation competence refers to pre-service teachers' ability to translate this interdisciplinary understanding into meaningful instructional practice. STEM-ready teachers are expected to design learning experiences around authentic problems, facilitate inquiry and problem solving, engage learners in engineering design or related design processes, and connect relevant science and mathematics concepts within the learning task. Project-based learning, problem-based learning, and inquiry-oriented approaches can provide appropriate pedagogical contexts for such integration (Dare et al., 2021; Koyunlu Ünlü & Dökme, 2022; Purwaningsih et al., 2020). Therefore, readiness is reflected not only in knowing what STEM integration means, but also in being able to plan, facilitate, and evaluate learning experiences in which STEM disciplines are meaningfully connected.

Technological competence represents a complementary dimension of STEM readiness rather than a defining feature of STEM itself. Technology is included because integrated STEM learning frequently requires teachers to select and use technological tools that support investigation, modeling, data collection and analysis, design, communication, or the development and testing of solutions. From this perspective, technological competence concerns teachers' ability to make pedagogically meaningful decisions about technology use rather than simply their ability to operate digital tools. This interpretation is consistent with the TPACK perspective, which

emphasizes the integration of technological knowledge with pedagogical and content knowledge (Koehler & Mishra, 2009), and with integrated STEM frameworks that identify technological literacy as interconnected with scientific inquiry, engineering design, and mathematical thinking (Kelley & Knowles, 2016).

The selection of these dimensions is also informed by empirical research on STEM teaching readiness and practice. For example, (Karpudewan et al., 2023) demonstrated that teachers' knowledge of interdisciplinary and related pedagogical strategies, perceived difficulties, and self-efficacy were associated with integrated STEM teaching practices. However, their study examined factors related to STEM teaching practices rather than providing a comprehensive definition of STEM readiness. Therefore, the present study does not use (Karpudewan et al., 2023) as the sole conceptual basis for defining readiness; instead, the study draws on integrated STEM frameworks to establish the conceptual structure and uses (Karpudewan et al., 2023) as supporting empirical evidence concerning teacher-related factors associated with STEM implementation.

Importantly, the three dimensions should be understood as interdependent rather than isolated competencies. Conceptual understanding provides the disciplinary and interdisciplinary foundation, pedagogical competence enables its translation into instructional design and classroom practice, and technological competence supports the use of appropriate tools and resources when they are pedagogically relevant. Within this framework, engineering design and mathematical reasoning are explicitly incorporated into the conceptual and pedagogical dimensions rather than treated as separate readiness dimensions. This approach recognizes that integrated STEM education can vary in the extent and manner in which the four STEM disciplines are connected, and that not every STEM learning experience necessarily gives equal emphasis to all four domains (Kelley & Knowles, 2016; Roehrig et al., 2021).

Factors influencing STEM teaching implementation

The implementation of integrated STEM teaching is influenced by a combination of constraining and enabling conditions operating across teacher preparation, curriculum, institutional, technological, and policy contexts. Constraining factors may limit pre-service teachers' opportunities to develop and enact STEM teaching practices, whereas enabling factors provide the resources, structures, guidance, and collaborative conditions that facilitate implementation.

Constraining factors

Several conditions may constrain the development and implementation of STEM teaching among pre-service teachers. One important factor is the adequacy of STEM-related training and teaching experience. Pre-service teachers may have limited exposure to STEM pedagogy during their coursework or practicum, which can reduce opportunities to develop confidence and practical competence in integrating STEM approaches into classroom instruction (Margot & Kettler, 2019). Limited access to resources and infrastructure can further restrict implementation, particularly where laboratories, experimental tools, and STEM-related instructional materials are not readily available (Saldívar-Almorejo et al., 2024).

Curriculum structure can also constrain integrated STEM implementation when disciplinary content is organized rigidly within separate subject areas. In Indonesia, for example, STEM-oriented approaches have been described as relatively fragmented within subject-specific curricula, which may provide pre-service teachers with more theoretical exposure than practical experience in implementing interdisciplinary and project-based STEM teaching (Chai et al., 2020). Curriculum rigidity is therefore considered a constraining condition rather than a supporting factor because it may limit opportunities to connect disciplinary knowledge, engage in interdisciplinary learning, and develop authentic STEM teaching practices. These challenges highlight the importance of more flexible and practice-oriented teacher education curricula that provide opportunities to connect STEM concepts with pedagogical design and classroom practice.

Enabling factors

In contrast, several systemic and institutional conditions can facilitate the effective implementation of STEM teaching. Strong policy support and structured teacher development programs can provide a foundation for developing pre-service teachers' readiness and opportunities to engage in STEM teaching practices. Evidence from Malaysia and Thailand indicates that structured teacher development initiatives can support STEM capacity development through pedagogical training, access to STEM facilities, and mentoring opportunities (Ali et al., 2021; Faikhanta & Lertdechapat, 2021).

Access to appropriate educational technologies can also facilitate STEM teaching by enabling pre-service teachers to visualize complex concepts and develop instructional activities involving investigation, simulation, modeling, data analysis, and problem solving. Technologies such as virtual simulations, digital laboratories, and online learning platforms can therefore support the development of instructional practices aligned with

contemporary STEM education goals (Koehler & Mishra, 2009). However, the contribution of technology depends on its pedagogical use rather than on access to digital tools alone.

Collaboration across universities, schools, and industry can provide additional opportunities for connecting theoretical preparation with authentic STEM practices. In Malaysia, for example, collaboration with industrial sectors has supported practical training and helped connect teacher education coursework with real-world applications (Liew & Teoh, 2023). Such collaboration can strengthen opportunities for pre-service teachers to experience interdisciplinary problem solving and develop a more contextualized understanding of STEM teaching.

Taken together, these factors suggest that STEM teaching readiness should not be understood solely as an individual characteristic of pre-service teachers. Rather, readiness develops through the interaction between individual preparation and the conditions in which pre-service teachers learn, practice, and receive support. Effective STEM teacher preparation therefore requires both opportunities to develop pedagogical and interdisciplinary competence and enabling conditions such as coherent policies, appropriate resources, mentoring, technological support, and collaboration across educational and professional contexts.

Planning, implementation, and evaluation of STEM teaching

The implementation of STEM learning in classrooms typically involves three essential stages: planning, implementation, and evaluation. Each stage contributes significantly to the effectiveness of STEM education, particularly in preparing students for the challenges of the Industrial Revolution 4.0 and technology-driven societies (Bybee, 2013).

1. Planning stages involves developing lesson plans, selecting appropriate instructional models, and holistically integrating STEM elements into the learning design. Effective STEM lesson design should be inquiry-based, exploratory, and oriented toward authentic problem-solving relevant to students' daily lives (Ichsan et al., 2023; Jamali et al., 2020). The success indicators of this stage include pre-service teachers' ability to design balanced and integrative STEM lessons, the availability of innovative learning media, and the use of relevant formative assessment tools (Chai et al., 2020).
2. The implementation stage refers to the enactment of lesson plans in the classroom, emphasizing active student engagement through exploration, experimentation, and problem-solving (Rusydiah et al., 2021; Trevallion & Trevallion, 2020). Indicators of success at this stage include the extent of student participation, the effective application of project-based learning, and the meaningful use of digital tools to support conceptual understanding.
3. Evaluation is a key process in assessing the overall effectiveness of STEM learning in achieving cognitive, psychomotor, and affective objectives (Bybee, 2013). Continuous formative assessment and reflective practice are essential to monitor students' progress and improve instructional quality. When summative assessments demonstrate that students can apply STEM concepts and 21st-century skills in their projects, and when teachers engage in reflective teaching practices, the evaluation stage can be considered successful.

