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PREFACE

Special Issue: Southeast Asian Teacher Education Programme (SEA-TEP)

The Southeast Asian Journal of STEM Education (SAJSE) is pleased to present this Special Issue featuring research emerging from the Southeast Asian Teacher Education Programme (SEA-TEP), a regional initiative led by SEAMEO STEM-ED in collaboration with educational institutions, teacher education providers, researchers, and policymakers across Southeast Asia and beyond.

This special issue represents a significant milestone in advancing evidence-based STEM teacher education through regional collaboration. The collection brings together research studies conducted by participating teams from Cambodia, Indonesia, Malaysia, Kazakhstan, Thailand, and partner institutions, reflecting a shared commitment to strengthening teacher preparation, enhancing classroom practices, and improving learning outcomes. By showcasing innovative learning resources and STEM pedagogies, the collection highlights efforts to build science competencies aligned with the PISA framework, reinforcing the importance of equipping teachers with the tools to foster deeper engagement and achievement in STEM education.

At the heart of SEA-TEP is the belief that quality teacher education is fundamental to transforming education systems and preparing learners with the competencies required for the twenty-first century. Through collaborative professional development, joint research initiatives, and the implementation of learning units grounded in the Claim-Evidence-Reasoning (CER) and modelling frameworks, SEA-TEP has fostered a vibrant community of educators and researchers dedicated to advancing STEM education across diverse educational contexts.

The papers featured in this special issue highlight the collective efforts of researchers and practitioners who have examined the effectiveness of SEA-TEP implementation, explored innovative approaches to teaching and learning, and generated valuable evidence to inform educational policies and practices. While each study reflects unique national and institutional contexts, together they provide important insights into how collaborative teacher education programmes can strengthen pedagogical capacity, promote critical thinking and scientific reasoning, and support sustainable educational improvement.

This special issue also demonstrates the power of regional partnerships in addressing common educational challenges. By engaging educators, researchers, and stakeholders across countries, SEA-TEP has enabled the sharing of expertise, resources, and experiences, creating opportunities for mutual learning and continuous improvement. The findings presented herein contribute not only to the growing body of knowledge on STEM teacher education but also to broader discussions on educational transformation, teacher professional development, and evidence-informed policymaking in Southeast Asia.

We extend our sincere appreciation to all researchers, teacher educators, partner institutions, reviewers, and implementation teams whose dedication and collaborative spirit made this special issue possible. Their contributions exemplify the value of regional cooperation in generating knowledge and advancing educational excellence.

Thank you for being a part of this journey.

Warm regards,

SEAMEO STEM-ED

EDITORIAL

Welcome to SAJSE, the leading platform for advancing STEM education and encouraging innovation in Southeast Asia. Our journal exemplifies the spirit of collaboration, creativity, and capacity building. We are dedicated to making STEM education accessible to all, while also offering chances for educators and students to share their research, teaching techniques, and new ideas. This open-access journal serves as a beacon for researchers, educators, policymakers, and students seeking excellence in STEM education.

A Platform for Diverse Voices

The Southeast Asian Journal on STEM Education transcends its role as a mere repository of information, establishing itself as a vibrant forum that embraces a plurality of perspectives. This journal curates a comprehensive array of contributions, encompassing seminal research articles from seasoned scholars, innovative pedagogical methodologies from educators, and introspective analyses on integrated STEM disciplines authored by students. It operates as a platform that acknowledges and values the diverse viewpoints of all constituents within the educational sphere, thereby facilitating a collective ethos of learning and developmental synergy.

Bridging Policy and Practice

A distinctive feature of this journal is its specialised policy section, designed to stimulate dialogue on the development and enactment of educational policies, with a particular emphasis on STEM disciplines. This section covers a broad spectrum, from theoretical propositions to empirical research and the exchange of best practices. The journal aims to contribute to and impact policy-making processes that determine the trajectory of educational advancement. It represents an effort to reconcile policy with practice, guaranteeing that educational innovations are firmly anchored in the practical landscape and meet the requirements of learners.

Global Perspectives with a Local Focus

Although the journal invites submissions from educators, policymakers, teachers, and students globally, it prioritises local implementations, research, or practices from Southeast Asian countries. This emphasis underscores a dedication to tackling the distinct challenges and seizing the opportunities present in the region, advocating for solutions that are informed by global perspectives yet tailored to local contexts.

A Call to Action

We warmly invite all stakeholders, particularly teachers and students, to contribute to the Southeast Asian Journal on STEM Education. Your contributions to research, practices, and reflections do more than enrich our collective knowledge; they play an active role in sculpting

a future where STEM education is universally accessible, inclusive, and profoundly influential. This journal stands as a testament to the strength of collaborative effort, reinforcing the notion that every contribution, regardless of its size, is instrumental in unlocking the vast potential of STEM.

The Southeast Asian Journal on STEM Education serves as a beacon, illuminating the path toward a more enlightened future via the progression of STEM education. It summons all who are dedicated to nurturing scientific thought and leveraging scientific inquiry to elevate the quality of teaching and learning. United in purpose, let us venture forth on this path of exploration and innovation, laying the foundations for future generations to build upon.

Best regards,

SAJSE Editors

TRANSFORMING TEACHER EDUCATION: INSIGHTS FROM THE SEA-TEP RESEARCH INITIATIVE AND COLLABORATION

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ABSTRACT

The Southeast Asian Teacher Education Programme (SEA-TEP) initiative, led by the Southeast Asian Ministers of Education Organization Regional Centre for STEM Education (SEAMEO STEM-ED), is a collaborative effort among educational organisations, institutions, and stakeholders in Cambodia, Indonesia, Malaysia, Kazakhstan, and Thailand. The initiative aims to advance STEM teacher education in the region. Building on commitments to capacity building, innovation, and evidence-based policy, this study reviews five research projects conducted by independent teams alongside the participating countries' implementation teams to identify common factors influencing project outcomes. These projects examine the effectiveness of the SEA-TEP programme, assess the quality and relevance of learning units integrating the Claim, Evidence, and Reasoning (CER) and modelling frameworks, strengthen collaborative research capacity, and support evidence-informed decision-making for education reform. A shared research framework and common instruments were developed through facilitated partnerships, enabling comparable analyses while allowing contextual adaptation. Findings indicate that integrating CER and modelling approaches significantly enhances conceptual understanding, critical thinking, and the application of STEM concepts. Cross-country collaboration strengthened professional networks, encouraged innovation in instructional design, and improved STEM learning approaches for learners. The research also highlights key strengths, including the adaptation of learning units to diverse educational and cultural contexts, the establishment of professional learning communities, and active stakeholder engagement to sustain programme outcomes. However, challenges remain, including resource disparities, differences in institutional readiness, and the need for continuous professional development to support long-term integration of these pedagogical approaches. By embedding structured frameworks such as CER and modelling into training programmes, SEA-TEP addresses immediate capacity needs while laying a sustainable foundation for enhancing STEM education quality, fostering pedagogical innovation, and informing policy across diverse education systems in the region. Implications for future cross-country teacher education programmes include shared implementation and research practices, improved resource allocation, and sustained support for continuous professional development.

Keywords: Southeast Asian Teacher Education, STEM Education, CER and Modelling Framework, Regional Collaboration, Evidence-Based Decision Making, Policy Recommendations

1. Introduction

1.1 Background and Rationale

The quality of teacher education is a critical determinant in shaping the future of Science, Technology, Engineering, and Mathematics (STEM) learning and in fostering 21st-century skills among students. In Southeast Asia, diverse educational contexts and varying institutional capacities present opportunities and challenges for advancing teacher development. The Southeast Asian Teacher Education Programme (SEA-TEP), coordinated by the Southeast Asian Ministers of Education Organization Regional Centre for STEM Education (SEAMEO STEM-ED) and funded by Chevron, was established as a regional initiative to strengthen teacher education practices, promote innovative pedagogies, and provide evidence-based guidance for policy formulation and implementation.

A core focus of the SEA-TEP initiative is the integration of structured learning frameworks, specifically the Claim, Evidence, and Reasoning (CER) approach and modelling strategies to enhance conceptual understanding, critical thinking, and the practical application of STEM concepts. By engaging educational organisations, institutions, and stakeholders from Cambodia, Indonesia, Kazakhstan, Malaysia, and Thailand, the programme fosters cross-country collaboration, facilitates knowledge exchange, and strengthens professional learning networks in STEM education.

This paper introduces the SEA-TEP research initiative, outlining its objectives, collaborative design, and methodologies for evaluating programme effectiveness. It further presents key findings, highlights strengths and challenges, and discusses implications for advancing STEM teacher education across the region. Through this initiative, participating organisations, institutions, and stakeholders demonstrate the value of regional partnerships in driving systemic change, fostering innovation, and promoting evidence-informed decision-making in teacher education.

2. Literature Review

2.1 STEM Teacher Education and 21st-Century Skills

Recent research highlights the critical role of STEM teacher education in equipping teachers to foster 21st-century skills among students, including critical thinking, problem-solving, collaboration, and digital literacy (AlAli, 2024; Dare et al., 2021). The preparation of teachers for these competencies extends beyond mastery of subject matter, requiring the development of pedagogical content knowledge and the capacity to implement inquiry-based instructional methodologies. A balanced emphasis on content and pedagogy enables STEM teacher education to prepare educators better to foster active, student-centred learning environments. These efforts align with international education goals, including the United Nations (UN) Sustainable Development Goals (SDGs), particularly SDG 4 on quality education, and with the Southeast Asian Ministers of Education Organization (SEAMEO)'s strategic priorities of promoting educational excellence and regional capacity-building (Southeast Asian Ministers of Education Organization, 2021; United Nations Department of Economic and Social Affairs, n.d).

Empirical studies suggest that innovative, evidence-based professional development strengthens teachers' professional engagement, instructional planning, and confidence in implementing scientific approaches (Meng, 2023; Colclasure et al., 2022). In particular, inquiry-based training encourages teachers to design lessons where students generate hypotheses, test ideas, and analyse results, supporting deeper understanding of scientific concepts. Related evidence also indicates that such programmes can update teachers STEM knowledge and skills while building supportive school–university networks that enable idea-sharing, motivation, and ongoing professional support (Saat et al., 2021)

Building on these findings, pedagogical models such as the CER framework and scientific modelling serve as critical tools for fostering comprehensive teacher competencies. By guiding pre-service teachers to construct evidence-based explanations and visualise and represent complex STEM concepts, these approaches advance cognitive and practical skills. Integrating such frameworks within teacher education programs strengthens conceptual understanding and enhances educators' ability to deliver effective, reflective, and student-centred STEM instruction. To sustain and scale these gains, research points to collaborative professional learning, such as professional learning communities and cross-institutional networks, together with coherent, adequately supported professional development as key conditions for impact (Darling-Hammond et al., 2017; Desimone, 2009).

2.2 Integration of CER and Modelling Framework in STEM Education

STEM pedagogy is increasingly characterised by integrated, design- and problem-centred learning that connects disciplinary ideas with authentic contexts and collaborative practice (Portillo-Blanco et al., 2024). Recent syntheses show that well-designed integrated STEM tends to yield positive effects on achievement and higher-order thinking, while also revealing heterogeneous impacts moderated by implementation choices such as the type of integration and the balance of inquiry and design (Zhou et al., 2024). Within this approach, the science and engineering practices, especially constructing explanations, using models, and engaging in argument from evidence, provide a unifying spine for classroom activity and assessment, aligning content goals with epistemic practices (National Research Council, 2012; National Research Council, 2013). Against this backdrop, pedagogies that explicitly scaffold reasoning with evidence, including scientific argumentation and model-based inquiry, naturally complement integrated STEM and provide a direct bridge to CER (Carroll, 2024; Li et al., 2022).

The CER framework is widely recognised as a powerful approach for strengthening scientific reasoning, argumentation, and conceptual understanding in science education (McNeill et al., 2006; McNeill & Krajcik, 2011; Imansharipova et al., 2025; Diola et al., 2025). By prompting learners to make a clear claim, justify it with appropriate evidence, and connect the two through logical reasoning, CER helps students analyse data, construct evidence-based explanations, and engage in reflective, critical thinking. A large-scale study involving 605 students show that CER can improve multiple components of critical thinking, including analysis, interpretation, inference, explanation, self-regulation, and is often well received by students because it aligns closely with lesson goals and supports higher-order thinking (Daraman et al., 2025). It also strengthens students' written scientific arguments and can foster more positive attitudes and interest toward science (Samosa, 2021).

When integrated with modelling, the CER framework further enhances learning by linking structured explanations with visual representations that help learners better understand complex or abstract STEM concepts (Valeeva et al., 2023; Lozada & Cortez, 2025; Buntha et al., 2024). Evidence from diverse educational contexts indicates that these approaches also support teachers by strengthening their confidence, refining instructional planning, and promoting more active student engagement through CER-based laboratory activities that clarify lesson structure and enhance participation (Wangmo et al., 2025). Given its adaptability across grade levels and subject areas, CER serves as a versatile and equity-focused strategy for improving instructional quality and student learning outcomes within evidence-informed STEM initiatives.

2.3 Evidence-Based Decision Making in Education

Evidence-based decision making has become a cornerstone of contemporary education reform, ensuring that instructional strategies, curriculum design, and policy decisions are grounded in empirical data and rigorous research (Owen et al., 2022; Slavin, 2020). Within the context of STEM teacher education, the approach facilitates continuous improvement by enabling educators to systematically monitor student outcomes, assess the effectiveness of instructional interventions, and refine pedagogical practices accordingly. Integrating monitoring and feedback mechanisms into professional development initiatives has enhanced teacher confidence, promoted reflective practice, and elevated instructional quality, aligning closely with SEA-TEP's overarching objective of connecting research, policy, and practice.

Despite significant progress in STEM teacher education, persistent challenges remain. These include sustaining innovative pedagogical approaches, mitigating disparities in access to teaching and learning resources, and aligning regional initiatives with the specific realities of diverse classroom contexts (Chari, 2024; Li et al., 2021). In particular, few studies have systematically evaluated the combined impact of the CER and modelling frameworks within cross-country professional development programmes. Similarly, limited longitudinal research tracks how such interventions influence teacher practices and student learning outcomes over extended periods. Addressing these gaps is critical for ensuring that STEM education reforms are practical and scalable across diverse educational settings.

The SEA-TEP initiative addresses these challenges by embedding structured pedagogical frameworks within teacher education and professional development programmes while fostering regional collaboration among participating countries (SEAMEO STEM-ED, 2024). By emphasising evidence-based approaches, SEA-TEP enhances instructional quality and supports the generation of actionable insights to inform policy and practice. The programme's research component facilitates systematic evaluation of pedagogical interventions, captures the experiences of educators across multiple contexts, and contributes to a growing body of knowledge on effective STEM teacher education. Through this integration of practice, research, and policy, SEA-TEP exemplifies a model for sustaining innovation, promoting equity, and advancing educational quality in STEM across the region.

2.4 Regional Collaboration and Professional Development

In recent years, Southeast Asian countries have placed increasing emphasis on developing STEM education to respond to rapid global changes and equip students with the skills required for the 21st century. Nevertheless, a recent study by Haniza et al. (2024) revealed that many nations across the region continue to encounter persistent challenges. These include a shortage of teachers with expertise in STEM disciplines, insufficient training opportunities for teachers in STEM subjects, and limited access to high-quality resources. To address these shared concerns, cross-border collaboration is promising for constructive and sustainable development.

Regional collaboration has become increasingly integral to advancing STEM teacher education, particularly in contexts where disparities in resources and expertise exist. Cross-border professional learning communities and networks enable teachers to share expertise, co-design curriculum, and access specialised resources at scale, with positive associations with teachers' efficacy and instructional change when collaboration is sustained, purposeful, and well-supported (Gartland & Gokpinar, 2024; Liu et al., 2025). Technology-enabled and online/hybrid professional development has expanded access to regional and cross-cultural exchange in digitally connected contexts while maintaining effectiveness when mentoring, active learning, and follow-up are built in (Huang et al., 2024). These findings underscore the significance of regional collaboration as a lever for equity and quality, provided implementation is carefully staged and resourced.

Empirical evidence further underscores the effectiveness of regional collaborations, highlighting the benefits of cross-cultural professional development. For instance, research by Wang et al. (2025) found that STEM educators participating in teacher training programmes demonstrated enhanced intercultural competence and a more sustainable approach to teaching innovation. By integrating local educational needs with international pedagogical frameworks, these programs empower educators to adapt and thrive in diverse teaching contexts, contributing to the broader goals of STEM education reform. Moreover, establishing networks reflects evidence that sustained, collaborative professional development and professional learning communities are associated with improved teaching quality and student outcomes (Cordingley et al., 2015). Building on these principles, SEA-TEP was launched as a regionally coordinated initiative that operationalises this model of collaboration at scale, exemplifying how cross-country partnerships can enhance professional development and instructional quality.

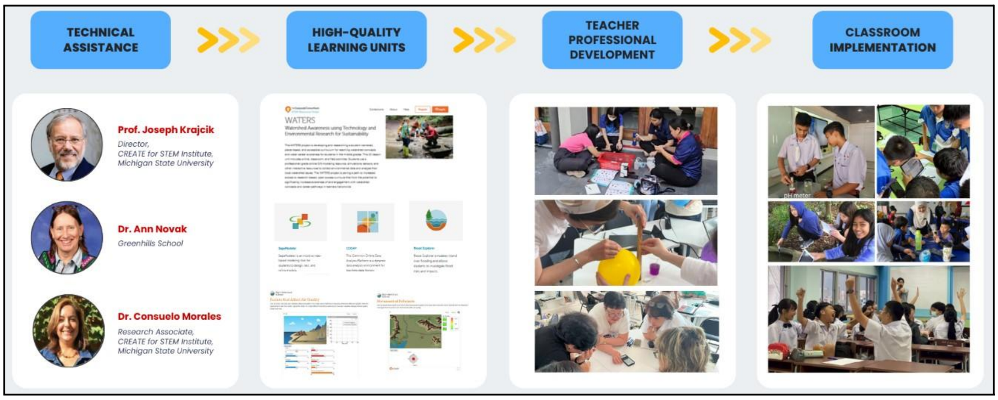
2.5 SEA-TEP Initiative and Collaboration

The SEA-TEP, initiated by SEAMEO STEM-ED, constitutes a significant regional initiative to strengthen STEM teacher education across Southeast Asia. Established in 2023, SEA-TEP seeks to address identified gaps in pre-service teacher education, particularly in effective pedagogy and classroom practice by adopting a STEM-focused approach to teacher preparation (SEAMEO STEM-ED, 2026). Implemented with ministries and strategic partners in Cambodia, Indonesia, Kazakhstan, Malaysia, and Thailand, the programme emphasises cultivating critical thinking, scientific practices, and problem-solving among pre-service and in-service educators by implementing innovative curricula and targeted professional training (SEAMEO STEM-ED, 2026). Notably, the programme had delivered professional development to over 120 educators from 24 universities and teacher development institutes, which was cascaded to more than 1,500 pre- and in-service teachers across 214 schools, evidencing a scalable regional model (SEAMEO STEM-ED, 2025; SEAMEO STEM-ED, 2026).

To broaden its impact, SEAMEO STEM-ED collaborates with partner institutions to integrate STEM learning units into national education systems, drawing on evidence-based pedagogical approaches such as the CER framework and scientific modelling. The research component of SEA-TEP further contributes to the knowledge base on effective teacher education and professional development by assessing programme outcomes, documenting participants' experiences, and generating insights to inform policy, pedagogical practice, and continuous improvement in STEM education. Figure 1 illustrates the overview implementation of the SEA-TEP initiatives.

Figure 1

Overview of the SEA-TEP Initiatives Interventions



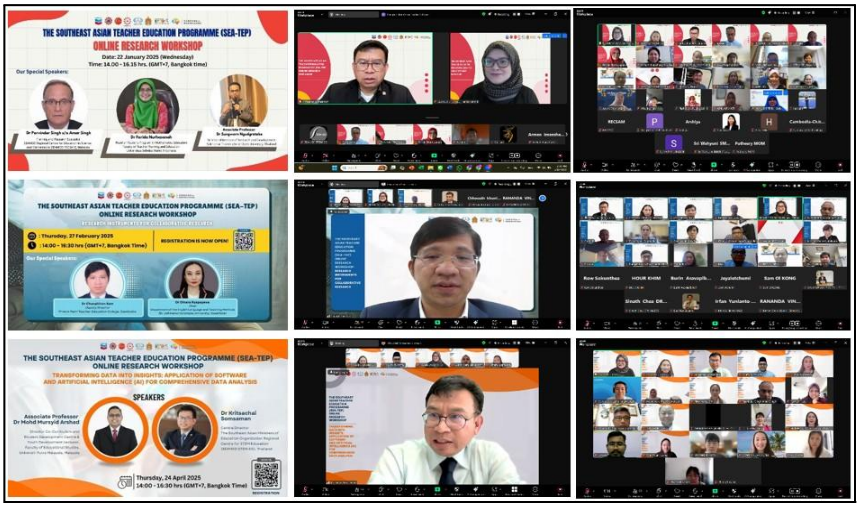
2.6 Research Studies Assessing the Effectiveness of the SEA-TEP Initiative

To evaluate the effectiveness of the SEA-TEP initiative, the research teams from each participating country were working closely with the implementation teams. The evaluation covers examining the quality and relevance of learning units incorporating the CER and modelling frameworks, enhancing collaborative support for research capacity, identifying supporting factors for the implementation of the programme, and promoting evidence-informed decision-making in advancing educational reform.

In support of these objectives, a series of online research workshops, as shown in Figure 2, was convened by SEAMEO STEM-ED to facilitate collaborative learning, exchange methodological expertise, refine research instruments across participating countries, and integrate the application of software and artificial intelligence (AI) for comprehensive data analysis. This collaborative engagement fosters the exchange of best practices among educators from diverse contexts, enriching the teacher preparation process and cultivating a regional community of practice dedicated to sustained advancements in STEM education.

Figure 2

Series of SEA-TEP Research Online Workshops



3. Methodology

The data used in this study were extracted from final summary research reports from five participating countries (Cambodia, Indonesia, Kazakhstan, Malaysia, and Thailand) and articles in SEA-TEP special issue of The Southeast Asian Journal of STEM Education (SAJSE) (see Appendix). Those reports were designed to evaluate the impact of the SEA-TEP initiative on STEM instructional practices and student outcomes. The studies aimed to provide a holistic understanding of SEA-TEP's effectiveness and contextual factors influencing STEM teacher education by capturing diverse perspectives across multiple countries and institutional contexts. Each country implemented its own research design in accordance with its respective educational and cultural context. Nevertheless, all participating countries shared a common objective to examine the potential effectiveness of the SEA-TEP initiative. In light of the evidence generated across countries, the present study sought to answer the following research questions:

RQ1: What research approaches and study contexts were used across participating countries?

RQ2: What evidence was reported regarding the effectiveness of the SEA-TEP initiative across participating countries?

RQ3: What strengths and implementation challenges of the SEA-TEP initiative were identified across participating countries?

4. Results

4.1 Research Approaches and Contexts

4.1.1 Research Design and Approach

To address these objectives, the researchers of the countries employed a mixed-methods research design across the five participating countries, guided by a shared analytical framework. These country-specific research designs are summarised in Table 1. The mixed-methods approach strengthened the robustness of the study by integrating quantitative and qualitative data, thereby enabling triangulation and enhancing the validity and reliability of the findings across diverse educational contexts. This approach allowed the study to examine both measurable outcomes in STEM competencies and nuanced, contextual insights into programme implementation, aligning with best practices in programme evaluation (Soicher et al., 2024; Nzabonimpa, 2023; Zhumabay et al., 2024). Furthermore, this approach provided a comprehensive perspective on the programme’s impact by integrating measurable outcomes with contextual experiences. This approach is consistent with best practices in programme evaluation, as outlined in recent literature (Nzabonimpa, 2023).

Table 1

Research Design and Approach for SEA-TEP Initiatives According to Countries

Country	Research Design and Approach
Cambodia	A mixed-methods approach incorporating a quasi-experimental design, action research, and a convergent parallel design, with data collected simultaneously.
Kazakhstan	Mixed-methods design evaluating the impact of professional development on instructional readiness.
Indonesia	Explanatory sequential mixed-methods design. Includes a quasi-experimental component using a non-equivalent control group design.
Malaysia	A mixed-methods explanatory sequential design, beginning with quantitative data collection followed by qualitative elaboration; it also incorporated a qualitative case study design for thematic exploration.
Thailand	Evaluative research using a mixed-methods approach.

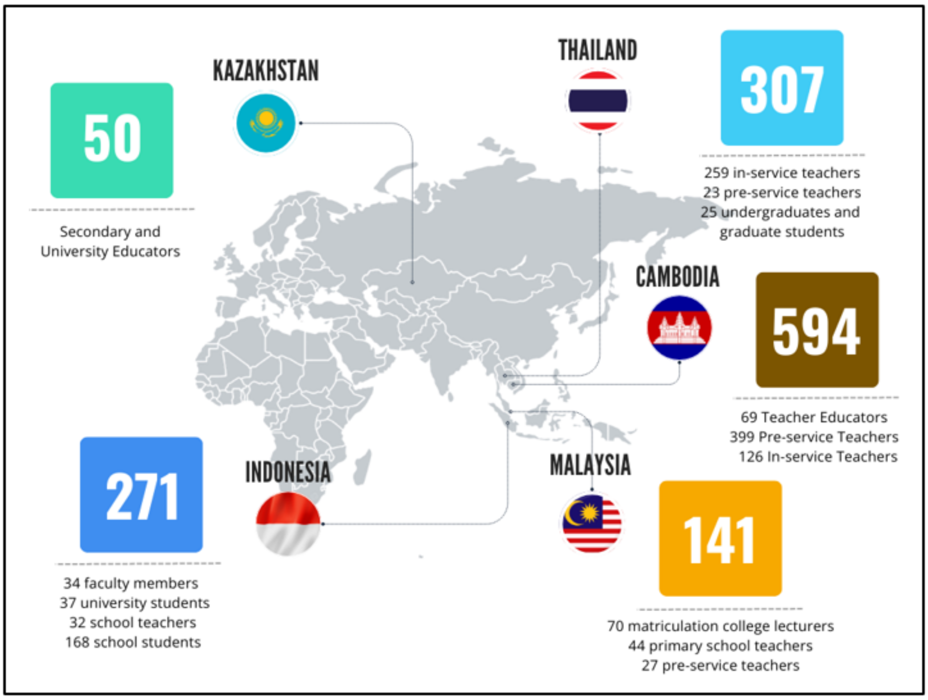
Following the research design and approach, the quantitative component focuses on measuring the influence of learning units incorporating the CER and modelling frameworks on students' and teachers' STEM competencies. This method aligns with recent studies highlighting the efficacy of mixed-methods designs in evaluating educational interventions, particularly in STEM education contexts (Zhumabay et al., 2024). The qualitative component explored the experiences, perceptions, and challenges faced by teacher educators and institutional stakeholders during the implementation of the SEA-TEP programme. This phase utilised interviews and focus group discussions (FGD) to gather in-depth insights, facilitating a nuanced understanding of the contextual factors influencing the programme's effectiveness. Such qualitative methodologies are essential for capturing the complexities of educational interventions and are widely recognised in recent academic research (Soicher et al., 2024; Margot & Kettler, 2019).

4.1.2 Participants and Sampling

The included studies drew participants from multiple groups, including students, teacher educators, pre-service and in-service teachers, and university faculty members. Figure 3 illustrates the participant distribution by country. In Indonesia, the initiative was spearheaded, with a total of 271 respondents participating in the study across three universities: Universitas Ahmad Dahlan (UAD), Universitas Islam Negeri (UIN) Raden Fatah in Palembang, and Universitas Sebelas Maret (UNS) in Surakarta. The study in Indonesia involved 34 faculty members, 37 university students, 32 school teachers, and 168 school students, employing proportional random sampling for quantitative metrics and purposive sampling to select specific schools and qualitative informants. Malaysia focused on 141 participants comprising 70 matriculation college lecturers, 44 primary school teachers, and 27 pre-service teachers, who were selected through convenience and purposive sampling based on their availability and direct involvement in the professional development phases.

Figure 3

Participants Based on Countries



The sample was composed of the Cambodia team involved a total of 594 individuals, including 69 educators, 399 pre-service teachers, and 126 in-service teachers, with a primary quantitative sample of 264 pre-service teachers from three national Teacher Education Institutions (TEIs), including the National Institute of Education (NIE), Phnom Penh Teacher Education College (PTEC), and Battambang Teacher Education College (BTEC), selected via purposive sampling. For the qualitative phase, a total of 90 pre-service teachers participated in focus group discussions, and 42 key informants were interviewed. In Thailand, the research included 307 educators, with 259 in-service teachers, 23 pre-service teachers, and 25 undergraduates and graduate students. The study used propensity score matching to balance the experimental and control groups for a robust evaluation. Kazakhstan engaged 50 teachers and university educators specialising in natural sciences from schools, colleges, and gymnasiums, with researchers analysing a dataset of 68 valid classroom observations to assess the programme's practical impact.

4.1.3 Data Collection Methods

Multiple data collection methods were employed to ensure comprehensive coverage of the SEA-TEP programme's effectiveness, capturing both measurable outcomes and in-depth contextual insights. A mixed-methods approach was adopted, integrating quantitative and qualitative techniques with different data collection tools involved to provide a holistic understanding of the programme's implementation and impact (Zhumabay et al., 2024; Soicher et al., 2024). Table 2 presents the data collection tools used for the SEA-TEP research based on countries.

Table 2

Table 2 presents the data collection tools used for the SEA-TEP research based on countries.

Country	Data Collection Tools					
	Test	Survey/ Questionnaire	Interview	Focus Group Discussion	Observation	Artifact/ Documentation
Cambodia	✓	✓	✓	✓	✓	✓
Indonesia	✓	✓	✓	✓	✓	✓
Kazakhstan		✓	✓		✓	✓
Malaysia	✓	✓		✓	✓	✓
Thailand		✓	✓	✓		

Based on the review, for the quantitative component, structured surveys were administered to pre- and in-service teachers to assess their knowledge, skills, and application of the CER and modelling frameworks. The surveys included closed-ended and *Likert*-scale items, enabling the measurement of competence, confidence, and instructional readiness. For example, participants were asked to rate their ability to guide students in formulating evidence-based scientific explanations. These quantitative instruments provided objective evidence of the programme's impact on teacher and student STEM competencies (Bush et al., 2022).

Qualitative data which have been collected in SEA-TEP research study were collected through interview sessions employing FGD and key informant interviews (KIIs), with teacher educators, pre- and in-service teachers, and university faculty members. These methods explored participants' experiences, perceptions of the frameworks, and institutional practices supporting STEM teacher education. Classroom observations complemented these data, allowing researchers from participating countries to directly examine instructional practices, student engagement, and the integration of CER and modelling principles in lesson delivery, as shown in Figure 4.

Figure 4

Classroom Observations in SEA-TEP Research

Additionally, document analysis of lesson plans, curriculum modules, and institutional reports provided tangible evidence of alignment with the frameworks. The combination of surveys, interviews, observations, and document review facilitated comprehensive triangulation and a nuanced understanding of programme implementation and effectiveness (Nzabonimpa, 2023; Zhumabay et al., 2024).

4.1.4 Data Analysis

The data collected from multiple sources were systematically analysed to generate comprehensive insights into the effectiveness of the SEA-TEP programme. This approach allowed the country's research team to identify patterns, corroborate evidence across data sets, and capture the nuanced realities of programme implementation (Soicher et al., 2024; Zhumabay et al., 2024). The data analysis methods based on the countries are shown in Table 3.

Table 3

Data Analysis Methods Based on Countries

Country	Data Analysis Methods	
	Quantitative	**Qualitative**
Cambodia	• Descriptive statistics, Paired-sample *t*-tests to compare scores and *Cohen*'s *d* to determine effect sizes.	• Six- step thematic analysis of FGD transcripts and observation notes.
Indonesia	• Descriptive statistics, Simple regression, Normalised Gain (N-Gain), and Mann–Whitney U tests	• *Miles and Huberman* interactive model (reduction, display, verification) and thematic analysis.