METHOD

Research design

This study employed a qualitative descriptive research design using a multiple case study approach. A descriptive design allows for the presentation and interpretation of data to describe a particular phenomenon in depth (Nassaji, 2020) while a qualitative approach is appropriate for exploring complex, context-dependent, and dynamic issues that cannot be captured through quantitative methods. The case study approach was chosen because it enables a holistic and in-depth investigation of a bounded system—such as an educational program, event, or group—within its real-life context (Mills et al., 2007). This design was considered appropriate for this research because it aimed to explore the readiness of pre-service teachers in implementing STEM teaching across three national contexts, Indonesia, Malaysia, and Thailand, by describing and comparing institutional and pedagogical practices.

The focus of this study was on pre-service teachers' readiness to implement integrated STEM teaching. Based on the conceptual framework described above, STEM readiness was examined through three interrelated dimensions: (1) conceptual understanding of STEM integration, including understanding of the relationships among science, technology, engineering, and mathematics; (2) pedagogical and implementation competence, including the ability to design, facilitate, and evaluate authentic, inquiry-oriented, project-based, and engineering-design-related STEM teaching experiences; and (3) technological competence, referring to the ability to select and use relevant technologies to support STEM teaching processes such as investigation, modeling, data analysis, design, and communication. Teaching experience, institutional support, and perceived barriers were examined as contextual factors that could shape the development and enactment of these readiness dimensions rather than as independent components of the conceptual definition of STEM readiness.

Research sites and participants

The study was conducted at four universities representing three Southeast Asian national contexts: Indonesia, Malaysia, and Thailand, described in [Table 2](#). The Indonesian case involved Universitas Negeri Yogyakarta (UNY), while the Malaysian cases involved Universiti Teknologi MARA (UiTM) and Universiti Pendidikan Sultan Idris (UPSI). The Thai case involved Kasetsart University. These institutions were purposively selected because their teacher education programs provide contexts in which STEM-related learning, curriculum development, and teaching practices could be examined. The study was conducted between April and October 2025.

In addition to the pre-service teachers and lecturers involved in the participating teacher education programs, the study examined relevant national policy frameworks and teacher education curriculum documents at the tertiary education level in Indonesia, Malaysia, and Thailand. These documents were selected to provide contextual information on how STEM education is positioned and integrated within the preparation of pre-service teachers.

Table 2

Research sites and participant characteristics

No	Country	University	Participant Group	n	Relevant Background
1	Indonesia	Universitas Negeri Yogyakarta	Pre-service teachers	42	Departments of Mathematics Education, Science Education, Physics Education, Chemistry Education, and Biology Education (4-6 Semester).
			Lecturers/academic supervisors	16	Departments of Mathematics Education, Science Education, Physics Education, Chemistry Education, and Biology Education (4-6 Years Experience)
2	Malaysia	Universiti Teknologi MARA (UiTM)	Pre-service teachers	12	Bachelor of Science Education programs in Biology, Physics, Chemistry, and Mathematics (4-6 Semester).
			Lecturers/academic supervisors	15	Bachelor of Science Education programs in Biology, Physics, Chemistry, and Mathematics (6-8 Years Experience).
		Universiti Pendidikan Sultan Idris (UPSI)	Pre-service teachers	12	Bachelor of Education in Chemistry, Mathematics Education, and Science Education (4-6 Semester).
			Lecturers/academic supervisors	8	Bachelor of Science Education programs in Biology, Physics, Chemistry, and Mathematics (6-8 Years Experience).
3	Thailand	Kasetsart University	Pre-service teachers	8	Mathematics Education and Science Education programs (4-6 Semester).
			Lecturers/academic supervisors	2	Mathematics Education and Science Education programs (4-6 Years Experience).

The primary participants were pre-service teachers enrolled in STEM-related teacher education programs at the participating universities. A total of 74 pre-service teachers participated in the study, comprising 42 from Indonesia, 24 from Malaysia, and 8 from Thailand. In addition, 41 lecturers or academic supervisors participated as key informants to provide institutional and professional perspectives on pre-service teachers' preparedness to implement STEM teaching.

Participants were selected using purposive sampling. Pre-service teachers were included because they were currently enrolled in teacher education programs and had received STEM-related coursework or participated in teaching practice. Lecturers or academic supervisors were selected based on their involvement in teaching, supervising, mentoring, or developing STEM-related learning within the respective teacher education programs. The study therefore drew on three complementary sources of evidence: (1) pre-service teachers as the primary participants, (2) lecturers or academic supervisors as key informants, and (3) policy and curriculum documents related to STEM teacher education in the three countries.

A total of 115 participants were involved in the study, comprising 74 pre-service teachers and 41 lecturers/supervisors across the four participating universities. The pre-service teachers constituted the primary participant group because the study focused on their readiness to implement STEM teaching. The

lecturers/supervisors were included as complementary informants because of their roles in teaching, supervising, mentoring, and observing pre-service teachers during their teacher preparation. Their perspectives provided additional evidence concerning pre-service teachers' readiness, teaching practices, implementation challenges, mentoring experiences, and institutional support. Thus, lecturers' and supervisors' accounts were not treated as a separate measure of STEM readiness but were used to contextualize and triangulate the evidence obtained from pre-service teachers, together with the observations and policy/curriculum documents.

Data collection methods

Data were collected using four complementary techniques: questionnaires, in-depth interviews, document analysis, and classroom or microteaching observations.

1. **Questionnaire.** A structured Likert-scale questionnaire was administered to pre-service teachers to assess their readiness to implement STEM teaching. The questionnaire covered four dimensions of STEM readiness and used a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The questionnaire was administered to 74 pre-service teachers across the four participating universities. The responses provided descriptive evidence of patterns of perceived STEM readiness across the three national contexts.
2. **In-depth Interviews.** Semi-structured interviews were conducted with both pre-service teachers and lecturers or academic supervisors. Interviews with pre-service teachers explored their understanding of STEM, experiences in planning and implementing STEM teaching, perceived challenges, access to institutional support, and opportunities for professional learning. Interviews with lecturers or academic supervisors focused on their perceptions of pre-service teachers' readiness, mentoring practices, institutional support, curriculum implementation, and challenges in facilitating STEM teaching. The interviews were used to elaborate the questionnaire findings and to identify contextual explanations for similarities and differences in STEM readiness across the three countries. In total, 12 pre-service teachers and 41 lecturers/academic supervisors participated in the interviews.
3. **Document Analysis.** Relevant teacher education curricula, course-related documents, and national or institutional policy documents were analyzed to examine how STEM education was positioned and integrated within teacher education programs in Indonesia, Malaysia, and Thailand. The documents were used to contextualize the participant data and identify institutional, and policy conditions associated with STEM teacher preparation.
4. **Classroom or Microteaching Observations.** Microteaching observations were conducted to obtain complementary descriptive evidence of pre-service teachers' actual teaching practices. The observations involved 10 pre-service teachers participating in a microteaching setting and were conducted by three observers using a structured observation guide/checklist. The observation instrument was adapted to the context of STEM teaching and focused on six main areas: (1) lesson introduction and learning orientation, including the communication of learning benefits, objectives, and activation of students' prior knowledge; (2) STEM content and contextualization, including systematic explanation and connections to real-life contexts and current issues; (3) instructional strategies and learning resources, including the use of active learning approaches, media, and learning resources; (4) questioning, critical thinking, and problem solving, including the use of progressive and higher-order questions and opportunities for students to think and respond; (5) student engagement and facilitation, including participation, guidance, collaboration, and motivation; and (6) assessment, feedback, and reflection, including monitoring learning progress, assessment, feedback, and reflective activities. Observation data were analyzed descriptively to identify patterns in the observed teaching practices and were used as complementary evidence for triangulating questionnaire and interview findings.