Kazakhstan	• Paired t-tests, *Spearman*'s rank correlation for non-normally distributed data, and descriptive statistics.	• Content analysis of developed lesson plans and instructional videos.
Malaysia	• Descriptive statistics, paired-sample t-tests, and Exploratory Factor Analysis (EFA) to validate instruments.	• Inductive content analysis and *Braun and Clarke*'s six-step thematic framework.
Thailand	• Propensity Score Analysis (matching treated/control groups), independent samples t-tests, and descriptive means.	• Thematic content analysis of the interview data

According to Table 3, quantitative survey data were analysed using descriptive statistics, including mean scores, frequency distributions, and percentage breakdowns, to assess pre- and in-service teachers' knowledge, skills, and application of the CER and modelling frameworks in most of the countries. For example, the study showed that Malaysian educators felt significantly confident in their ability to teach STEM content effectively (*Mean* = 3.09) and believed they could positively influence student attitudes toward the subject. Inferential statistics, such as paired-sample t-tests, were employed where appropriate to examine significant differences between pre- and post-intervention results, providing robust evidence of programme effectiveness (Marshall & Jonker, 2011).

Multiple researchers conducted thematic coding to ensure inter-rater reliability and reduce interpretative bias (Nzabonimpa, 2023). The reviews of the findings report also highlight that interview data were transcribed, coded, and subjected to thematic analysis. Recurring themes and subthemes such as "*integration of CER into teaching practice," "institutional support mechanisms*," and "challenges in adapting modelling frameworks to local contexts" were identified. Teacher educators described using real-life phenomena, including regional climate change impacts, to apply CER principles in classroom discussions. For instance, in Indonesia and Cambodia, water quality serves as a primary context for CER due to its cultural relevance and status as a pressing regional environmental challenge.

Observational data were analysed using structured coding sheets aligned with the study's conceptual framework. This analysis focused on the frequency and quality of CER and modelling practices in classrooms, including the use of scientific models to predict outcomes and scaffolded questioning to encourage student reasoning. Observational patterns were compared with interview and survey findings to assess consistency and reinforce validity.

Some of the cases, document analysis was conducted through content analysis of curriculum materials, lesson plans, and institutional reports, focusing on explicit and implicit references to CER and modelling. For example, in Cambodia, the program utilised localised thematic units adapted from Michigan State University, which were specifically designed to train educators in applying scientific modelling frameworks. From the review, the teacher training manual contained a dedicated lesson plan on constructing and evaluating scientific models, corroborating evidence from interviews and classroom observations regarding the programme's emphasis on modelling in the classroom.

By synthesising data from surveys, interviews, observations, and documents, the analysis provided a comprehensive understanding of the SEA-TEP programme's successes, challenges, and contextual variations across participating countries. This triangulated approach strengthened the validity of the conclusions and informed evidence-based recommendations for scaling and sustaining effective STEM teacher education practices (Zhumabay et al., 2024; Soicher et al., 2024).

4.2 Effectiveness of SEA-TEP Across Participating Countries

4.2.1 Effectiveness of the SEA-TEP Programme and Learning Units Integrating CER and Modelling Frameworks

The analysis of multiple data sources from the participating researchers demonstrated that the SEA-TEP programme was effective in enhancing both teacher and student competencies in STEM education across the participating countries. The results indicated significant improvements in pre- and in-service teachers' knowledge, skills, and confidence in applying the CER and modelling frameworks. Mean scores of the findings also revealed that teachers were better able to guide students in constructing evidence-based scientific explanations and facilitating inquiry-based learning activities. Table 4 provides a detailed review of the SEA-TEP initiative across Malaysia, Indonesia, Kazakhstan, and Cambodia, highlighting their core pedagogical frameworks and key impacts and findings.

The findings also indicated that integrating CER and modelling frameworks substantially improved pre- and in-service teachers' conceptual understanding, critical thinking, and problem-solving abilities in STEM education. For instance, the results from Kazakhstan confirm that even short-term, practice-oriented professional development can significantly shift instructional approaches. Statistical analysis showed a significant improvement in the application of the CER methodology after training (p = 0.042). Teachers became more confident and systematic in applying CER, transferring theoretical knowledge into practice to create environments where students were required to justify their assertions with empirical data, suggesting that participants became more adept at structuring lessons around claims supported by relevant data and logical reasoning.

Table 4

Core Pedagogical Frameworks, Key Impacts and Findings

Country	Core Pedagogical Frameworks	Key Impacts and Findings
Cambodia	CER, Modelling, and the 5E Model applied to thematic units like "*Health in Our Hands*", Scientific Modelling and Systems Thinking. 3-Dimensional (3D) Learning. Inquiry-Based Science Education (IBSE)	Profound increase in CER understanding (*Mean* = 56.06 to 97.50, p<.001). Large effect size (d = 2.20). Shift from "content delivers" to facilitators of inquiry.
Indonesia	STEM-PjBL and Project-Based Learning (PjBL) focused on Water Quality, 3D Learning [Disciplinary Core Ideas (DCI), Science and Engineering Practices (SEP), Crosscutting Concepts (CCC), CER and SAGE Modeler.	Significant CER skill improvement (*N-Gain* of 0.618 to 0.724 in experimental groups). 60.4% of academic variance explained by program-driven motivation and participation.
Kazakhstan	CER, PBL, SageModeler digital tools, and 5E Instructional Method.	Significant improvement in CER application (p = 0.042). Strong positive correlation (ρ = 0.758) between SageModeler use and active student participation.

Country	Core Pedagogical Frameworks	Key Impacts and Findings
Malaysia	CER, Scientific Modelling, and 3D Learning (DCI, SEP, CCC).	Significant improvement in pedagogical confidence and understanding of CER subcomponents ($p < .001$).
Thailand	CER and Modelling-Based Instruction (MBI)	CER and modelling-based instruction shows strong potential to improve science education quality with high post-training self-efficacy (*Mean*=4.38) and knowledge (*Mean*=4.22). Teacher questioning identified as a critical tool to stimulate reasoning.

Data from interviews reinforced these findings, with pre-service teachers highlighting that CER provided a clear structure for guiding student thinking processes, while modelling frameworks offered tangible tools for visualising and testing scientific ideas. For example, in Indonesia, students investigated water quality using indicators like pH, conductivity, and turbidity, transitioning from simple descriptive observations to sophisticated, analytically grounded claims. These investigations allowed students to connect environmental problems with experimental evidence obtained through hands-on testing. The findings in Thailand indicated that collaborative learning was significantly enhanced among teachers, leading to the formal recommendation that establishing teacher Professional Learning Communities (PLCs) is an important step for sharing best practices and ensuring the sustainability of modelling-based instruction.

Classroom observations indicated that teachers effectively applied CER and modelling techniques to scaffold student learning, encourage scientific reasoning, and promote active engagement. For instance, findings from Malaysia indicate that scaffolded lesson templates and rubrics functioned as essential "*pedagogical maps*", enabling teachers to organise the flow of instruction and reduce planning-related anxiety. In Cambodia, educators demonstrated advanced Pedagogical Content Knowledge (PCK) by successfully mapping the CER framework onto the 5E instructional model within localised thematic units such as "*Interactions*" and "*Water Quality*". Collectively, these findings suggest that SEA-TEP successfully enhanced STEM teaching competencies, strengthened institutional support for innovative pedagogy, and improved students' engagement and reasoning skills across diverse educational contexts.

4.2.1 Effectiveness of the SEA-TEP Programme and Learning Units Integrating CER and Modelling Frameworks

The next recurring theme of the findings review is the collaborative effort across countries. The SEA-TEP programme fostered robust regional collaboration, creating a platform for knowledge sharing and mutual capacity building in STEM teacher education. Through joint workshops, participants engaged in co-designing learning units that integrated CER and modelling frameworks, allowing for the blending of diverse pedagogical traditions with contemporary evidence-based practices. These sessions provided opportunities to exchange technical expertise and cultivate a shared vision for advancing STEM education in the region.

A key feature of this collaboration was the development of shared resources, lesson plans, and tools, which were adapted and trialled in each country's local context. For example, the research framework and lesson plan initially designed in a particular country were later modified for use in other classroom settings, incorporating locally relevant examples. These findings can be shown in Indonesia in which the research framework was modified for Junior Islamic Schools (Madrasah Tsanawiyah) by centring CER and PjBL on local environmental challenges like the "*Safety Drinks*" project. This adaptation ensured that scientific inquiry remained culturally authentic by aligning with the Islamic principles of environmental stewardship while maintaining the rigor of the CER framework. These adaptations showcased how collaborative design could respect cultural and contextual differences while maintaining pedagogical integrity.

PLCs established during the programme continued to operate beyond the formal workshop period, strengthening regional networks for ongoing STEM teacher development. Through regular meetings, participants reflected on classroom implementation, shared successes and challenges, and co-developed solutions to instructional barriers. Most educators noted that these cross-country exchanges broadened their perspectives on classroom practice and deepened their appreciation of diverse educational contexts. This sustained collaboration ensured that the benefits of SEA-TEP extended well beyond the initial training, fostering a long-term culture of shared learning and continuous professional growth.

4.3 Key Strengths of the SEA-TEP Programme

4.3.1 Effective Integration of CER and Modelling Frameworks

One of the key strengths of the SEA-TEP initiative based on the analysis is its effective integration of CER and modelling frameworks into STEM teacher education. These structured pedagogical approaches were purposefully embedded in training modules to bridge the gap between theoretical knowledge and practical classroom application. Thematic analysis of participant feedback revealed that this dual-framework approach significantly enhanced pre-service teachers' ability to engage in critical thinking, scientific reasoning, and systematic problem-solving.

Participants reported that CER helped them construct well-organised, evidence-based explanations, enabling them to justify claims using relevant data and logical reasoning. For instance, students in Indonesia used CER and engaged in hands-on lab work to collect empirical data, such as measuring the time (in seconds) required for a visible change to occur at varying temperatures. Similarly, in Kazakhstan, the use of digital tools like SageModeler further supports this process, enabling students to test hypotheses and visualise abstract concepts in a dynamic learning environment. Such modelling activities are often integrated with the CER framework, creating an iterative inquiry cycle where students generate evidence to justify their scientific assertions. This approach has been found to strengthen student engagement and foster the critical thinking necessary for students to "think and act like scientists".

The combined use of CER and modelling ensured that innovative teaching practices were introduced and meaningfully applied in real and simulated classroom contexts. This integration strengthened pre-service teachers' capacity to connect abstract scientific theories to tangible classroom activities, ultimately fostering deeper conceptual understanding among their future students. The initiative established a sustainable model for advancing evidence-based STEM pedagogy across diverse educational settings by embedding these approaches into the SEA-TEP training process.

4.3.2 Regional Partnership and Knowledge Exchange

Another prominent strength identified through thematic analysis is the strong emphasis on regional partnership and knowledge exchange fostered by the SEA-TEP initiative. Bringing together teacher educators, pre- and in-service teachers, and university faculty members from the programme created a vibrant cross-country knowledge exchange and mutual learning platform. This collaborative structure expanded professional networks and allowed participants to explore innovative teaching practices shaped by diverse cultural and educational contexts.

Insights from interviews and workshop discussions revealed that participants highly valued exposure to various pedagogical strategies. For example, Cambodian and Malaysian teacher educators introduced inquiry-based STEM approaches tailored to different class sizes, while the Indonesian counterparts shared approaches to integrating digital tools into STEM instruction. Such exchanges enabled participants to reflect critically on their methods, adapt effective practices, and address local challenges with fresh perspectives.

Based on the observations, the collaborative efforts also fostered a sustained sense of professional community. Through joint lesson plan development, online forums, and follow-up workshops, participants could maintain ongoing dialogue and support beyond the initial training sessions and partnership between countries. This continuity encouraged sharing classroom experiences, troubleshooting instructional challenges, and co-creating teaching resources.

The SEA-TEP’s regional partnership and collaboration approach significantly enhanced the quality and reach of STEM teacher education. By connecting educators across borders, the initiative advanced teaching practices and contributed to building a resilient network committed to long-term improvement of STEM education in the region.

4.3.3 Capacity Building and Professional Development

The next theme identified as a significant strength of the SEA-TEP initiative is its strong emphasis on building the capacity of teacher educators. Through a combination of workshops, mentoring sessions, and collaborative activities, the programme substantially enhanced educators’ confidence and competence in implementing innovative STEM pedagogies. These structured professional development opportunities created a supportive environment for participants to experiment with, adapt, and refine new teaching strategies within their contexts.

Thematic analysis revealed that participants developed a deeper understanding of CER and modelling frameworks, along with insights into their practical applications in the classroom. For example, teacher training is essential for effective implementation of CER and classroom modelling-based instruction in Thailand. Another key point is that the programme implemented in Cambodia integrated job-embedded coaching and mentorship to provide educators with the support needed to transition from traditional lecturing to inquiry-based facilitation. These sessions helped teachers overcome uncertainty, turning "mastery experiences" into a significant boost in instructional self-efficacy. This experiential approach ensured that professional learning was both theoretically grounded and practically oriented.

By strengthening the skills and knowledge of teacher educators, SEA-TEP’s capacity-building strategy improved the immediate quality of teacher preparation and laid the foundation for the long-term sustainability of innovative practices. In Malaysia, the initiative is recognised as a working model of scalable, cost-effective, and locally responsive professional development, while in Cambodia, the integrated approach of workshops and job-embedded coaching is viewed as a viable blueprint for scaling to all Teacher Education Institutions (TEIs) across the country. This scaling is supported by the alignment of the programme with national policy directives like the Teacher Policy Action Plan (TPAP).

4.3.4 Evidence-Based Approach and Practical Application

The thematic analysis identified SEA-TEP's emphasis on evidence-based practices as a key strength of the programme. By integrating research findings, continuous monitoring, and structured feedback mechanisms, the initiative ensures that instructional innovations are not only grounded in empirical evidence but also responsive to learners' evolving needs. This alignment between research and practice helps bridge the gap between theory and classroom application, making STEM teacher education more effective and contextually relevant.

Participants reported that applying data-driven insights, including formative assessment results, student performance trends, and peer feedback enabled them to refine lesson plans, adapt instructional strategies, and make informed pedagogical decisions. For example, in Kazakhstan, expert video observations were critical for identifying a strong positive correlation (ρ = 0.758) between the use of Sage Modeler tools and active student participation. This provided actionable evidence that digital tools directly reduced student passivity.

This evidence-based approach also fosters a culture of reflective practice, encouraging educators to critically evaluate the effectiveness of their methods and make adjustments based on measurable outcomes. For the case of Indonesia, structured observations using a specialised protocol allowed researchers to document how the "See-Think-Wonder" strategy functioned as an effective bridge for students moving from simple observations to sophisticated claims. This provided teachers with the specific insight that consistent scaffolding was the primary mediator for student success. As a result, participating institutions are better positioned to adopt sustainable, research-informed improvements in STEM teacher education, ensuring that teaching strategies remain innovative and impactful over time. The summary of the key strength themes based on countries are shown in Table 5.

Table 5

Key Strengths Themes Based on Countries

Country	**Key Strengths Themes based of the Countries**			
	Effective Integration of CER and Modelling Frameworks	**Regional Collaboration and Knowledge Exchange**	**Capacity Building and Professional Development**	**Evidence-Based Approach and Practical Application**
Cambodia	Pre-service teachers' CER understanding scores rose significantly from a mean of 56.06 to 97.50 ($p < .001$). Educators successfully mapped CER onto the 5E instructional model and specific subject applications.	Localisation of Michigan State University materials into Khmer ensured institutional relevance. DRI and three TEIs collaborated on research and implementation.	Significant gains in teacher self-efficacy (d = 2.09) were driven by "*mastery experiences*" during classroom trials. Professional Learning Communities (PLCs) were described as a "*family*" that reduced isolation.	A mixed-methods action research design involved 264 pre-service teachers. Community-connected investigations, including water quality testing, triggered high student engagement and unprompted inquiry.