The four methods were integrated through methodological triangulation. Questionnaire data provided an overview of perceived readiness, interviews captured participants' and lecturers' experiences and interpretations, document analysis provided institutional and policy context, and observations provided evidence of STEM-related pedagogical enactment. This combination enabled the study to examine STEM readiness across the participating institutions and national contexts from multiple sources of evidence.

Research instruments and validation

This study employed three main instruments to collect data: a STEM Readiness Questionnaire for pre-service teachers, an Interview Guide for Pre-Service Teachers, and an Interview Guide for Lecturers or Supervisors. Each instrument was designed to capture different dimensions of STEM readiness and contextual understanding across Indonesia, Malaysia, and Thailand.

Table 3
Instrument matrix for data collection

Instrument	Aspects	Indicators / Sample Items	Purpose / Data Obtained
STEM Readiness Questionnaire (Pre-Service Teachers)	Conceptual Understanding of STEM	Understanding of STEM teaching strategies and active learning approaches	To measure teachers' pedagogical readiness for STEM instruction
	Implementation Ability and Experience	Integration of science, technology, engineering, and mathematics concepts	To assess conceptual mastery and interdisciplinary understanding
	Barriers and Institutional Support	Ability to use digital tools and media in teaching	To evaluate technological competence supporting STEM teaching
	Attitudes toward STEM Educations	Prior experience designing or delivering STEM lessons	To gauge practical readiness and exposure to STEM-based practice
Interview Guide for Pre-Service Teachers	Understanding of STEM	Knowledge and perceptions of STEM learning	To explore in-depth understanding and conceptual readiness
	Experience in Teaching Practice	Experience during microteaching or coursework	To identify pedagogical implementation experiences
	Challenges and Barriers	Perceived constraints in resources, time, or knowledge	To uncover key obstacles affecting STEM readiness
	Support and Policy	Institutional support and curriculum relevance	To understand structural factors influencing readiness
Interview Guide for Lecturers/Supervisors	Perception of Student Readiness	Evaluation of students' knowledge and teaching competence	To gain expert evaluation of pre-service teacher readiness
	Mentoring Strategies	Guidance and support methods applied by lecturers	To examine effective mentoring practices for STEM learning
	Institutional Support	Faculty or university-level support and training opportunities	To analyze policy and structural support for STEM integration
	Challenges	Constraints faced in supervising STEM practice	To identify systemic and practical limitations in teacher preparation
Microteaching Observation Guide/Checklist	Lesson Introduction and Learning Orientation	Communicating learning benefits and objectives, activating prior knowledge, and presenting the lesson structure clearly	To obtain descriptive evidence of observable teaching practices
	STEM Content and Contextualization	Systematic explanation of content, use of real-life examples, current issues, and contextual STEM applications	To examine how STEM concepts are contextualized during teaching
	Instructional Strategies and Learning Resources	Use of active learning strategies, media, tools, and learning resources; opportunities for students to engage with resources	To examine the enactment of active and STEM-oriented instructional practices
	Questioning, Critical Thinking, and Problem Solving	Use of progressive questioning, wait time, critical thinking, problem solving, creativity, and literacy-oriented questions	To examine practices that promote higher-order thinking and STEM-related competencies
	Student Engagement and Facilitation	Student participation, individual/group/class guidance, collaboration, motivation, and respectful interaction	To examine the quality of facilitation and student engagement
	Assessment, Feedback, and Reflection	Monitoring learning progress, assessment, follow-up, feedback, summarizing, reflection, and self-evaluation	To examine formative assessment and reflective teaching practices

The STEM Readiness Questionnaire was developed based on the conceptualization of STEM teaching readiness presented in the theoretical framework. The development process began by translating the identified dimensions of readiness into measurable aspects and indicators relevant to pre-service teachers' STEM teaching contexts. The questionnaire was organized into four dimensions: (1) Conceptual Understanding of STEM, (2) Implementation Ability and Experience, (3) Barriers and Institutional Support, and (4) Attitudes toward STEM Education. Items were formulated to capture pre-service teachers' perceptions and experiences related to these dimensions and were presented using a five-point Likert response scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The draft questionnaire was reviewed by three experts in STEM education and educational research methodology to examine the alignment among constructs, dimensions, indicators, and items, as well as the clarity and relevance of the statements. The questionnaire was subsequently pilot tested with a small group of pre-service teachers in Indonesia to identify unclear or potentially ambiguous wording. Revisions were made based on the expert review and pilot feedback before the questionnaire was administered to the study participants. Because the questionnaire was intended primarily to provide descriptive evidence within the comparative case study, no psychometric internal-consistency analysis, such as Cronbach's alpha, was conducted.

The questionnaire was subjected to expert review prior to data collection. Three experts with expertise in STEM education and educational research methodology reviewed the alignment between the intended constructs, dimensions, indicators, and questionnaire items, as well as the clarity and relevance of the statements. The review was used to refine the wording and ensure that the items adequately represented the dimensions of STEM readiness examined in this study. The instruments were subsequently pilot tested with a small group of pre-service teachers in Indonesia to identify unclear or potentially ambiguous wording and to improve the comprehensibility of the statements.

The questionnaire was primarily used to provide descriptive evidence of pre-service teachers perceived STEM readiness and to complement the qualitative findings. Because the questionnaire was developed and used within the scope of this comparative case study, no psychometric validation of internal consistency, such as Cronbach's alpha, was conducted for the constituent dimensions. Accordingly, the questionnaire results are interpreted as descriptive evidence rather than as evidence of a fully psychometrically validated measurement scale. The complete questionnaire is provided in the Appendix to allow readers to examine the constructs, dimensions, indicators, and item wording.

The Interview Guide for Pre-Service Teachers was constructed to explore qualitative areas of readiness, focusing on five areas: (1) understanding of STEM, (2) experience in teaching practice, (3) challenges faced, (4) institutional or pedagogical support, and (5) perceptions of education policy related to STEM. The interviews were conducted semi-structurally, allowing probing and follow-up questions to gain deeper insights into personal and institutional experiences.