Country	**Key Strengths Themes based of the Countries**			
	Effective Integration of CER and Modelling Frameworks	**Regional Collaboration and Knowledge Exchange**	**Capacity Building and Professional Development**	**Evidence-Based Approach and Practical Application**
Indonesia	Experimental groups receiving explicit instruction achieved *N-Gain* of 0.618 to 0.724 in scientific argumentation. The Claim component saw the highest mastery improvements (up to 89%).	Supported by SEAMOLEC, the initiative aligned STEM education with Islamic environmental values within the Madrasah system with the support from the universities.	STEM-PjBL increased teacher confidence by providing empirical data to support students' opinions. Success was attributed to systematic scaffolding, specifically the "*See-Think-Wonder*" strategy.	Adopted an explanatory sequential design across three university clusters. Regression analysis showed 60.4% of academic variance was explained by program-driven motivation and participation.
Kazakhstan	Statistical analysis revealed a significant improvement in the application of the CER methodology post-training (p = 0.042). SageModeler digital tools showed a strong positive correlation (ρ = 0.758) with active student activity.	Developed by "*Caravan of Knowledge*", aligning with the national Society 5.0 strategy. Encouraged peer reflection through national and international collaboration.	PD shifted teacher mindsets toward evidence-driven and technology-enhanced instruction. Modelling was associated with deeper teacher reflection (r = 0.29), aiding instructional decision-making.	Researchers utilised expert video observations to triangulate data against teacher self-assessments. Interaction and CER application were identified as the strongest predictors of student engagement.
Malaysia	Participants achieved statistically significant gains in understanding CER subcomponents (mean gains > 2.4 points, p < .001). Integration of 3D Learning simplified abstract concepts like heat transfer through iterative representational tools.	Managed by SEAMEO RECSAM, the programme shared its findings at regional forums, including "*Thai CER 2025*". Teachers utilised active online groups to sustain collaboration post-training.	Pedagogical confidence was a major strength (cited by 34% of participants), enabling teachers to facilitate student-led discussions. Structured lesson templates acted as "*pedagogical maps*".	The study used an explanatory sequential design to validate program scalability. Application to real-world contexts, such as air pollution, improved the organization of student lab reports.
Thailand	CER and modelling techniques were directly aligned with the Thai National Curriculum to develop 21st-century skills. The frameworks showed strong potential to improve overall quality in science education.	Fostered high-level partnerships between CU, NU, and KMUTT. Results contributed to a regional evidence base during international sharing events.	Trained 307 educators who demonstrated high self-efficacy (*Mean*=4.38) and knowledge (*Mean*=4.22). The project produced a free online course on 3D learning and CER.	Utilised propensity score analysis and interviews to assess effectiveness. Identification of teacher questioning as a critical guiding tool to stimulate student reasoning.

4.4 Challenges in the Implementation

While integrating the CER and modelling framework and the SEA-TEP initiative have shown promising results in the five countries, several challenges persist. Based on the reviews, disparities in resources, differences in institutional readiness, and the need for continuous professional development are among the key obstacles that need to be addressed to ensure the sustainability and scalability of these initiatives, as shown in Figure 5.

Figure 5

Challenges in the SEA-TEP Implementation

4.4.1 Resource Disparities between Countries

Analysis of the SEA-TEP initiative and integrating the CER and modelling frameworks revealed several key themes related to the programme's challenges. One prominent theme was varying access to teaching and learning resources across institutions. Differences in technological tools, laboratory facilities, and instructional materials affected the consistency and quality of programme implementation, highlighting the need for targeted support to ensure equitable participation. Institutions with greater resources could more fully adopt innovative STEM teaching practices, while those with limited resources faced difficulties in applying CER and modelling frameworks consistently. This theme highlights the importance of targeted support and equitable resource allocation to ensure that all institutions can benefit from the initiative.

For example, while some institutions experienced constraints due to limited access to laboratory equipment and digital simulation tools, these challenges present opportunities for growth and capacity building for this programme. However, institutions in Thailand and Malaysia, with better-equipped classrooms and access to the educational platforms, were able to implement CER-based lessons and modelling exercises more effectively. This theme underscores the importance of targeted support and equitable resource allocation to ensure that all institutions consistently implement innovative STEM pedagogies.

4.4.2 Institutional Readiness and Time Constraints

Another recurring theme was the variation in institutional capacity and preparedness. Differences in teacher educators' experience, familiarity with innovative STEM pedagogies, and organisational structures influenced how effectively initiatives could be implemented. Institutions with stronger readiness were able to adopt CER and modelling frameworks more fully, while others encountered barriers to integration. Time constraints have also posed a notable challenge in implementing the SEA-TEP programme. Coordinating activities among participants, aligning schedules for workshops, implementation tasks, and collaborative efforts, and adhering to project deadlines often limit the depth of engagement and reflection that participants can achieve.

Differences in experience, familiarity with STEM pedagogies, and organisational preparedness influenced how CER and modelling frameworks could be successfully integrated into teacher education. Institutions with strong readiness could implement the frameworks more effectively, while others required additional guidance and support. Addressing this theme is critical for ensuring that innovative pedagogical practices are adopted consistently and sustainably across different contexts.

For instance, teacher educators in Indonesia recognised the theoretical benefits of CER and modelling approaches. The participants expressed enthusiasm for building their skills in facilitating collaborative, inquiry-based lessons and presenting professional growth and capacity development opportunities. Meanwhile, universities in Kazakhstan showcased strong readiness by successfully integrating CER and modelling frameworks into their existing curricula, facilitating discussions, and mentoring new educators. These examples illustrate that fostering institutional readiness and supporting skill development are key enablers for successfully adopting and scaling pedagogical innovations across diverse contexts.

4.4.3 Sustainability and Scalability

A third theme emphasised the critical importance of ongoing professional development. Teacher educators expressed the need for sustained training, mentorship, and collaborative support to maintain pedagogical innovations, strengthen instructional practices, and scale the initiatives effectively. Across themes, the challenge of sustaining and expanding the programme emerged as central. Ensuring long-term impact requires addressing disparities, enhancing institutional readiness, and embedding professional development within institutional practices.

Sustaining the SEA-TEP initiatives requires embedding professional development into institutional practices and ensuring long-term support for both educators and administrators. Thematic insights also point to the value of longitudinal research to assess the lasting impact of CER and modelling frameworks on pre-service teachers' critical thinking and STEM learning outcomes, as well as the need for strategies to overcome challenges, including scalable training programs and stronger institutional support.

For example, SEA-TEP workshops in Kazakhstan provided mentorship and collaborative sessions, which participants reported as essential for improving lesson design and instructional strategies. However, many educators noted the need for ongoing training beyond the initial workshops to maintain the quality of implementation. Thematic insights suggest that longitudinal research could assess the long-term impact of CER and modelling frameworks on students' critical thinking and STEM learning outcomes. Developing scalable professional development programs and strengthening institutional support will also be crucial to sustaining and expanding the initiative across Southeast Asia.

Future research should focus on longitudinal studies to assess the long-term impact of the CER framework on students' critical thinking and STEM learning outcomes. Additionally, exploring strategies to overcome the identified challenges, such as developing scalable professional development programs and fostering institutional support, will be crucial in advancing STEM education in the region.

5. Discussion and Implications for Policy and Practice

The findings indicate that SEA-TEP's regional, collaborative model provides a robust platform for transforming STEM teacher education. By combining structured pedagogical frameworks with cross-country collaboration, the initiative supports evidence-based policy formulation, enhances teacher capacity, and fosters the development of 21st-century skills among pre-service teachers.

5.1 Encourage Shared Implementation and Practices

The findings underscore the importance of shared implementation and research practices for strengthening both programme quality and the credibility of cross-country evidence. Establishing common pedagogical expectations (e.g., core features of CER and modelling-based learning units) and shared routines for planning, classroom trials, reflection, and revision can reduce variation in delivery while still allowing countries to adapt materials to local curricula and cultural contexts. In parallel, aligned research practices, such as shared outcome indicators, common instruments, and consistent reporting structures, support meaningful synthesis of effectiveness-related findings across diverse study designs and settings.

From a policy and practice perspective, education authorities and partner institutions should institutionalise these shared practices through a regional implementation guide and a minimum common evaluation package. This could include agreed templates for learning-unit design, monitoring tools for implementation fidelity, and a shared repository for resources and analytic support. Regular cross-country research clinics and professional learning community activities can further strengthen methodological capacity, promote knowledge exchange, and sustain improvements beyond the project period. Future research should examine how the degree of alignment in implementation and evaluation influences programme effectiveness and sustainability across contexts.

5.2 Promote Equitable Resource Allocation

The findings from the SEA-TEP research initiative provide several important implications for future research and educational practice. First, addressing resource disparities should be prioritised in research and practice. Future studies could investigate how variations in access to laboratory facilities, technology, and instructional materials influence the effectiveness of CER and modelling frameworks. Similarly, policymakers and institutional leaders should focus on equitable resource allocation to ensure that all teacher education institutions can implement innovative STEM pedagogies consistently.

Policies should ensure that all teacher education institutions can access adequate teaching and learning resources, including laboratory equipment, digital tools, and instructional materials. Targeted funding and support mechanisms can help reduce disparities and enable consistent implementation of CER and modelling frameworks across diverse contexts. Despite these challenges, effective time management, clear prioritisation of core tasks, and proactive planning have been essential strategies to ensure that SEA-TEP objectives are met while maintaining the quality of teacher training and research activities.

Enhancing institutional readiness is critical for the sustainability of the SEA-TEP initiative. Future research could explore strategies for building capacity among teacher educators, such as targeted training programs, peer mentoring, and knowledge-sharing networks. In practice, institutions should assess their organisational structures, curriculum flexibility, and faculty expertise to identify areas requiring support, ensuring that CER and modelling frameworks are integrated effectively into teacher education programs.

Education authorities should support institutions in assessing and improving their organisational capacity to implement innovative STEM pedagogies. This initiative may include providing guidance on curriculum design, establishing mentorship programs for teacher educators, and fostering institutional structures that facilitate the integration of evidence-based frameworks.

5.3 Support Continuous Professional Development

Education policies should support continuous and targeted professional development for teacher educators, focusing on applying CER and modelling frameworks, and inquiry-based STEM teaching. By providing flexible, scalable training programs and fostering collaborative workshops and peer-learning networks, institutions can enhance teaching capacity, encourage the sustained use of innovative pedagogies, and ensure that effective practices are consistently implemented over time.

Policymakers should promote cross-country collaboration and knowledge-sharing initiatives. Establishing platforms for joint research, workshops, and professional learning communities can enhance the quality of teacher education and foster innovation through shared practices and experiences. The importance of continuous professional development and long-term sustainability emerged as a key theme. Longitudinal studies are recommended to examine the sustained impact of CER and modelling frameworks on pre-service teachers' critical thinking, problem-solving abilities, and STEM learning outcomes. From a practical perspective, education systems should implement ongoing professional development programs, including workshops, collaborative sessions, and mentorship opportunities, to maintain high-quality implementation. Developing scalable and adaptable training modules will further support the expansion of these initiatives across diverse institutional contexts.

Education policy frameworks should emphasise evidence-based decision-making, ensuring that data and research findings guide curriculum design, teacher training, and program evaluation. By integrating continuous monitoring and evaluation mechanisms, education authorities can track progress, identify challenges, and make informed adjustments to improve the quality and effectiveness of STEM teacher education initiatives. This approach promotes accountability, supports sustainable pedagogical innovations, and ensures that interventions are responsive to the evolving needs of both educators and learners.

6. Conclusion

The SEA-TEP research initiative demonstrates the significant potential of regional collaboration and innovative pedagogical frameworks in transforming STEM teacher education across Southeast Asia. Integrating CER and modelling frameworks into pre-service teacher programs has enhanced participants' critical thinking, problem-solving, and scientific reasoning skills. The findings underscore that structured pedagogical approaches, combined with hands-on application and reflective practices, can meaningfully improve teaching and learning outcomes in diverse educational contexts.

Collaboration across Cambodia, Thailand, Indonesia, Malaysia, and Kazakhstan emerged as a key factor contributing to the success of SEA-TEP. Cross-country workshops, professional learning communities, and knowledge-sharing platforms enabled teacher educators and university faculty members to exchange ideas, adapt practices to local contexts, and build strong professional networks. Thematic analysis highlighted that such collaboration enriched pedagogical practices and fostered a sense of community and mutual support, which is critical for sustaining innovation in teacher education.

Despite these achievements, the study identified challenges that must be addressed to ensure long-term sustainability and scalability. Resource disparities, variations in institutional readiness, and the need for continuous professional development were recurring themes. Addressing these challenges requires targeted policies, equitable resource allocation, and ongoing capacity-building initiatives supporting educators and institutions in adopting and maintaining innovative STEM teaching practices.

The SEA-TEP initiative presents a compelling model for evidence-based, collaborative, and contextually responsive teacher education. Its success underscores the importance of integrating structured pedagogical frameworks with professional development, institutional support, and sustained regional collaboration. By fostering partnerships between SEAMEO centres, universities, and educational institutions, the initiative facilitates knowledge exchange, capacity-building, and the co-creation of innovative STEM curricula that respond to local and regional needs.

Furthermore, the initiative aligns closely with international and regional priorities, particularly the UN SDGs, including SDG 4 on inclusive and equitable quality education, as well as SEAMEO's strategic objectives of promoting educational excellence, regional cooperation, and sustainable learning outcomes. By translating these insights into policy and practice, the education systems can strengthen STEM teacher preparation, cultivate 21st-century skills among students, and achieve long-term improvements in teaching quality and student learning outcomes across the region.

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Appendix

Sources of Research Reports and Article Publications

No	Title	Author(s)	Year	Country	Description	Type of Report
1.	Evaluation of the Effectiveness and Efficiency of the Strengthening Teacher Education Program (STEP) in Enhancing the Quality of STEM-Based Education	Wahyudi, Ferdi Widiputera, Ihya Ulumuddin, & Grendi Hendrastomo	2025	Indonesia	A comprehensive evaluation of the STEP-STEM program's impact on instructional quality and student academic outcomes across three partner universities [Universitas Ahmad Dahlan (UAD), Universitas Islam Negeri (UIN) Raden Fatah in Palembang, Universitas Sebelas Maret (UNS) in Surakarta].	Final Summary Research Report
2.	Enhancing CER Approach, Modelling, and 3D Learning Among Pre-service and In-service Teachers in Malaysia	SEAMEO RECSAM	2025	Malaysia	Evaluates the effectiveness and scalability of SEA-TEP frameworks among 141 Malaysian educators using an explanatory sequential mixed-methods design.	Final Summary Research Report
3.	Navigating the Path to Regional Collaboration: The Southeast Asian Teacher Education Programme (SEA-TEP) Final Research Report	Heng Kreng, Chhoeuth Khunleap, Sam Chanphirun, Nov Sokmady, Kao Sovansophal, Chea Sinath, Meas Soth, Vong Pisey, Var Moni Satya, Choeun Huy, So Sokhon, Sat Thida, & Pov Ouk	2025	Cambodia	Evaluates PD effectiveness for 264 pre-service teachers across three national Teacher Education Institutions [Battambang Teacher Education College (BTEC), the National Institute of Education (NIE), and Phnom Penh Teacher Education College (PTEC)].	Final Summary Research Report
4.	Strengthening Teaching Education Program Research Report	Caravan of Knowledge	2024–2025	Kazakhstan	Assesses the impact of professional development on 50 teachers' motivation and readiness to integrate CER and digital modelling tools.	Final Summary Research Report

No	Title	Author(s)	Year	Country	Description	Type of Report
5.	Evaluating the Effectiveness of the Southeast Asian Teacher Education Programme (SEA-TEP) in Thailand	Sungworn Ngudgratoke & Siwaporn Poopan	2025	Thailand	A mixed-methods study analysing teacher self-efficacy and pedagogical knowledge gains in CER and modelling-based instruction.	Research Article
6.	Developing Claim-Evidence-Reasoning Skills Through STEM Based Problem-Based Learning: A Study of Water Quality in Junior Islamic Schools	Pandu Jati Laksono, Suhadi, Ravensky Yurianty Pratiwi, Faizatul Mabruroh Jamiatul Khairunnisa Putri, Miftahussa'adiah, Dini Afriansyah, Retni Paradesa, Arvin Efriani, Harisman Nizar, & Feli Ramury	2024	Indonesia	A sequential mixed-methods study focusing on the development of CER competencies through STEM-PjBL in Palembang madrasahs.	Research Article
7.	Implementation of a STEM-PjBL Module Grounded in CER to Enhance Junior Secondary Students' Scientific Argumentation Skills	Murni Ramli, Aliyya Syafa Safia, Dwi Oetomo, & Ari Syahidul Shiddiq	2026	Indonesia	Evaluates gains in scientific argumentation for students in Surakarta using a quasi-experimental nonequivalent control group design.	Research Article
8.	Enhancing Teacher Capacity in STEM Through Professional Development: A Case Study of the SEA-TEP Program in Malaysia	Parvinder Singh Amar Singh, Shamimah Parveen Abd Rahim, & Bala Murali Tanimale	2025	Malaysia	A qualitative case study exploring teacher confidence, collaborative reflection, and implementation enablers for 141 participants.	Research Article
9.	Enhancing STEM Teaching Through CER, PBL, and Modeling in Teacher Professional Development in Kazakhstan	Sayinov D, Imansharipova A., & Ryspayeva D	2025	Kazakhstan	Evaluates how effectively participants integrate STEM methods and explores the relationship between lesson planning quality and classroom outcomes.	Research Article

No	Title	Author(s)	Year	Country	Description	Type of Report
10.	Supportive Factors for Implementation of SEA-TEP in Malaysia	Nanthini Jayaram, Shamimah Parveen Abd Rahim, Sanura Jaya, Parvinder Singh Amar Singh, & Shazmin Kithur Mohamed	2025	Malaysia	Identifies qualitative themes such as pedagogical clarity and student feedback that positively influenced the implementation of the programme.	Research Article
11.	Navigating the path to regional collaboration: The Southeast Asian Teacher Education Programmes (SEA-TEP)	Chanphirun Sam, Khunleap Chhoeuth, Kreng Heng, Huy Choeun, & Sathya Chea	2026	Cambodia	Evaluates the effectiveness and implementation of the SEA-TEP, a collaborative PD initiative in Cambodia aimed at enhancing pre-service teachers' capacity in modern, inquiry-based STEM pedagogies	Research Article
12.	Southeast Asian Teacher Education Programmes (SEA-TEP) Final Sharing and Reflection	Sungworn Ngudgratoke & Siwaporn Poopan	2025	Thailand	Outlines an evaluative study of the SEA-TEP research initiative in Thailand, which focuses on the effectiveness of CER and modelling-based instruction in science education. The study identifies how these pedagogical approaches enhance student reasoning, classroom engagement, and collaborative learning.	Final Research Sharing

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EMPOWERING MALAYSIAN TEACHERS THROUGH SEA-TEP: INSIGHTS INTO SUPPORTIVE IMPLEMENTATION FACTORS

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ABSTRACT

This study investigates the supportive factors facilitating the implementation of the Southeast Asian Teacher Education Programme (SEA-TEP) in Malaysia, focusing on the perspectives of 141 pre-service and in-service teachers. Qualitative data were analysed thematically to address the research objective and questions, particularly in identifying additional factors that most positively influenced teachers' ability to implement SEA-TEP and how these factors shaped their teaching practices. As SEA-TEP emphasises key STEM pedagogical approaches such as the Claim–Evidence–Reasoning (CER) framework and three-dimensional (3D) learning models, the study explored how these frameworks were integrated and supported in classroom practice. Five key themes emerged: increased teacher confidence, enhanced student engagement, greater pedagogical clarity through SEA-TEP tools, alignment with curriculum requirements, and motivational support through recognition and community. These themes are illustrated through relevant narrative quotations from participants. The findings show that SEA-TEP strengthened teachers' confidence and motivation, enhanced inquiry-driven classroom interactions, provided clearer instructional guidance aligned with curricular standards, and fostered supportive communities of practice. The results are discussed in relation to SEA-TEP's broader objectives and the advancement of regional STEM education. Beyond the SEA-TEP programme itself, this study contributes insights into how internal, social, and contextual supports interact to sustain STEM pedagogical reform in resource diverse Southeast Asian education systems. The findings highlight the importance of designing STEM professional development that builds teacher confidence, aligns with curricular demands, and fosters communities of practice, offering implications for policymakers, professional development providers, and school leaders seeking to scale effective STEM initiatives across the SEAMEO region.

Keywords: SEA-TEP, CER, 3D Learning, Supportive Factors, Classroom Implementation

1. Introduction

In Southeast Asia, where student achievement gaps are still a problem, it is very important to improve the teaching of science and mathematics (Maamin et al., 2021). Educational stakeholders in Malaysia, like those in other countries in the region, know that better teacher training is the key to better student outcomes (Ahmad et al., 2018). Recent regional evaluations have revealed inconsistent performance in science and mathematics at the primary level, emphasising the necessity for enhanced teacher support and instructional quality (UNICEF & SEAMEO, 2020). Research demonstrates that equipping teachers with effective pedagogical frameworks can markedly enhance student learning; for instance, the incorporation of inquiry-based methodologies such as the Claim-Evidence-Reasoning (CER) framework has been proven to improve students' analytical abilities. (Siverling et al., 2021) But many traditional teacher education programmes don't have the resources or training they need to use these frameworks on a large scale (Gardner et al., 2019). This challenge has led to efforts to change how teachers are trained in the area.

One such effort is the Southeast Asian Teacher Education Programme (SEA-TEP), which is a joint effort by regional organisations to improve STEM teacher education in several countries. The goal of SEA-TEP is to give both new and experienced teachers structured professional development in core STEM teaching practices, such as CER and three-dimensional (3D) learning models. SEA-TEP wants to help teachers become better at inquiry-based, student-centred teaching by focusing on lesson study, hands-on workshops, and mentoring. In the end, the goal of the programme is to create a new generation of teachers who can help students improve their higher-order thinking and problem-solving skills, which will help resolve systemic problems with the quality of education.

The Malaysian government, recognising the critical need for an enhanced STEM-capable workforce in an era of rapid technological advancement, has also prioritised the establishment of a robust framework to guide educators in implementing effective STEM teaching practices (Lim & Chongo, 2025; Karpudewan et al., 2022). Policymakers in Malaysia have therefore advocated for the integration of project, problem, and inquiry-based learning strategies to contextualise STEM lessons, thereby embedding knowledge, skills, and values essential for cultivating STEM practices (Karpudewan et al., 2022).

In Malaysia, SEA-TEP has been implemented as a pilot to assess its effectiveness and scalability. A mixed-methods research study was conducted to evaluate several SEA-TEP outcomes, such as teachers' understanding and use of CER and three-dimensional (3D) learning models, the integration of STEM units into practice, and the identification of factors that support or impede implementation. This paper focuses on the qualitative insights derived from a pilot implementation of the Southeast Asian Teacher Education Programme in Malaysia. Specifically, we examine the additional, less-explored factors, beyond traditional considerations like resources, administrative support, and peer collaboration, that Malaysian pre-service and in-service teachers identified as most conducive to integrating SEA-TEP methodologies into their teaching practices. By illuminating these previously underexplored teachers identified enablers, this study addresses the existing literature gap and contributes to a more comprehensive understanding of effective STEM professional development, aligning with broader Malaysian initiatives to reform segmented STEM teaching into integrated approaches, with relevance for STEM professional development initiatives across Southeast Asia.

1.1 Research Objective

What factors are perceived as most supportive in implementing SEA-TEP?

1.2 Research Questions

1. Can you describe other factors (apart from resources, administrative support, peer collaboration) that have most positively influenced your ability to implement SEA-TEP in your teaching?
2. How have these factors impacted your teaching practices?

2. Methodology

2.1 Research Design and Context

This study is part of a larger mixed-methods research project evaluating the SEA-TEP pilot in Malaysia. This paper will particularly focus on supportive factors for implementation; we draw on the qualitative components of the study. An open-ended survey was administered to participants after they had engaged with SEA-TEP training and applied its approaches in their teaching.

2.2 Participants

A total of 141 participants took part in the study, including both pre-service and in-service educators. The sample comprised 27 pre-service teachers, 44 primary school teachers, and 70 matriculation college lecturers. Participants were selected through convenience sampling based on their involvement in SEA-TEP and availability (Etikan, Musa, & Alkassim, 2016). While convenience sampling has limitations in generalisability (Creswell & Creswell, 2017), our sample included a diverse range of educational contexts, which helps provide a broad view of the supportive factors across different school levels. All participants completed the full sequence of the SEA-TEP programme and the associated research instruments (pre-test, post-test, and survey), ensuring that they had substantial exposure to the programme and could reflect on its implementation in practice.

2.3 Data Collection

2.3.1 Open Ended Survey Questions

Participants responded in writing to several open-ended questions probing various potential supportive factors as presented in Table 1.

Table 1

Research Questions and Associated Items Used

Research Question	Items
Can you describe other factors (apart from resources, administrative support, peer collaboration) that have most positively influenced your ability to implement SEA-TEP in your teaching?	1. Please describe how your personal motivation about teaching has influenced your implementation of SEA-TEP.
	2. How have professional communities contributed to your success in implementing SEA-TEP?
	3. In what ways has your institution's environment supported your efforts in applying SEA-TEP principles?
	4. How has students' engagement impacted your application of SEA-TEP methodologies? 5. Can you discuss any professional development experiences that have enhanced your ability to implement SEA-TEP?
How have these factors impacted your teaching practices?	1. Can you describe how professional development opportunities have affected your teaching practices in relation to SEA-TEP?
	2. How have your institution's policies influenced your approach to implementing SEA-TEP in your classroom?

	3. In what ways have technological resources supported / hindered your application of SEA-TEP methodologies?
	4. Can you discuss how feedback from students has shaped your teaching practices under SEA-TEP?
	5. How has involvement from the community or parents impacted your implementation of SEA-TEP strategies?

2.3.2 Data Analysis

The main approach employed for analysing the qualitative data was content analysis (Yazan & De Vasconcelos, 2016). This technique facilitated a systematic classification process for coding and identifying patterns or themes within textual data. The procedure comprised several essential stages:

All qualitative responses and texts were thoroughly reviewed to achieve a comprehensive understanding of the data. This initial phase enabled the researchers to identify preliminary ideas and potential coding schemes. An inductive coding approach was utilised, allowing codes to emerge directly from the data instead of being pre-established. This method is especially beneficial in exploratory research contexts where theoretical categories remain undeveloped (Thomas, 2006).

Each text was examined systematically, with significant units being assigned descriptive codes. Responses such as "*I now feel more confident applying CER in my science lessons" were coded as "Increased teacher confidence.*" After the coding process, codes were grouped into broader categories and themes through thematic grouping techniques (Braun & Clarke, 2021). Themes were analysed and adjusted to ensure internal coherence while maintaining distinctiveness from one another.

To enhance qualitative rigor and trustworthiness, additional strategies were applied during the analysis process. Credibility was enhanced through repeated reading of participants' written responses, careful examination of emerging themes, and the use of rich narrative quotations to illustrate each theme. Analytic consistency was further strengthened through team-based discussion of preliminary codes and themes, providing peer review and validation while reducing individual researcher bias. These strategies align with established qualitative trustworthiness frameworks emphasising credibility, dependability, and confirmability in thematic analysis (Lincoln & Guba, 1985; Braun & Clarke, 2021).

3. Results

The qualitative findings revealed a set of supportive factors that participants consistently cited as aiding their implementation of SEA-TEP in the classroom. These factors are coded into five themes as presented in Figure 1 and the frequency of participants by each theme is presented in the Table 2.

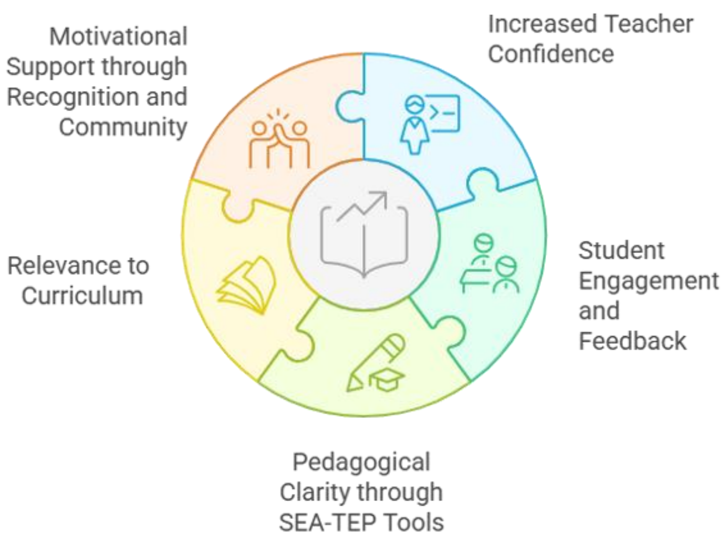
Table 2

Frequency of Participants by Theme

Theme	Number of Participants	Percentage (%)
Increased Teacher Confidence	48	34.0%
Student Engagement and Feedback	39	27.7%
Pedagogical Clarity through SEA-TEP Tools	26	18.4%
Relevance to Curriculum	18	12.8%
Motivational Support through Recognition and Community	10	7.1%
Total	**141**	**100%**

Figure 1

Coded Themes on Supportive Factors Enabling SEA-TEP Implementation



3.1 Increased Teacher Confidence

Forty-eight participants reported that the SEA-TEP experience had enhanced their confidence in trying innovative teaching strategies, particularly the CER framework and modelling techniques.

Selected Narrative Evidence for Increased Teacher Confidence Theme:

> "*I now feel more confident applying CER in my science lessons. I used to avoid open-ended questions, but now I encourage them.*"
>
> "*After the SEA-TEP workshops, I found myself less hesitant to try out new teaching strategies*."
>
> "*The programme empowered me to take risks in my teaching methods*."
>
> "*Implementing CER has become second nature, boosting my teaching confidence*."
>
> "*SEA-TEP has transformed my teaching mindset, making me more confident*."

One teacher noted that they "*used to be nervous about student-led discussions, but now [they] facilitate them with ease.*"

3.2 Student Engagement and Feedback

Thirty-nine participants highlighted increased student engagement and feedback as both an outcome of SEA-TEP methods and a reinforcing factor that motivated them to continue implementation.

Selected Narrative Evidence for Student Engagement and Feedback Theme:

> "*My students ask more questions now. They're curious, especially when we do CER. It makes me want to plan better*."
>
> "*I was surprised how well my pupils responded to the claim-making task. It sparked real discussion*."
>
> "*Positive reactions from students encourage me to continue using modelling*."
>
> "*Feedback from students indicates they enjoy the new teaching methods*."
>
> "*Implementing SEA-TEP has led to more lively classroom discussions*."

Teachers frequently mentioned being "*surprised*" or "*encouraged*" by how students responded to SEA-TEP–inspired lessons. One primary teacher said that a CER activity "*sparked real discussion*" among her pupils, which was both unexpected and gratifying. Another teacher mentioned that students' enthusiasm "*makes me want to plan better*."

3.3 Pedagogical Clarity through SEA-TEP Tools

Twenty-six participants reported that pedagogical clarity provided by SEA-TEP's structured tools and templates was a key support.

Selected Narrative Evidence for Pedagogical Clarity through SEA-TEP Tools Theme:

> "*I use the CER worksheet from the SEA-TEP module in almost every class. It gives my lesson a clear direction*."
>
> "*The lesson templates helped organise my thoughts. I feel like I'm teaching with purpose*."
>
> "*I finally understand how to structure reasoning tasks thanks to the SEA-TEP examples*."
>
> "*Having structured templates reduces the time I spend on planning*."
>
> "*Using SEA-TEP frameworks has made complex topics easier to teach*."

Using a CER worksheet in every class gave one teacher's lessons a "*clear direction*." Another teacher mentioned that with provided templates, they feel like they are "*teaching with purpose.*"

3.4 Relevance to Curriculum

Eighteen participants noted the alignment of SEA-TEP strategies with existing curriculum standards and assessment practices as a key supportive factor.

Selected Narrative Evidence for Relevance to Curriculum Theme:

> "*The programme fits with our curriculum standards. It didn't feel like extra work, it complemented what we already do*."

> "*Assessment tasks improved because SEA-TEP helps guide evidence-based thinking*."
>
> "*The CER format is easy to mark and aligns with HOTS-based evaluation*."
>
> "*SEA-TEP complements our existing curriculum frameworks*."
>
> "*Using SEA-TEP has enhanced the quality of our assessments*."

One teacher remarked that the programme *"didn't feel like extra work" because it matched curriculum standards. Another pointed out that using CER made it "easy to mark"* student work and aligned with HOTS evaluations.