The Interview Guide for Lecturers or Supervisors was used to gather institutional perspectives and professional reflections regarding pre-service teachers' preparedness for implementing STEM teaching. The instrument covered four main areas: (1) lecturers' perceptions of preservice teacher's readiness, (2) mentoring strategies, (3) challenges in guiding STEM implementation, and (4) policy and institutional support.

The interview guides were also reviewed by the three experts and pilot tested to improve the clarity and relevance of the questions. Data credibility was further supported through triangulation across respondent groups (pre-service teachers and lecturers/supervisors) and data collection methods, including questionnaires, interviews, observations, and document analysis.

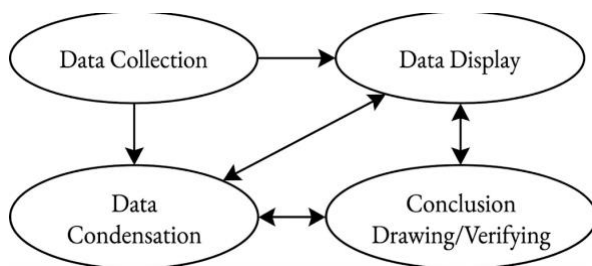
The microteaching observation guide/checklist was used to document the observable teaching practices of pre-service teachers during microteaching. The observation areas were aligned with the pedagogical enactment of STEM teaching and included lesson introduction and learning orientation, STEM content and contextualization, instructional strategies and learning resources, questioning and higher-order thinking, student engagement and facilitation, and assessment, feedback, and reflection. The guide was used by three observers to observe 10 pre-service teachers in a microteaching setting. The observation data were analyzed descriptively and used as complementary evidence to compare observable teaching practices with pre-service teachers' reported readiness and experiences.

Data analysis procedures

Data analysis followed the model proposed by Miles, Huberman, and Saldaña (2014), consisting of three interactive stages: data condensation, data display, and conclusion drawing/verification.

Figure 1

Miles and Huberman data analysis procedure (Huberman et al., 2014)



During data condensation, information from multiple instruments was classified, coded, and simplified. Quantitative questionnaire data were organized by STEM readiness indicators, while qualitative data from interviews, observations, and documents were coded according to emerging areas such as “STEM implementation barriers,” “supporting factors,” and “cross-country differences.” In the data display stage, condensed data were organized into thematic matrices, charts, and comparative summaries. Quantitative findings were presented descriptively using frequency tables and visual diagrams, while qualitative patterns were illustrated through narrative and tabular comparison among the three countries.

For the document analysis, relevant national policy frameworks and teacher education curricula were examined systematically to identify how STEM education was positioned and integrated within teacher preparation across Indonesia, Malaysia, and Thailand (Table 4). The analysis focused on explicit references to STEM education, STEM-related learning objectives and curriculum content, approaches to STEM integration, opportunities for developing STEM teaching competencies, and forms of national or institutional support for STEM implementation. Relevant information and passages were extracted from the documents and coded according to these analytical areas. The coded information was then organized into comparative summaries to identify similarities and differences across the three national contexts. Findings from the document analysis were subsequently compared with evidence from questionnaires, interviews, and classroom or microteaching observations to support triangulation and to provide contextual explanations for the observed patterns in pre-service teachers’ STEM readiness.

Table 4

Document Analysis Matrix

Analytical Dimension	What was Examined
STEM Policy Orientation	National priorities, objectives, and directions related to STEM education
STEM Curriculum Integration	Presence and integration of STEM-related content in teacher education curricula
Pedagogical Preparation	Opportunities to develop STEM teaching and instructional practices
Practical/Professional Preparation	STEM-related teaching practice, projects, microteaching, or experiential learning
Technological Integration	Use of technology, digital tools, coding, robotics, or other STEM-related technologies

Finally, conclusion drawing and verification involved synthesizing data to identify key patterns and relationships concerning pre-service teacher readiness for STEM teaching. Conclusions were continuously refined through triangulation and peer debriefing to ensure the validity and confirmability of the interpretations. Trustworthiness was established following Lincoln and Guba’s criteria of credibility, transferability, dependability, and confirmability (Alexander, 2019). The combination of multiple data sources, cross-national contexts, and diverse collection techniques provided a robust basis for interpreting the findings within and across the three cases studied.

RESULTS AND DISCUSSION

National policies and institutional support

Findings indicate that the implementation of STEM education in Malaysia and Thailand has been strongly supported by national policies, while in Indonesia, systematic initiatives began to emerge more prominently in 2025. In Malaysia, the *Malaysia Education Blueprint (2013–2025)* serves as the main policy framework, embedding STEM integration from primary to higher education. STEM is positioned not merely as a pedagogical approach but as a national strategy to cultivate a workforce capable of addressing the challenges of the Fourth Industrial

Revolution. Throughout the blueprint's implementation, several initiatives were launched, such as the *National STEM Action Plan*, *MySTIE Framework*, and NGO-driven programs like *Teach for Malaysia* and *STEM Teacher Ambassadors*.

Industry engagement also plays a crucial role, notably through Petronas' funding support for laboratory development and teacher training programs. At the state level, initiatives like the *Penang STEM Centre* have offered over 250 STEM-based programs, including innovation exhibitions, teacher workshops, and inclusive programs for underprivileged families to ensure equitable access to STEM teaching opportunities.

In Thailand, Kasetsart University has integrated STEM education within the broader framework of the *Sustainable Development Goals (SDGs)*. Programs such as *STEM Camps*, *coding and robotics workshops*, and *environmental projects* highlight the integration of science, technology, engineering, and mathematics in real-world problem-solving contexts. The emphasis on *fun learning* aims to nurture sustained student engagement. Both countries demonstrate that successful STEM implementation depends on the synergy between national policy, industrial partnerships, and educational innovation across universities and schools.

Teacher education curriculum and teaching practice

In Malaysia and Thailand, STEM integration within teacher education programs is characterized by experiential and collaborative curriculum design. At *Universiti Teknologi MARA (UiTM)*, the STEM Education course is structured into three main phases. The first four weeks focus on strengthening theoretical and philosophical foundations, including transdisciplinary concepts and their linkage with digital technology. The second phase consists of a two-week workshop where students engage in project design based on the *Engineering Design Process (EDP)*. During the final phase, students develop integrative projects incorporating technologies such as IoT, TinkerCad, 3D printing, and gamified platforms like *Minecraft*, *Roblox*, and *AR/VR* applications. These projects are presented as part of course assessment, training pre-service teachers to develop innovative instructional media for classroom use.

At *Universiti Pendidikan Sultan Idris (UPSI)*, the curriculum emphasizes the use of the *Modul Bimbingan dan Mobiliti (MOBIM)*, an open instructional module that guides teachers in implementing *Project-Based Learning (PjBL)* effectively. The module provides project templates, worksheets, and collaborative tasks that integrate multiple disciplines. Microteaching activities are centered on developing simple yet technology-supported instructional media for STEM classrooms. Meanwhile, *Kasetsart University* in Thailand adopts experiential approaches through coding, robotics, and environmental STEM projects that foster creative problem-solving and sustainability awareness among pre-service teachers.