3.5 Motivational Support through Recognition and Community

Ten participants described various forms of motivational support that sustained their commitment to SEA-TEP practices.

Selected Narrative Evidence for Motivational Support through Recognition and Community Theme:

> "*Being acknowledged by my trainer and seeing peers succeed inspired me to continue the SEA-TEP methods*."
>
> "*The WhatsApp group for SEA-TEP is still active, and it keeps me going*."
>
> "*Small recognition from students and colleagues pushes me to do better*."
>
> "*Sharing experiences with fellow teachers motivates me to improve*."
>
> "*Recognition from school leadership boosts my morale*."

Several participants also referred to ongoing communication with peers, such as through a WhatsApp group, as a form of continued support.

4. Discussion

This study focused on the supportive factors that Malaysian pre-service and in-service teachers perceived as aiding their implementation of the SEA-TEP initiative. Through a qualitative thematic analysis of participant narratives (Braun & Clarke, 2021), five key themes were identified: increased teacher confidence; student engagement and feedback; pedagogical clarity; relevance to curriculum; and motivational support. These themes provide a comprehensive overview of what teachers' need in order to translate professional development into classroom practice. Notably, the findings suggest that successful implementation is reinforced not only by external support such as resources or policies, but also by internal and social factors including confidence, student response, and professional community.

4.1 Increased Teacher Confidence as a Driver of Implementation

Teachers felt empowered by the training and resources, which translated into greater willingness to take risks and adapt their pedagogy. They often described feeling "*more equipped*" and "*less nervous*" in facilitating inquiry-based lessons after the programme.

This increased self-assurance enabled teachers to overcome prior hesitations such as fear of open-ended student questions or uncertainty in handling student-led activities and to adopt a more exploratory approach in their teaching.

These reflections show that building confidence was a pivotal support for implementation, as teachers who believe in their capacity to teach in new ways are more likely to sustain and expand their instructional practices.

By gaining familiarity with CER and other SEA-TEP methodologies in a guided setting, teachers felt a stronger sense of self-efficacy to apply these approaches in their own classrooms.

4.2 Student Engagement and Feedback as Reinforcing Mechanisms

Teachers observed that using the CER framework, modelling, and other interactive strategies made lessons more dynamic and sparked curiosity among students. Many described their students as more active, asking questions and participating in discussions at higher rates than before.

This positive change in student behaviour served as a powerful encouragement for teachers, creating a reinforcing feedback loop in which student engagement boosted teacher enthusiasm and commitment, which in turn led to further use of the SEA-TEP approaches.

The enjoyment expressed by students reassured teachers that the additional effort required to implement new techniques was worthwhile, reinforcing teachers' motivation and confirming the effectiveness of the SEA-TEP methods in practice.

4.3 Pedagogical Clarity through Structured SEA-TEP Tools

Participants appreciated that the programme provided concrete lesson-planning templates (for CER, modelling, etc.) and clear examples of how to execute these strategies. This structure helped demystify abstract concepts and gave teachers a sense of direction when designing their lessons. Many teachers noted that they finally understood how to organise inquiry-based lessons and reasoning tasks, which had previously felt daunting or confusing. The SEA-TEP materials (such as CER worksheets, lesson plan formats, and reasoning prompts) served as scaffolds that made their teaching more coherent and purposeful.

Teachers reported that the frameworks "*streamline the lesson planning process*" and bring "*consistency*" to their teaching methods. Notably, reducing planning time by following well-defined models was an added benefit, as it alleviated the workload burden of adopting new strategies.

4.4 Alignment with Curriculum and Assessment Practices

Rather than perceiving the programme's techniques as an "*add-on*" or extra work, many teachers found that CER and related strategies complemented their required syllabus and could be integrated into what they were already teaching. This relevance made it easier for them to adopt SEA-TEP practices, as the new methods did not clash with curriculum objectives or examination formats. Teachers did not have to significantly deviate from or overhaul their mandated curriculum; instead, they could infuse SEA-TEP methodologies into their lesson plans in ways that “streamlined” or even “enhanced” their usual teaching routines.

Some teachers also observed improvements in how they conducted assessments, for example by incorporating evidence-based reasoning in tests or by finding it easier to evaluate higher order thinking skills (HOTS) using the CER framework.

From these reflections, it is evident that curricular and assessment alignment of SEA-TEP content played an important role in easing implementation. The compatibility of SEA-TEP with national education goals and standards minimised resistance and gave teachers a sense of legitimacy and support for their changed practices. This suggests that SEA-TEP strategies reinforced competencies that the curriculum already values, thereby supporting teachers in meeting their professional requirements while innovating their pedagogy.

4.5 Motivational Support through Recognition and Community

Participants mentioned that recognition whether from programme trainers, school leadership, colleagues, or even students provided an emotional boost and validation of their efforts. For instance, being praised by a mentor or having a school administrator acknowledge their innovative teaching boosted teachers’ morale. Likewise, positive feedback or appreciation from students served as a reminder of the impact they were making, fuelling their motivation to continue. Recognition meets teachers’ psychological needs for competence and esteem; when a teacher’s efforts are noticed, it reinforces their sense of efficacy and professional identity.

Another important element was peer collaboration and community. The teachers formed networks during and after the SEA-TEP training where they continued to share experiences and support each other. Hearing a mentor or principal commend their classroom implementation validated teachers’ investment in change, while belonging to an active community helped reduce feelings of isolation and provided opportunities to troubleshoot, celebrate small wins, and maintain enthusiasm. Being part of a professional learning community made teachers feel they were not alone in overcoming challenges, and they drew inspiration from each other’s successes.

In sum, the social recognition and collegial support network functioned as a scaffold for teachers’ motivation, helping them persevere and innovate in their SEA-TEP journey, even when facing obstacles such as busy schedules or initial classroom management challenges associated with active learning.

5. Conclusion

Linking back to SEA-TEP’s objectives, the supportive factors observed are encouraging signs for programme scalability. Teachers are more likely to champion and spread SEA-TEP practices when they feel confident, see alignment with their daily teaching requirements, and are intrinsically motivated by student outcomes and peer relationships.

For educational leaders and policymakers in Malaysia and the region, this underscores the importance of creating enabling environments around teacher initiatives. By investing in teachers’ continuous development, recognising their efforts, and aligning reforms with curricular frameworks, we can empower teachers as change agents in STEM education.

In conclusion, the SEA-TEP experience in Malaysia demonstrates that teacher-centric support is fundamental to pedagogical innovation. As Southeast Asian countries strive to improve STEM education quality, programmes like SEA-TEP can serve as models, showing that when teachers are given the right mix of knowledge, tools, encouragement, and contextual alignment, they can indeed transform classroom practices. Future research could expand on these findings by examining how these supportive factors play out in different cultural or subject contexts, or by investigating the long-term impact on student learning. This study provides valuable insights for the development of future teacher professional development in the region, thereby enhancing the effectiveness of the STEM education ecosystem.

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MAKING DATA INQUIRY POSSIBLE IN RESOURCE-LIMITED CLASSROOMS: STRATEGIC USE OF CODAP TO FOSTER STATISTICAL REASONING IN A RURAL PRIMARY SCHOOL

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ABSTRACT

Integrating digital data tools in classrooms with limited technological infrastructure remains a major challenge for STEM education, particularly in rural schools where access to devices is scarce. In such contexts, meaningful technology integration depends not only on hardware availability but also on pedagogical design and teacher orchestration. This research examines how a primary school teacher redesigned the NASA paper helicopter activity to support statistical reasoning using the Common Online Data Analysis Platform (CODAP) in a one laptop–one screen classroom environment. The investigation involved fourteen 5th grade students in a rural Thai classroom. Data sources included instructional artifacts, teacher interviews, classroom documentation, and students' work samples. The teacher transformed the original engineering activity into a structured statistical investigation with repeated trials and pooled class data, enabling collaborative analysis through a shared CODAP interface. Evidence of technology amplification and transformation underscores the importance of purposeful integration in supporting students' statistical reasoning and data interpretation. Findings show that strategic classroom orchestration—such as rotational data entry, shared-screen discussion, and prompts—enabled students to collectively explore patterns in the dataset. Students' reasoning progressed from comparing individual results to recognising variation, averages, and associations within the aggregated data. These results highlight how thoughtful instructional design and collaborative data practices can support meaningful statistical inquiry, even in classrooms with severely limited technological resources.

Keywords: Resource-Constrained Classrooms, Statistical Reasoning, Technology Integration, Data Inquiry

1. Introduction

Digital technologies increasingly play a central role in contemporary education, enabling learners to engage with complex information, explore patterns in data, and construct evidence-based explanations through inquiry-oriented learning environments. Such technologies support forms of reasoning that resemble authentic scientific and professional practices, particularly within STEM education. However, the growing reliance on digital tools has also intensified concerns about the digital divide, a persistent disparity in access to technological infrastructure and opportunities for meaningful participation in digital learning environments (Warschauer, 2004). In many educational systems worldwide, including Thailand, a substantial number of schools still operate with limited access to digital devices and internet connectivity. This scarcity often compels teachers to rely on traditional, teacher-centred instructional approaches that emphasise procedural knowledge rather than exploratory reasoning, thereby reinforcing existing educational inequalities.

The challenge is particularly evident in small rural primary schools that serve communities with limited socioeconomic resources. In such contexts, schools often lack the financial capacity to provide students with individual digital devices. As a result, classrooms frequently operate with extremely constrained technological resources, where the teacher's personal laptop may function as the only available digital tool. Rather than the commonly envisioned one-to-one device model, these environments often reflect a "*one-to-many*" technology configuration, where a single device must support the learning of an entire class. Although this constraint is typically viewed as a barrier to technology integration, it also invites reconsideration of how digital tools can be pedagogically orchestrated to support collective inquiry rather than individual device usage.

Importantly, research on the second-level digital divide suggests that addressing inequities in technology use requires more than simply increasing hardware availability. Hargittai (2002) argues that disparities in digital participation are often rooted in differences in users' digital skills, pedagogical practices, and opportunities to meaningfully engage with technology. Similarly, Ertmer et al. (2012) emphasise that the educational value of digital tools depends heavily on how teachers integrate them within instructional design. Without purposeful pedagogical strategies, technology may be physically present in classrooms yet fail to contribute meaningfully to learning. In resource-constrained educational environments, this issue becomes even more pronounced, as limited access to digital tools may also restrict students' opportunities to develop data literacy and analytical competence, skills that are increasingly necessary for participating in data-driven societies and for advocating within marginalised communities (Fielding et al., 2025; Zapata-Cardona, 2025).

Within this context, the development of statistical reasoning and data literacy has become an essential component of contemporary STEM education (English, 2017). Statistics is no longer regarded merely as a branch of mathematics focused on procedural calculations; rather, it functions as a powerful epistemic tool for explaining natural phenomena, evaluating evidence, and supporting informed decision-making. For primary school students, early engagement with statistical reasoning provides a foundation for scientific inquiry by encouraging learners to interpret variability, analyse patterns, and construct evidence-based explanations. Research in statistics education further highlights the importance of exposing learners to informal statistical inference at an early stage, as this helps students view data not simply as numerical values but as evidence that can be used to support arguments and explanations (Makar & Rubin, 2009). Such experiences also contribute to reducing mathematics anxiety and promoting positive dispositions toward quantitative reasoning.

Digital platforms designed for dynamic data exploration can significantly support these forms of reasoning. One such tool is the Common Online Data Analysis Platform (CODAP), a web-based environment specifically developed to facilitate statistical investigation and data exploration in educational settings (Finzer & Damelin, 2014). CODAP allows learners to manipulate data through intuitive actions such as sorting, filtering, grouping, and visualising variables within interactive graphs and tables. These actions, often referred to as "*Data Moves,*" enable students to explore relationships between multiple variables and identify patterns within datasets (Hudson et al., 2024; Mojica et al., 2019). Through these processes, students can engage in exploratory data analysis, transforming raw data into visual representations that reveal variability and emerging trends (Konold et al., 2015). By automating the technical aspects of graph construction and data organisation, CODAP reduces procedural demands and allows students to concentrate on interpreting data and constructing explanations (Frischemeier et al., 2021).

Despite these pedagogical affordances, the implementation of data exploration platforms such as CODAP remains challenging in small rural schools where digital devices are scarce. When students must manually record, tabulate, and graph data using paper-based methods, much of the instructional time may be consumed by procedural tasks rather than analytical thinking.

As Hudson et al. (2024) note, excessive time spent on data organisation can limit opportunities for deeper reasoning about patterns and variability. Consequently, the potential benefits of digital data tools may appear unattainable in classrooms that lack sufficient technological infrastructure.

However, emerging perspectives in technology integration suggest that the effectiveness of digital tools in resource-limited settings depends less on the number of available devices and more on how teachers orchestrate their use within collaborative learning environments (Dillenbourg, 2013; Ertmer et al., 2012). When strategically implemented, even a single digital device can function as a shared analytical platform that supports collective data exploration and reasoning. In such contexts, technology shifts from being a personal learning device to becoming a catalyst for collaborative inquiry, where students collectively generate, analyse, and interpret data under the guidance of the teacher.

This study investigates how a teacher strategically redesigned a STEM activity to integrate CODAP in a small rural primary classroom characterised by severe limitations in digital infrastructure. The teacher, who participated in the SEA-TEP (Southeast Asian Teacher Education Programme) professional development workshop where the Claim–Evidence–Reasoning (CER) framework and CODAP were introduced, adapted a traditional engineering activity into a data-rich learning experience that supported statistical reasoning. Through deliberate instructional orchestration, collaborative data collection, and structured reasoning prompts, the teacher transformed a single digital device into a platform for whole-class data inquiry.

Using a qualitative single case study design, this research examines how strategic pedagogical design enables the productive use of CODAP in resource-limited classrooms. Rather than focusing on technological abundance, the study highlights how teacher orchestration, collaborative data practices, and structured reasoning prompts can enable meaningful engagement with data even in contexts where digital resources are scarce. By documenting how a teacher leveraged CODAP as a shared tool for reasoning, this study contributes to ongoing discussions about how educators can navigate the digital divide and promote statistical inquiry in under-resourced educational settings.

Using a qualitative single case study design, this research aims to:

1. Investigate how a teacher strategically redesigns a traditional STEM activity to integrate CODAP within a resource-constrained classroom environment characterised by a “one laptop–one screen” technological setup.
2. Examine how teacher orchestration and instructional scaffolding support collaborative data practices when CODAP is used as a shared analytical tool rather than an individual device.
3. Analyse how students’ statistical reasoning develops through collective data exploration and visualisation during the CODAP-supported STEM activity.

2. Literature Review

2.1 Statistical Reasoning in STEM Education

Statistical reasoning is widely recognised as a core competency in modern STEM education because it enables learners to interpret data, identify patterns, and make evidence-based decisions. Rather than focusing solely on procedural calculations, statistical reasoning involves understanding relationships among data, variability, graphical representations, and contextual interpretation. Garfield (2002) describes statistical reasoning as the process by which individuals' reason with statistical ideas and make sense of statistical information, including interpreting datasets, graphical displays, and statistical summaries. This process requires learners to connect statistical concepts such as measures of centre, spread, and distribution in order to develop meaningful interpretations of data.

Within STEM education, statistical reasoning supports inquiry-based learning and data-driven problem solving. Ben-Zvi and Garfield (2004) distinguish statistical reasoning from statistical literacy and statistical thinking. Statistical literacy refers to understanding statistical terminology and representations, while statistical reasoning involves explaining why statistical measures are used and how they reveal patterns within data. Statistical thinking extends this process by applying statistical concepts to complex decision-making situations. Thus, statistical reasoning functions as a bridge between understanding statistical information and applying it to real-world contexts.

Research shows that students develop stronger statistical reasoning when they engage in authentic data investigations rather than isolated computational exercises (Ben-Zvi & Garfield, 2004; Makar & Confrey, 2004). Inquiry-based environments allow learners to explore variability, analyse patterns, and interpret data using real datasets. Technology-enhanced environments further support this learning process by enabling students to visualise and manipulate data dynamically, which promotes deeper engagement with statistical concepts (Chance et al., 2007).

Integrating statistical reasoning with experimental activities can further strengthen conceptual understanding. Engineering design tasks such as the paper helicopter investigation enable students to generate datasets through repeated trials and experimentation. Through these investigations, learners observe variability and recognise the need for statistical summaries to interpret patterns across observations. Such activities provide meaningful contexts for applying statistical reasoning and connecting empirical experimentation with data interpretation (Lehrer & Schauble, 2004).

2.2 Data Inquiry and the Data Analysis Cycle

Data inquiry is central to contemporary statistics education and involves engaging learners in a systematic process of questioning, collecting data, analysing patterns, and communicating conclusions. This process is commonly described as the data analysis cycle, which includes posing questions, gathering data, organising information, analysing patterns, and interpreting results. The cycle reflects the investigative nature of statistical practice and emphasises that statistical analysis is iterative rather than purely procedural (Wild & Pfannkuch, 1999).

Modern statistics education encourages students to participate in authentic data investigations that mirror the practices of statisticians and data scientists. Through such investigations, learners examine datasets, identify patterns, and construct explanations supported by empirical evidence (Gould, 2017). This process helps students interpret variability and reason about relationships among variables, which are key aspects of statistical understanding.

Within technology-supported data inquiry, students engage in actions that transform and interpret datasets to reveal patterns and relationships. These actions are often described as transnumerative processes, which involve transforming data into multiple representations such as graphs, tables, and statistical summaries (Wild et al., 1999). Moving between these representations supports deeper conceptual understanding because learners can examine the same dataset from different analytical perspectives.

2.3 CODAP as a Tool for Data Exploration and Statistical Reasoning

The Common Online Data Analysis Platform (CODAP) is a web-based open-source tool designed to support data exploration and statistical reasoning in educational settings (Finzer & Damelin, 2014). CODAP provides an interactive environment where learners can manipulate datasets, construct visualisations, and explore relationships among variables using a drag-and-drop interface. By simplifying the technical procedures involved in creating graphs and statistical summaries, the platform allows students to focus more on interpreting patterns and reasoning about data.

Dynamic data tools such as CODAP support exploratory data analysis by enabling learners to organise, visualise, and analyse multivariate datasets. These tools allow users to interact with data through linked representations, meaning that actions performed in one representation automatically update other representations within the workspace. This feature helps students explore relationships among variables and supports the development of statistical reasoning (Hudson et al., 2024).

One important feature of CODAP is its support for dynamic linked representations, which connect multiple visualisations of the same dataset. When a user selects a case in one representation, such as a graph, the corresponding data points are highlighted in other representations, including tables or maps. This capability helps learners understand relationships among different representations and promotes deeper reasoning about data patterns. Research on dynamic statistics software suggests that such tools enhance conceptual understanding by enabling students to visualise and explore multivariate relationships interactively (Mojica et al., 2019).

2.4 Teacher Orchestration in Technology-Supported Learning

Although digital tools provide valuable opportunities for data exploration, the effectiveness of technology-supported learning depends strongly on the role of teachers in orchestrating classroom activities. Teacher orchestration refers to the ways teachers guide students' interactions with technological tools, structure inquiry tasks, and facilitate discussions that support conceptual understanding (Dillenbourg & Jermann, 2010).

Research in technology-enhanced learning environments emphasises that digital tools alone do not guarantee meaningful learning outcomes. Instead, teachers must design activities that encourage purposeful inquiry and help students interpret data within meaningful contexts. Effective teacher orchestration includes guiding students with targeted questions, facilitating collaborative discussions, and encouraging learners to justify their conclusions using evidence from data (Trouche et al., 2012).

2.5 PICRAT Model for Analysing Technology Integration

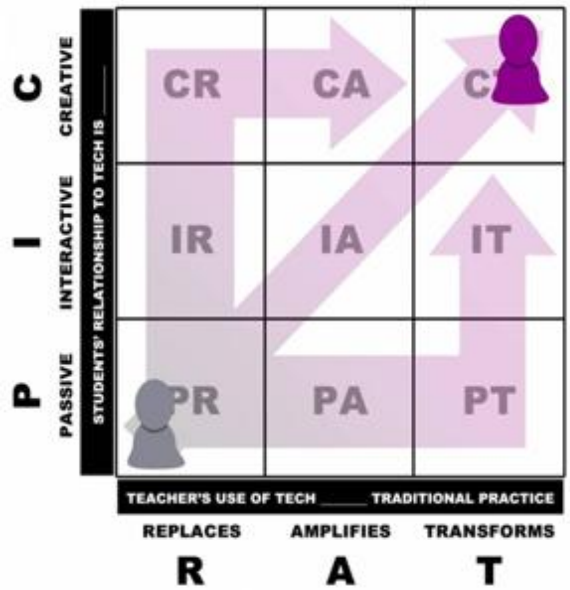
The PICRAT model, developed by Royce Kimmons and colleagues (Kimmons et al., 2020), provides a framework for evaluating how technology is integrated in classroom instruction. As illustrated in Figure 1, the model combines two dimensions: students' relationship with technology (PIC) and teachers' pedagogical use of technology (RAT).

The PIC dimension describes how students engage with technology. At the Passive (P) level, students mainly receive information through technology, such as viewing content or demonstrations. At the Interactive (I) level, students actively manipulate or respond to digital tools, for example by adjusting graphs or exploring datasets. At the Creative (C) level, students use technology to produce new ideas, artifacts, or explanations, such as generating visualisations or constructing interpretations from data.

The RAT dimension examines how teachers use technology in instruction. Replacement (R) occurs when technology substitutes traditional tools without changing the learning process, such as replacing hand-drawn graphs with digital ones. Amplification (A) increases efficiency or expands learning possibilities, for instance by enabling faster data aggregation or dynamic visualisation. Transformation (T) represents the highest level, where technology enables learning experiences that would be difficult to achieve without digital tools.

Figure 1

PICRAT Model for Technology Integration Colleagues (Kimmons et al., 2020)



3. Methodology

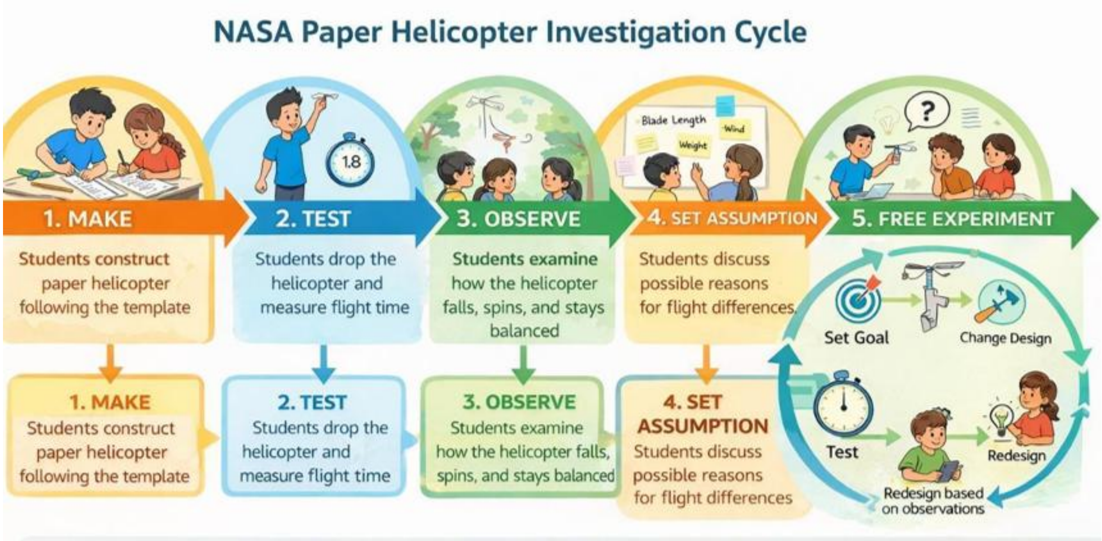
3.1 Research Design

This study employed a qualitative single case study design (Yin, 2018) to examine how a teacher strategically redesigned a NASA original activity to promote statistical reasoning in a resource-constrained classroom. A single exemplary case was selected to provide an in-depth understanding of how pedagogical decisions and classroom management strategies emerged when technological resources were scarce. The focus of the case was how a single digital interface could be transformed into a communal tool that supported collaborative data inquiry and collective reasoning among students.

The instructional intervention was based on the Paper Mars Helicopter activity, an engineering design task developed by NASA (Lutz, 2025), see Figure 2. In this activity, students construct a simple paper rotorcraft using basic materials such as paper, scissors, and tape. Students then conduct flight tests by dropping the helicopter from a fixed height and recording observations such as flight time and rotor movement. Through repeated trials, students modify design variables—including blade length, wing shape, or weight distribution—to examine how these changes influence flight performance. The activity encourages iterative experimentation and generates datasets that can be analysed to identify patterns between design variables and flight outcomes.

Figure 2

Original Flow of NASA Paper Helicopter Activity



3.2 Participants and Setting

The case involved a 27-year-old Thai female primary school teacher with three years of teaching experience. At the time of the study, she was pursuing a Master's degree in Mathematics Education, which supported her ability to implement inquiry-based STEM instruction. Her experience using the Common Online Data Analysis Platform (CODAP) and the Claim–Evidence–Reasoning (CER) framework was developed through professional development provided by the SEA-TEP Project (Southeast Asian Teacher Education Programme) at Naresuan University, Thailand.

The study was conducted in a rural classroom of 14 Grade 5 students in a community with limited economic resources. The classroom exemplified the first-level digital divide, as technological infrastructure was minimal. The only digital device available was the teacher's personal laptop connected to a television screen. This "*One Laptop/One TV*" configuration required the teacher to redesign the lesson so that the digital platform could be used collectively rather than individually.

3.3 Data Collection

Multiple qualitative data sources were collected to ensure data triangulation. These included instructional artifacts, teacher interviews, visual documentation, and samples of students' work. Instructional artifacts consisted of the teacher's original lesson plans, revised lesson plans integrating CODAP, and instructional field notes documenting classroom events and student interactions. These notes served as a proxy for classroom observation. A semi-structured narrative interview was conducted to explore the teacher's pedagogical reasoning and instructional decisions during the intervention. This was supplemented by written post-teaching reflections describing how the technological limitations influenced classroom engagement and learning. Visual documentation included photographs of the classroom setup and students' learning artifacts. These artifacts consisted of paper helicopter prototypes, handwritten data tables, and screenshots of CODAP visualisations produced during the lesson. Together, these materials provided evidence of how students collected, organised, and interpreted experimental data.

3.4 Data Analysis

The collected data were analysed using qualitative procedures to address the three research objectives: (1) examining how the STEM activity was redesigned for a resource-constrained classroom, (2) analysing teacher orchestration in the shared-screen environment, and (3) identifying students' development of statistical reasoning during the activity.

First, a document and artifact analysis compared the original NASA Paper Helicopter activity with the teacher's adapted lesson plan. The analysis focused on pedagogical modifications in the experimental design, data collection procedures, and the integration of CODAP for digital visualisation. Particular attention was given to the shift between the original STEM activity and the adapted version.

Second, thematic coding was applied to the teacher's narrative interview, instructional notes, and classroom documentation to examine orchestration strategies within the "*one laptop–one screen*" configuration. The analysis identified facilitation strategies such as role assignment, rotational data entry, whole-class discussion, and CER-based questioning, which together formed an Executive–Consultant shared-screen model that supported collaborative data exploration.

To further analyse the nature of technology integration, the PICRAT framework (Kimmons et al., 2020) was used as an analytical lens. PICRAT evaluates technology use across two dimensions: students' interaction with technology—Passive, Interactive, or Creative (PIC)—and the teacher's pedagogical use of technology—Replacement, Amplification, or Transformation (RAT). This framework allowed the researchers to examine whether CODAP primarily replaced traditional tools, amplified data analysis processes, or transformed the learning experience by enabling collaborative data visualisation and interpretation.

Third, students' statistical reasoning was analysed through their work samples, CODAP visualisations, and classroom interaction notes. The analysis followed the statistical reasoning framework of Garfield and Ben-Zvi (2008), focusing on reasoning about data, representations, variation, and associations. Students' explanations were also interpreted through the Claim–Evidence–Reasoning (CER) framework, which supports evidence-based argumentation in mathematical inquiry.

4. Results

4.1 Strategic Redesign of the STEM Activity in a Resource-Constrained Classroom

The findings indicate that the teacher did not merely adapt the activity to accommodate limited technological resources; rather, she implemented a series of strategic pedagogical redesigns that transformed the original NASA Paper Helicopter activity into a structured statistical investigation supported by CODAP.

In the original NASA activity (Figure 2), the task emphasised engineering experimentation, where students freely modified helicopter designs and observed flight outcomes. While this design supported exploratory learning, the results remained largely qualitative and individually interpreted. In contrast, the adapted lesson introduced a controlled experimental protocol, where specific blade lengths were tested and each condition was repeated three times. This modification generated a standardised dataset, enabling systematic data collection and comparison across trials.

The redesigned activity shifted the focus from individual experimentation to collective statistical inquiry. Instead of relying on individual observations, students pooled their results into a shared dataset consisting of 42 experimental trials (14 students × 3 trials). This dataset was entered into CODAP and displayed through a single laptop connected to a classroom screen. As a result, shown in Figure 3, the digital interface functioned as a communal analytical tool, enabling students to collaboratively explore patterns within the data.

Figure 3

Classroom Scenario in the Paper Helicopter Investigation with Shared CODAP Interface

Table 1

Modification to Original NASA Activity to Statistical-Based Inquiry with CODAP Integration

Original NASA Activity	Adapted Statistical inquiry	CODAP Feature	Teacher Facilitation
Free experimentation with helicopter design	Structured protocol with fixed blade lengths and repeated trials	Spreadsheet data entry	Role assignment for data recording
Individual observation of results	Whole-class data pooling	Data highlighting and linking	Rotational data input among students
Hand-drawn graphs	Dynamic graph generation in CODAP	Drag-and-drop axis manipulation	Executive–Consultant role structure
Individual redesign decisions	Collective interpretation using CER discussion	Visualisation of aggregated dataset	Whole-class “data huddle” discussion

Through this redesign, the digital tool did not function simply as a presentation medium. Instead, it supported data aggregation, visualisation, and collaborative interpretation, allowing students to focus on identifying patterns rather than manually constructing graphs.

4.2 Technology Integration Through the PICRAT Lens

To further analyse how technology supported learning in this environment, the integration of CODAP was examined using the PICRAT framework (Kimmons et al., 2020). This framework evaluates technology use across two dimensions: students’ interaction with technology (Passive–Interactive–Creative) and teachers’ pedagogical use of technology (Replacement–Amplification–Transformation).

At the initial stage, CODAP functioned at the Replacement level, substituting traditional paper-based tables and graphs with digital data entry and visualisation. However, as students began entering experimental results and manipulating graphical representations, technology use shifted toward Amplification, as CODAP enabled rapid aggregation and visualisation of the class dataset. This process significantly reduced the cognitive load associated with manual graph construction, allowing students to concentrate on interpreting relationships between variables.

As the lesson progressed, the use of CODAP moved toward Transformation, where the shared digital interface enabled new forms of collaborative inquiry. Through manipulating axes, grouping data, and observing emerging patterns, students collectively explored the relationship between blade length and flight time. This collaborative analysis allowed students to generate explanations and construct generalised conclusions supported by visualised evidence.

Table 2

Analysis of Technology Integration Using the PICRAT Framework

Students' Relationship with Technology (PIC)	Replaces (R)	Amplifies (A)	Transforms (T)
Creative (C)		Students use axis manipulation to generate alternative graphical representations of the dataset.	Students construct generalised conclusions from class-generated graphs, using visualised data as evidence for collective interpretation.
Interactive (I)		Students enter experimental data and record multiple trials quickly using CODAP.	Data can be explored through different visual lenses (grouping, stacking, plotting), enabling students to identify emerging patterns collaboratively.
Passive (P)	CODAP functions as a digital replacement for hand-drawn graphs or manual tables.	Enables collaborative data representation through aggregated class datasets.	

4.3 Teacher Orchestration and Collaborative Data Practices

To manage the "one laptop–one screen" configuration, the teacher implemented what this study identifies as an Executive–Consultant Shared-Screen Collaborative Model.