Pre-service teachers' readiness and competency development

Teacher readiness was analyzed through four dimensions: pedagogical competence, STEM conceptual understanding, technological skills, and teaching experience. In Malaysia, the *Malaysian Qualifications Agency (MQA)* has outlined six key competencies for STEM teachers, emphasizing mastery of disciplinary knowledge across science, technology, engineering, and mathematics. Training for pre-service teachers is organized through modular blocks that involve cross-faculty collaboration between the Faculty of Engineering, Faculty of Pharmacy, and innovation centers such as *Make a Lab*.

Despite this strong framework, a prevalent *exam-oriented mindset* remains a challenge, with students often prioritizing grades over creativity and innovation. The development of project-based modules is expected to shift this orientation toward authentic problem-solving. In Thailand, teacher education programs focus on cultivating critical thinking, design skills, and environmentally oriented innovation. Students are encouraged to design engaging learning materials and foster student participation. Similar to Malaysia, the perception of STEM as a difficult and less lucrative field remains a barrier to broader student interest. These findings are complemented by quantitative and qualitative data collected from pre-service teachers through questionnaires and in-depth interviews, providing a comprehensive understanding of their readiness to implement STEM education.

Questionnaire analysis

The questionnaire assessed four main areas: (1) conceptual understanding of STEM, (2) implementation ability and experience, (3) perceived barriers and institutional support, and (4) attitudes toward STEM education. Each item was rated using a 5-point Likert scale.

Table 5
Average Scores of Pre-Service Teachers' STEM Readiness

No	Aspect of Readiness	Mean	Category
1	Conceptual Understanding of STEM	3.43	Fairly Good
2	Implementation Ability and Experience	3.45	Fairly Good
3	Barriers and Institutional Support	3.93	High
4	Attitudes toward STEM Education	4.17	Very Good

The descriptive results (Table 5) indicate that the highest average score (4.17) was obtained for the attitude aspect, suggesting generally positive motivation and enthusiasm among pre-service teachers toward STEM learning. This finding aligns with Dare et al. (2021) and Ichsan et al. (2023), who emphasized that positive attitudes toward educational innovation are crucial for 21st-century learning readiness.

The relatively high score for *barriers and institutional support* (3.93) suggests that pre-service teachers recognized the importance of institutional backing, technological availability, and cross-disciplinary collaboration in supporting STEM implementation. Meanwhile, *conceptual understanding* (3.43) and *implementation experience* (3.45) were categorized as moderately good, suggesting that respondents reported a reasonable foundational understanding of STEM but comparatively less practical experience. Respondents highlighted the need for more opportunities to practice through microteaching, workshops, and project-based assignments. Overall, the descriptive findings suggest that pre-service teachers reported positive attitudes and reasonable conceptual readiness for STEM implementation, while practical, technological, and collaborative aspects may require further development.

Across the three countries, conceptual understanding and positive attitudes toward STEM appeared relatively well established, whereas opportunities to enact integrated STEM teaching varied more substantially. Malaysia showed more structured opportunities for project development and microteaching, Thailand demonstrated stronger exposure to coding, robotics, and sustainability-oriented STEM activities, while Indonesia showed an emerging but more fragmented pattern of implementation and institutional support.

Interview findings: Pre-service teachers

Thematic analysis of pre-service teacher interviews revealed seven major areas, summarized in Table 6. The findings indicate that pre-service teachers generally have a clear conceptual understanding of STEM and recognize its role in interdisciplinary and real-world problem solving. This conceptual understanding was reflected in participants' descriptions of STEM as an approach that integrates multiple disciplines to address authentic problems. As one pre-service teacher stated, "*STEM combines science, technology, engineering, and math to solve real-life problems.*" This statement illustrates that participants understood STEM beyond individual disciplinary knowledge and recognized its integrative nature.

Table 6
Thematic Summary of Pre-Service Teacher Interviews

Theme	Key Findings	Representative Quote
Understanding of STEM	Viewed as integration of science, technology, engineering, and mathematics for real-world problem solving.	"STEM combines science, technology, engineering, and math to solve real-life problems."
Readiness and Experience	Theoretical readiness is adequate, but practical experience remains limited.	"I feel ready because I learned about STEM at university, but I have not had much teaching practice."
Learning Strategies	Project-Based Learning and Problem-Based Learning were most frequently applied.	"I use project-based learning to make students active and think critically."
Challenges	Limited facilities, time, and cross-disciplinary collaboration.	"The main challenge is lack of tools and experience working across disciplines."
Support Needs	Require further training, lab facilities, and institutional support.	"We need continuous training and better resources for STEM teaching."
Role of University	Programs provide foundational STEM courses, but practice opportunities are limited.	"Our program has a STEM course, but we need more practical sessions."
Policy Awareness	Awareness of STEM-related campus policies, though implementation remains partial.	"There is a STEM policy, but it's not fully implemented yet."

However, the interviews also revealed a gap between theoretical readiness and opportunities for practical implementation. One participant explained, *“I feel ready because I learned about STEM at university, but I have not had much teaching practice.”* This account illustrates that exposure to STEM concepts during teacher education does not necessarily provide sufficient opportunities to develop practical readiness for implementing integrated STEM teaching. Participants also identified limited facilities, time, and opportunities for cross-disciplinary collaboration as important challenges.

The interviews further highlighted the need for sustained institutional support and practical training. Participants reported that universities provided foundational STEM courses, but opportunities for hands-on practice remained limited. They also expressed the need for continuous training and better resources for STEM teaching. Taken together, these findings suggest that pre-service teachers possess a reasonable conceptual foundation and positive orientation toward STEM, while their practical readiness is shaped by the availability of teaching practice, resources, interdisciplinary collaboration, and institutional support.

Interview findings: Lecturers’ perspectives

Interviews with lecturers and academic supervisors revealed converging perspectives regarding pre-service teachers’ STEM readiness and institutional challenges. Thematic findings are summarized in [Table 7](#). Lecturers generally perceived that pre-service teachers had developed a basic conceptual understanding of STEM, but that this understanding was not always translated into fully integrated teaching practice. As one lecturer explained, *“They know what STEM means, but still struggle to design fully integrated lessons.”* This observation reinforces the finding that conceptual knowledge of STEM does not necessarily translate into the ability to design and implement integrated STEM lessons.

Table 7

Thematic summary of lecturer interviews

Theme	Key Findings	Representative Quote
Understanding of STEM	STEM is seen as an integrative approach fostering higher-order thinking and collaboration.	“STEM is about interdisciplinary thinking that connects theory with real-world context.”
Perception of Student Readiness	Students understand STEM conceptually but lack full integration in practice.	“They know what STEM means, but still struggle to design fully integrated lessons.”
Mentoring Practices	Lecturers integrate STEM through cross-course projects and collaborative practicums.	“We assign interdisciplinary projects to train collaboration.”
Challenges	Limited facilities, time constraints, and exam-oriented mindsets.	“The main challenge is limited tools and time, while students focus more on grades.”
Institutional Support	Appreciated but needs stronger inter-program coordination.	“Support exists, but collaboration across departments needs improvement.”
Recommendations	Suggest project-based and technology-integrated training for pre-service teachers.	“They need collaborative projects and technology training to enhance readiness.”

Lecturers perceived pre-service teachers as demonstrating generally positive conceptual readiness, while practical integration of STEM across disciplines remained limited. They emphasized the need for structured, cross-departmental collaboration, resource enhancement, and training focused on innovation and reflective practice. Institutional facilities such as *Maker Labs* and *STEM Corners* were viewed positively, although their utilization remained inconsistent. Lecturers also highlighted the importance of mentoring, collaborative projects, and institutional support in developing practical readiness. They described the use of cross-course projects and collaborative practicums as strategies for providing pre-service teachers with opportunities to integrate STEM concepts in practice. At the institutional level, however, existing support was perceived as requiring stronger coordination across programs or departments. As one lecturer noted, *“Support exists, but collaboration across departments needs improvement.”* This perspective suggests that institutional support needs to extend beyond the availability of resources toward more systematic coordination and interdisciplinary collaboration.

Lecturers further identified limited facilities, time constraints, and exam-oriented mindsets as challenges affecting STEM implementation. They recommended greater use of project-based and technology-integrated training to strengthen pre-service teachers’ readiness. Overall, the lecturer interviews reinforce the finding that developing STEM teaching readiness requires an interaction between individual preparation and the institutional conditions that provide opportunities for interdisciplinary practice, mentoring, and technology-supported learning.

Innovation and technology integration in STEM teaching

Innovative technology is increasingly integrated into teacher education curricula across institutions. At *UiTM*, pre-service teachers are trained to use gamified learning tools such as *Minecraft* and *Roblox*, develop digital media

with *TinkerCad*, and explore immersive experiences using *Virtual Reality (VR)* and *Augmented Reality (AR)*. Artificial intelligence tools such as *ChatGPT* and *Canva* are also introduced to support creative lesson design. At *UPSI*, microteaching emphasizes low-cost, technology-based media production to prepare future teachers for real classroom contexts, while *Kasetsart University* focuses on coding and robotics to enhance computational thinking.

Comparative analysis and emerging implications

The cross-country comparison indicates that pre-service teachers in Indonesia, Malaysia, and Thailand share several common characteristics, but the pathways through which STEM readiness is developed differ across national and institutional contexts. Across the three countries, the questionnaire and qualitative findings suggested generally positive attitudes toward STEM and a reasonable conceptual understanding of STEM as an interdisciplinary and problem-oriented approach. However, practical implementation experience was less developed. Interview findings further indicated that opportunities for cross-disciplinary collaboration, project-based learning, mentoring, and technology-supported practice were not equally available across institutions. Thus, the central issue was not a lack of recognition of the importance of STEM, but the extent to which teacher education systems translated this recognition into sustained opportunities for practice.

The Indonesian case illustrates a context in which STEM integration is emerging but remains relatively fragmented across institutional and programmatic initiatives. The findings indicate that pre-service teachers possess foundational conceptual readiness and positive attitudes, while practical experience, technological integration, and institutional support remain areas requiring further development. This pattern suggests a gap between policy aspirations and the systematic embedding of STEM within teacher preparation. In particular, opportunities for sustained interdisciplinary project work and access to adequate facilities appear important for translating conceptual understanding into classroom implementation. Therefore, the Indonesian context should not be interpreted simply as having lower STEM readiness; rather, it reflects a developing stage of institutionalization in which STEM practices are being established but are not yet uniformly embedded across teacher education experiences.

Malaysia presents a relatively structured pathway of STEM integration. The findings from *UiTM* and *UPSI* show that STEM preparation is embedded in curriculum activities that combine theoretical foundations, engineering design, project development, microteaching, and technology-supported instructional production. Industry and external-sector involvement further expands opportunities for practical STEM experiences. Nevertheless, the Malaysian case also demonstrates that the existence of strong policy and institutional infrastructure does not automatically eliminate implementation challenges. Pre-service teachers still require opportunities to integrate different STEM disciplines pedagogically and to translate technological competencies into meaningful learning experiences. The Malaysian experience therefore highlights the importance of moving beyond policy provision toward sustained curriculum-practice alignment.

Thailand demonstrates another distinctive pathway, characterized by experiential STEM activities involving coding, robotics, environmental projects, and connections with the Sustainable Development Goals. At *Kasetsart University*, these activities provide opportunities for pre-service teachers to engage with STEM through authentic problem-solving and sustainability-related contexts. Compared with the more technology- and engineering-design-oriented examples observed in the Malaysian cases, the Thai case illustrates how STEM teacher preparation can be connected more explicitly with computational thinking, environmental issues, and sustainability. This indicates that STEM integration may take different forms depending on national priorities and institutional expertise rather than following a single standardized model.

An important similarity across the three contexts is therefore the persistent gap between conceptual or affective readiness and practical implementation readiness. This pattern is consistent with broader international STEM education research, which increasingly emphasizes that effective STEM teaching requires more than disciplinary knowledge. Recent research on STEM teacher professional development highlights the importance of pedagogical knowledge, pedagogical content knowledge, technological knowledge, and technological-pedagogical integration, together with sustained professional learning opportunities. Similarly, recent systematic review evidence shows growing attention to computational thinking within pre-service teacher education, particularly through programming, visual programming, and technology-supported activities. These international developments provide a useful context for interpreting the technology, coding, robotics, and project-based practices identified in the Malaysian and Thai cases.

The findings also reflect a broader shift in STEM education toward authentic, interdisciplinary, and sustainability-oriented learning. Contemporary discussions increasingly connect STEM with real-world problem solving, computational thinking, digital transformation, and sustainability rather than treating STEM as the parallel teaching of four separate disciplines. This broader trajectory is also evident in international education agendas that increasingly link digital transformation with the green transition and climate-related learning. In this respect, the

environmental STEM projects observed in Thailand and the technology- and engineering-design-oriented activities in Malaysia represent different manifestations of a wider movement toward more authentic and future-oriented STEM learning.

Taken together, the three cases suggest that STEM readiness should be understood as a context-dependent developmental process rather than as a uniform national characteristic. Malaysia, Thailand, and Indonesia demonstrate different combinations of policy support, curriculum integration, technological resources, practical experiences, and external partnerships. The comparison therefore points to four interconnected conditions for strengthening STEM teacher preparation: (1) coherent policy and institutional support, (2) curriculum structures that connect STEM theory with authentic practice, (3) sustained opportunities for interdisciplinary and technology-supported project work, and (4) continuous professional learning and mentoring. Rather than simply transferring practices from one country to another, STEM teacher education initiatives should adapt these principles to local institutional capacity, educational priorities, and cultural contexts.

The comparative evidence consequently extends the discussion beyond a simple country-level ranking. It shows that the development of STEM readiness can follow different trajectories while addressing similar global challenges. The key implication is that strengthening STEM teacher education requires both alignment with international developments and sensitivity to local educational ecosystems. This perspective provides a more nuanced basis for understanding how Southeast Asian teacher education systems can develop STEM capacity while responding to emerging demands related to digital transformation, interdisciplinary problem solving, and sustainability.

IMPLICATIONS AND RECOMMENDATIONS

The results of this study provide several implications for STEM teacher education and policy development in Southeast Asia.

1. **Policy and Institutional Development.** Strong national policies, such as those in Malaysia and Thailand, demonstrate the importance of sustained governmental commitment and inter-sectoral collaboration. Indonesia may benefit from adopting similar models by establishing a comprehensive national STEM education framework that links teacher training, curriculum design, and industrial partnerships.
2. **Curriculum and Pedagogical Practice.** Teacher education programs should embed authentic, inquiry-driven, and project-based learning modules that reflect real-world STEM applications. Cross-faculty collaboration—between education, science, and engineering departments—can foster deeper interdisciplinary engagement and prepare pre-service teachers to design integrative STEM lessons.
3. **Technological and Professional Capacity Building.** Continuous professional development and exposure to educational technologies such as AR/VR, coding, and AI-based tools are essential for building teachers' confidence and creativity. Institutions should provide maker spaces and digital laboratories to support experimentation and innovation.
4. **Cultural and Mindset Transformation.** A shift from exam-oriented paradigms toward collaborative, process-oriented learning is critical. Teacher educators play a pivotal role in modeling reflective, research-informed practices that promote higher-order thinking and creativity among pre-service teachers.
5. **Future Research Directions.** Further studies should expand the comparative scope to include longitudinal data on teachers' classroom practices and the long-term effects of STEM-focused curriculum reforms. Mixed-method or design-based research approaches could also provide deeper insights into how institutional ecosystems influence STEM teaching readiness.

LIMITATION

Several methodological limitations should be acknowledged. First, although the STEM Readiness Questionnaire underwent expert review focusing on the alignment between the intended constructs, dimensions, indicators, and items, as well as pilot testing for clarity, the questionnaire was not subjected to psychometric validation of internal consistency. Cronbach's alpha or other reliability coefficients were not calculated for the constituent dimensions. Therefore, the questionnaire findings should be interpreted as descriptive evidence of pre-service teachers' perceived readiness rather than as evidence from a fully psychometrically validated measurement scale.

Second, although the researchers paid attention to the clarity and comprehensibility of the instruments during expert review and pilot testing, formal cross-linguistic validation was not conducted. In particular, procedures such as systematic translation-back-translation and empirical testing of measurement equivalence across Indonesia, Malaysia, and Thailand were not undertaken. Consequently, potential differences in language interpretation or cultural understanding cannot be completely excluded when interpreting the cross-country questionnaire

responses. Future studies should address these issues through systematic cross-cultural adaptation, translation–back-translation, and psychometric testing of measurement equivalence across the participating countries.

CONCLUSIONS

This study explored the readiness of pre-service teachers in Indonesia, Malaysia, and Thailand to implement STEM teaching, with attention to conceptual understanding, implementation ability and experience, attitudes toward STEM, and institutional support. The comparative findings indicate that STEM integration develops through different institutional and curricular pathways across the three contexts. Malaysia provided relatively structured opportunities through curriculum activities involving engineering design, project development, microteaching, and technology-supported practices, while Thailand emphasized experiential STEM activities involving coding, robotics, environmental projects, and sustainability. In Indonesia, STEM integration remains an emerging and relatively varied process, with opportunities for practical implementation and institutional support not yet uniformly embedded across teacher education experiences. These differences are better understood as different pathways of STEM development rather than as a simple hierarchy of national readiness.

Across all three countries, the descriptive questionnaire findings and qualitative evidence suggest that pre-service teachers generally reported positive attitudes toward STEM and a reasonable conceptual understanding of its interdisciplinary and problem-oriented nature. However, practical implementation experience was less developed, particularly in relation to interdisciplinary collaboration, project-based learning, mentoring, and technology-supported teaching. This gap was also evident in the interview data. As one pre-service teacher explained, “I feel ready because I learned about STEM at university, but I have not had much teaching practice.” Similarly, a lecturer observed, “They know what STEM means, but still struggle to design fully integrated lessons.” These accounts reinforce the finding that conceptual familiarity with STEM does not necessarily translate into extensive experience in implementing integrated STEM teaching.

Institutional conditions also emerged as important contextual considerations in the development of STEM teaching readiness. Participants highlighted the value of training, mentoring, facilities, interdisciplinary collaboration, and opportunities for practical experience. As one lecturer stated, “Support exists, but collaboration across departments needs improvement.” Rather than indicating a direct causal effect, this finding suggests that institutional arrangements provide important conditions for translating STEM knowledge into teaching practice. Overall, the findings suggest that readiness to implement STEM teaching is a context-dependent and developmental process that requires alignment among conceptual preparation, authentic teaching practice, interdisciplinary collaboration, technological opportunities, mentoring, and institutional support. The study therefore highlights the importance of strengthening teacher education environments in ways that connect STEM theory with sustained opportunities for practical and collaborative implementation while remaining responsive to local educational and institutional contexts.

Acknowledgement

The authors express their appreciation to Universitas Negeri Yogyakarta (UNY), Universiti Teknologi MARA (UiTM), Universiti Pendidikan Sultan Idris (UPSI), and Kasetsart University (KU) for their collaboration and support during the research process. The authors also thank all pre-service teachers and lecturers who participated in this study.

Funding

This research was funded by the Directorate of Research and Community Service (DRPM), Universitas Negeri Yogyakarta, through the Commissioned Research Scheme with Grant Number: 77.775/ DST/ UN34.9/ T/ PT.01.03/ 2026.

Ethical statement

This study was reviewed and approved by the Research Ethics Committee of Universitas Negeri Yogyakarta (UNY). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all participants prior to participation. Participants were informed about the study’s aims, procedures, voluntary nature, and confidentiality assurances.

Competing interests

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Author contributions

A.M.: conceptualization, methodology, instrument design, validation, supervision, writing—review and editing. R.A.T.: data collection, formal analysis, visualization, writing—original draft preparation, writing—review and editing. N.A.A.: instrument design, data collection, writing—original draft preparation, writing—review and editing. M.T.B.: instrument validation, data collection, writing—review and editing. M.H.I.: instrument validation, data collection, writing—review and editing. C.F.: instrument validation, data collection, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to institutional data-sharing restrictions, raw datasets are not publicly available.

AI disclosure

Artificial intelligence tools, specifically Grammarly (2025 version), were used only for language editing and formatting purposes during manuscript preparation. No AI tools were involved in research design, data analysis, or interpretation of results. All content was reviewed and approved by the authors.

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REFERENCES

- Alexander, A. P. (2019). Lincoln and Guba's quality criteria for trustworthiness. *IDC International Journal*, 6(4).
- Ali, G., Jaaffar, A. R., & Ali, J. (2021). STEM education in Malaysia: Fulfilling SMEs' expectation. In *Modeling economic growth in contemporary Malaysia* (pp. 43–57). Emerald Publishing. <https://doi.org/10.1108/978-1-80043-806-420211005>
- Aslam, S., Alghamdi, A. A., Abid, N., & Kumar, T. (2023). Challenges in implementing STEM education: Insights from novice STEM teachers in developing countries. *Sustainability*, 15(19), Article 14455. <https://doi.org/10.3390/su151914455>
- Berisha, F., & Vula, E. (2021). Developing pre-service teachers' conceptualization of STEM and STEM pedagogical practices. *Frontiers in Education*, 6, Article 585075. <https://doi.org/10.3389/feduc.2021.585075>
- Bybee, R. W. (2013). *The case for STEM education: Challenges and opportunities*. NSTA Press.
- Chai, C. S., Rahmawati, Y., & Jong, M. S.-Y. (2020). Indonesian science, mathematics, and engineering preservice teachers' experiences in STEM-TPACK design-based learning. *Sustainability*, 12(21), Article 9050. <https://doi.org/10.3390/su12219050>
- Chaisri Khureerung, A., & Thao-Do, T. P. (2022). Enhancing pre-service teachers' understanding of science teaching through STEM activities integrated inquiry learning with Thai context. *Journal of Educational Issues*, 8(2), 257. <https://doi.org/10.5296/jei.v8i2.20030>
- Dare, E. A., Keratithamkul, K., Hiwatig, B. M., & Li, F. (2021). Beyond content: The role of STEM disciplines, real-world problems, 21st century skills, and STEM careers within science teachers' conceptions of integrated STEM education. *Education Sciences*, 11(11), Article 737. <https://doi.org/10.3390/educsci11110737>
- Faikhanta, C., & Lertdechapat, K. (2021). STEM teacher education in Thailand. In T. W. Teo, A.-L. Tan, & Y. S. Ong (Eds.), *STEM education from Asia: Trends and perspectives*. Routledge. <https://doi.org/10.4324/9781003099888>
- Harrison, H., Birks, M., Franklin, R., & Mills, J. (2017). Case study research: Foundations and methodological orientations. *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, 18(1), Article 19. <https://doi.org/10.17169/fqs-18.1.2655>
- Ichsan, I., Suharyat, Y., Santosa, T. A., & Satria, E. (2023). Effectiveness of STEM-based learning in teaching 21st century skills in Generation Z students in science learning: A meta-analysis. *Jurnal Penelitian Pendidikan IPA*, 9(1), 150–166. <https://doi.org/10.29303/jppipa.v9i1.2517>
- Isasi-Sánchez, L., Castilla-Alcalá, G., Rivera-Riquelme, F. A., & Durán-Heras, A. (2023). Fostering youth entrepreneurship in STEM students for Industry 4.0 era. In [Book title] (pp. 29–38). Springer. https://doi.org/10.1007/978-3-031-29382-5_4
- Jamali, S. M., Md Zain, A. N., Ale Ebrahim, N., & Samsudin, M. A. (2020). The effect of STEM project based learning on self-efficacy among high-school physics students. *Journal of Turkish Science Education*, 17(1), 94–108. <https://doi.org/10.36681/tused.2020.15>
- Karpudewan, M., Krishnan, P., Roth, W.-M., & Ali, M. N. (2023). What research says about the relationships between Malaysian teachers' knowledge, perceived difficulties and self-efficacy, and practicing STEM teaching in schools. *The Asia-Pacific Education Researcher*, 32(3), 353–365. <https://doi.org/10.1007/s40299-022-00658-1>
- Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, 3(1), Article 11. <https://doi.org/10.1186/s40594-016-0046-z>
- Koehler, M. J., & Mishra, P. (2009). What is technological pedagogical content knowledge? *Contemporary Issues in Technology and Teacher Education*, 9(1), 60–70.
- Koyunlu Ünlü, Z., & Dökme, İ. (2022). A systematic review of 5E model in science education: Proposing a skill-based STEM instructional model within the 21st century skills. *International Journal of Science Education*, 44(13), 2110–2130. <https://doi.org/10.1080/09500693.2022.2114031>
- Liew, Y. F., & Teoh, H. K. (2023). STEM education in Malaysia: An organisational development approach? *International Journal of Advanced Research in Future Ready Learning and Education*, 29(1), 1–19. <https://doi.org/10.37934/frle.29.1.119>
- Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. *International Journal of STEM Education*, 6(1), Article 2. <https://doi.org/10.1186/s40594-018-0151-2>
- Marzuki, O. F., Teo, E. Y. L., Abdullah, W. N. Z. Z., Khairuddin, N., Inai, N. H., Saad, J. M., Aziz, M. H. A., & Asmawi, N. N. M. (2026). STEM education in Malaysia: A systematic review of learning outcomes, student engagement, and workforce readiness in the era of Industry 4.0. *Open Access Library Journal*, 13(3), 1–19. <https://doi.org/10.4236/oalib.1115044>
- Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). *Qualitative data analysis: A methods sourcebook* (3rd ed.). SAGE Publications.

- Nugraha, M. G., Kidman, G., & Tan, H. (2023). Pre-service teacher in STEM education: An integrative review and mapping of the Indonesian research literature. *Eurasia Journal of Mathematics, Science and Technology Education*, 19(5), Article em2262. <https://doi.org/10.29333/ejmste/13155>
- Purwaningsih, E., Sari, S. P., Sari, A. M., & Suryadi, A. (2020). The effect of STEM-PjBL and discovery learning on improving students' problem-solving skills of impulse and momentum topic. *Jurnal Pendidikan IPA Indonesia*, 9(4), 465–476. <https://doi.org/10.15294/jpii.v9i4.26432>
- Reyes, R. L., Isleta, K. P., Regala, J. D., & Bialba, D. M. R. (2024). Enhancing experiential science learning with virtual labs: A narrative account of merits, challenges, and implementation strategies. *Journal of Computer Assisted Learning*, 40(6), 3167–3186. <https://doi.org/10.1111/jcal.13061>
- Roehrig, G. H., Dare, E. A., Ellis, J. A., & Ring-Whalen, E. (2021). Beyond the basics: A detailed conceptual framework of integrated STEM. *Disciplinary and Interdisciplinary Science Education Research*, 3(1), Article 11. <https://doi.org/10.1186/s43031-021-00041-y>
- Rusdiyah, E. F., Indarwati, D., Jazil, S., Susilawati, S., & Gusniwati, G. (2021). STEM learning environment: Perceptions and implementation skills in prospective science teachers. *Jurnal Pendidikan IPA Indonesia*, 10(1), 138–148. <https://doi.org/10.15294/jpii.v10i1.28303>
- Saldívar-Almorejo, M. M., Flores-Herrera, L. A., Rivera-Blas, R., Niño-Suárez, P. A., Rivera-Blas, E. Z., & Rodríguez-Contreras, N. (2024). E-learning challenges in STEM education. *Education Sciences*, 14(12), Article 1370. <https://doi.org/10.3390/educsci14121370>
- Trevallion, D., & Trevallion, T. (2020). STEM: Design, implement and evaluate. *International Journal of Innovation, Creativity and Change*, 14(8).
- Zheng, L. (2021). A performative history of STEM crisis discourse: The co-constitution of crisis sensibility and systems analysis around 1970. *Discourse: Studies in the Cultural Politics of Education*, 42(3), 337–352. <https://doi.org/10.1080/01596306.2019.1637332>