In this model, the student operating the laptop assumed the role of Executive, responsible for executing data manipulations within the CODAP interface. The remaining students acted as *Consultants*, observing the shared screen and offering suggestions regarding graph construction, axis selection, and interpretation of trends. The roles were rotated throughout the activity, ensuring that each student participated in the digital analysis process.

This orchestration created a social negotiation process around data interpretation, where decisions about graph design and analysis were discussed collectively. Students debated which graph type best represented the data and evaluated whether visualisations clearly demonstrated the relationship between blade length and flight duration.

Table 3

Teacher Facilitation Strategies in the Shared-Screen Model

Instructional Strategy	Teacher Action	Collaborative Outcome
Role assignment	Students rotated between Executive and Consultant roles	Shared responsibility in digital analysis
Rotational data entry	Each student entered their own trial data	Increased data ownership
Whole-class "*data huddle*"	Projected CODAP screen for collective discussion	Group interpretation of results
CER discussion prompts	Students justified conclusions using evidence	Collaborative reasoning and argumentation

Through this orchestration, the digital screen became a shared epistemic object, around which students constructed and debated interpretations of the data. Rather than functioning as a simple display device, the screen served as a focal point for social-mathematical discourse, allowing students to collectively evaluate evidence and refine their conclusions.

4.4 Development of Students' Statistical Reasoning

Analysis of students' work samples, CODAP visualisations, and classroom discussions revealed that the collaborative use of CODAP supported several dimensions of statistical reasoning, consistent with the framework proposed by Garfield and Ben-Zvi (2008). As students interacted with aggregated class data, their reasoning gradually shifted from focusing on individual outcomes toward recognising broader patterns and relationships within the dataset.

Table 4

Observed Development of Students' Statistical Reasoning

Dimension of Statistical Reasoning	CODAP Support	Observed Student Behaviour and Discussion
Reasoning about Data	Axis manipulation and attribute dragging	Students initially focused on their own results, making statements such as "My helicopter stayed up longer than yours." After viewing the class dataset, students began to examine trends across multiple data points.
Reasoning about Representations	Switching between tables and graphs	Students experimented with multiple graphical representations before selecting one that clearly displayed the relationship between blade length and flight time.

Reasoning about Statistical Measures	Automated calculation and comparison of averages	Students compared flight durations using mean values from repeated trials, noting differences between blade lengths.
Reasoning about Uncertainty and Variation	Visualisation of variation across the class dataset	Students observed that results were not always identical, commenting that "*The 10 cm wing usually flies longer, but not always.*" This reflected emerging awareness of variability across trials.
Reasoning about Association	Linked visualisations and dynamic graphs	Students recognised a relationship between variables, explaining that "*The graph goes up when the wing gets longer.*" This indicated recognition of a positive relationship between blade length and flight time.

The progression of students' reasoning demonstrated a cognitive transition from "*looking at data*"—interpreting individual data points—to "*looking through data*", where students identified general patterns across the aggregated dataset. For example, students first compared individual trials (e.g., "*My 7 cm flight lasted longer than my 4 cm flight*"), but later recognised broader trends such as the overall increase in flight time associated with longer blades.
By the end of the activity, students were able to articulate explanations using the Claim–Evidence–Reasoning (CER) framework:

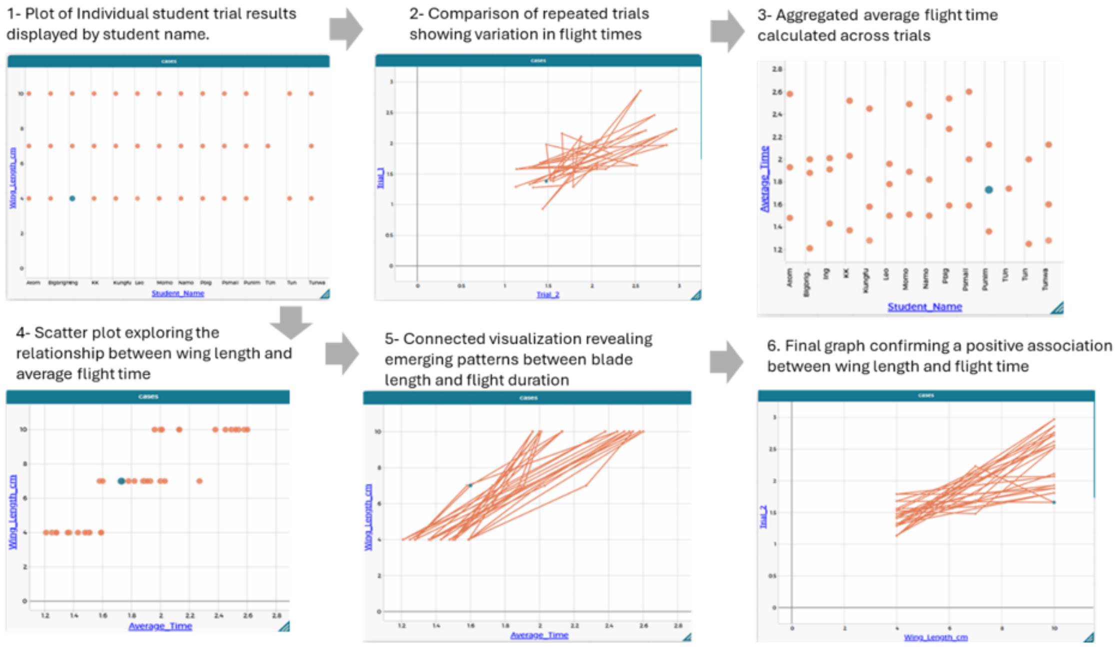
- Claim: Longer helicopter blades result in longer flight times.
- Evidence: Graphs generated in CODAP showed increasing flight durations as blade length increased from 4 cm to 7 cm to 10 cm.
- Reasoning: Longer blades increase air resistance, causing the helicopter to descend more slowly.

Students also acknowledged that some trials deviated from the general pattern due to factors such as wind or blade imbalance, demonstrating emerging reasoning about uncertainty and variability in experimental data.

Figure 4 illustrates a sequence of six CODAP visualisations showing how students progressively developed statistical reasoning through collaborative data exploration. The first graph displays individual trial results by student, where discussion initially focused on comparing personal outcomes. As students manipulated axes and reorganised variables, subsequent graphs revealed variation across trials and highlighted the usefulness of averaging results. The dataset was then reorganised to display average flight time, allowing students to compare helicopter performance more systematically. Further visualisations plotted wing length against average flight time, enabling students to explore relationships between design variables and outcomes. Through iterative graph manipulation and whole-class discussion, students eventually identified a positive association between wing length and flight time. This progression demonstrates a shift from examining isolated observations to recognising patterns across the aggregated dataset.

Figure 4

A Sequence of Six CODAP Visualisations from Students' collaborative Work



5. Conclusion

This qualitative single case study demonstrates that meaningful technology-supported STEM learning can occur even in classrooms with limited digital infrastructure. The teacher strategically redesigned the traditional NASA paper helicopter activity into a structured statistical investigation suitable for a "*one laptop–one screen*" environment. By introducing controlled experimental conditions and repeated trials, the activity generated a shared dataset that could be collectively analysed using CODAP.

Evidence from the teacher's interview and her adapted lesson plan shows that students first conducted hands-on experiments, recorded results on classroom charts, and then collaboratively explored the aggregated dataset through the shared CODAP interface. The teacher scaffolded the inquiry through a structured sequence—experimentation, observation, recording, planning, data collection, visual analysis, and drawing conclusions. Through strategic orchestration, such as rotational data entry and shared-screen discussions, students' statistical reasoning progressed from an initial focus on individual trials to a more sophisticated recognition of variation, averages, and the positive association between blade length and flight duration. This allowed the single digital device to function as a shared analytical tool, supporting collective graph manipulation and interpretation.

The findings reveal that the teacher's orchestration—transitioning from hands-on experimentation to collective data analysis—functioned as a catalyst for technology amplification and transformation. Ultimately, this study underscores that effective technology integration in resource-constrained contexts depends less on the quantity of hardware and more on purposeful pedagogical design, scaffolding, and classroom orchestration that promote collaborative engagement with data. These results contribute to developing practical frameworks for equitable STEM learning, suggesting that future research should further explore instructional models—such as shared-screen environments and rotating analytical roles—that leverage limited technological resources to sustain student participation and reasoning.

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MAKING SCIENCE MEANINGFUL: STEM PROFESSIONALDEVELOPMENT TO EMPOWER SCIENCE LECTURERS AND TEACHERS

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ABSTRACT

The educational reform needed to give more experiences to students to construct their conceptual understanding and competencies due to the changing world and society. The new teaching methodologies, strategies and techniques must be changed and developed linking with the educational reform and landscape in Cambodia. STEM integrating has become imperative for preparing students to thrive in the 21st-century workforce. To promote the STEM Education Learning Approach in teacher education and to habituate the scientific explanation as one of the competencies of students and student teachers. This study examined the effectiveness of a STEM Professional Development (PD) programme designed to empower science lecturers and attached schoolteachers at Phnom Penh Teacher Education College (PTEC) with competencies and mindsets to deliver high-quality STEM education. The participants engaged in workshops, Professional Learning Communities (PLCs), and job-embedded coaching over six months. The PD adapted Michigan State University STEM learning activities into Khmer and local contexts through three thematic units: Interaction, Water Quality (WQ), and Health in Our Hands (HiOH). Using a mixed-methods design, where the data were collected via pre- and post-surveys, classroom observations, and focus group discussions. Quantitative results indicated significant improvement in lecturers and teachers' self-efficacy (Mean of pre=2.87; Mean of post=4.26, $p<.001$) and pedagogical content knowledge (PCK) (Mean of pre = 2.91; Mean of post = 4.22, $p<.001$). Qualitative findings from focus groups revealed shifts in mindset toward inquiry-based teaching, stronger collaboration through PLCs, and improved confidence in facilitating student-centred STEM investigations. The programme demonstrates that localised, job-embedded PD aligned with Cambodia's Continuous Professional Development (CPD) Framework and Teacher Policy Action Plan (TPAP) can effectively enhance lecturers and teachers' instructional competence and mindset for STEM education.

Keywords: STEM Professional Development, Teacher Education, Professional Learning Community, Inquiry-Based Teaching

1. Introduction

The modern education landscape is changing rapidly, requiring a transition from memorisation techniques to instructional strategies that enable students to construct conceptual understanding, knowledge and develop core competencies. Cambodia, as a developing nation aiming to achieve upper-middle-income status by 2030, has acknowledged the vital importance of STEM (Science, Technology, Engineering, and Mathematics) education in equipping students for the challenges of the 21st century and creating a workforce ready for the future (Ayres, 2000; Bo, 2021). The demand for high-quality education, STEM education, has strengthened globally as nations prepare students for technological innovation, problem-solving, and critical thinking challenges (National Research Council, 2012; National Research Council, 2013). A challenge in developing countries such as Cambodia is transforming traditional, teacher-centred classrooms into learning spaces that are inquiry-driven and learner-centred (Ministry of Education, Youth and Sport, 2019). Moreover, the Ministry of Education, Youth and Sport (MoEYS) identifies teacher quality as the key driver of education reform. The Education Strategic Plan (ESP) 2019-2023 and ESP 2024-2028 emphasise enhancing teacher competence, reforming curricula, and incorporating 21st-century skills, while the Teacher Policy Action Plan (TPAP 2024-2030) and Continuous Professional Development Framework (2018) advocate for embedded, institutionalised professional development via Professional Learning Communities (PLCs) and mentorships within schools (Ministry of Education, Youth and Sport, 2023). Despite these improvements, teacher education institutions in Cambodia encounter difficulties in providing sustained, contextually appropriate professional development for STEM teaching and learning. Teachers and educators frequently report limited experience with inquiry-based teaching, insufficient localised resources, and fragmented Continuous Professional Development (CPD) opportunities (UNESCO, 2023). Recognising these needs, Phnom Penh Teacher Education College (PTEC) developed a contextualised STEM Professional Development (PD) programme to empower science lecturers and teachers through an integrated approach of workshops, PLCs, and classroom-based implementation. This study outlines the design, implementation, and assessment results of the PD programme. It contributes to the expanding literature on successful STEM professional development in Southeast Asia and illustrates the process of translating national policy frameworks into practical applications within institutions. Therefore, lecturers and teachers need specific structured pedagogical tools that go beyond routine memorisation to implement this policy imperative in the classroom. This study, one such fundamental tool, is the Claim-Evidence-Reasoning (CER) framework. In order to help students make claims that are supported by solid evidence and connected by logical reasoning, CER offers a clear model for scientific explanation. In order to enable Cambodian lecturers and teachers to provide the inquiry-based STEM education envisioned by national reforms, this study also explores a PD programme that centres on the mastery and pedagogical application of the CER framework.

This study was guided by the following research questions: 1) To what extent does a collaborative, practice-based STEM PD programme impact science lecturers and teachers' self-efficacy in understanding and applying the CER framework? 2) How does participation in the programme influence lecturers and teachers' pedagogical content knowledge (PCK) for designing and implementing inquiry-based STEM lessons using the CER framework? and 3) What are the perceived challenges, enabling factors, and impacts on teaching practice reported by lecturers and teachers following the implementation of CER-focused STEM lessons?

2. Literature Review

Effective PD is content-focused, active, sustained, and collaborative, according to numerous studies (Desimone, 2009; Darling-Hammond et al., 2017). According to Loucks-Horsley et al., (2010) teachers learn best when they co-design lessons, watch their peers, and get coaching and feedback. Additionally, PLCs improve professional communication and group effectiveness (Vescio et al., 2008). The educational system in Cambodia has been shaped by a complex history that includes the devastation caused by the Khmer Rouge regime as well as the effects of French colonialism (Bao et al., 2025). This study showed that while the socialist regime caused major losses and the destruction of many educational facilities over the course of more than three decades, the educational model created during the French colonial era has persisted in its institutional structure. The field of education in Cambodia has recovered. Currently, the government has demonstrated strong policy commitment to STEM education through a range of national initiatives. The Rectangular Strategy Phase IV particularly highlights the importance of human resource development and aims to improve the quality of education, science, and technology (Bao et al. 2025). At the same time, international development partners have backed Cambodia's efforts in STEM education. A notable instance is the World Bank's project, which builds upon earlier successful initiatives that established 67 academic programmes, financed 53 research projects, and improved 147 laboratories (Un and Sok, 2022; Heng, 2025).

STEM education emphasises the integration of scientific practices- modelling, inquiry, data analysis, and explanation- with cross-cutting concepts and real-world relevance (National Research Council, 2012). However, Cambodia's STEM education landscape faces several persistent challenges: 1) decreasing student engagement in STEM: A significant reduction has been observed in the proportion of students opting for the science pathway in upper secondary education which nearly 50% of those who enrol in the science pathway in Grade 11 transition to the social science pathway in Grade 12 (Bao et al., 2025). This declining interest poses a risk to Cambodia's long-term objectives for human resource development in STEM disciplines. 2) Quality and resource constraints: In the context of ASEAN, Cambodia is positioned lower regarding higher education, innovation capabilities, and research (Bao et al., 2025). The nation encounters and struggles in the quality of education, especially in mathematics and science, and is deficient in both innovation capacity and human resources. According to one education expert, the public education sector lacks systematic evaluation of teachers, which affects education quality (Heng, 2025). 3) Curriculum and Implementation Gaps: Although national policies emphasise the importance of STEM education, the execution within classrooms continues to pose difficulties. The necessity for curriculum reform that promotes critical thinking and is in harmony with 21st-century skills has been acknowledged in the newly established Education Strategic Plan 2024-2028 (Bao et al., 2025). Thus, PD is needed for equipping teachers and lecturers in upgrading knowledge and skills based on current context. The PD that immerses teachers and lecturers in hands-on investigations and data interpretation helps them internalise the process of scientific reasoning (Windschitl et al., 2018).

The theory of sense making provides a significant framework for comprehending how educators and teachers perceive and apply innovations in STEM education. This theoretical viewpoint recognises that when educators are introduced to novel methodologies such as integrated STEM education, they participate in a dynamic process in which they utilise their pre-existing knowledge, beliefs, values, experiences, and identity to either accommodate or assimilate these new concepts (Gavrilas & Kotsis, 2025; Holmlund et al., 2018). For example, the Ministry of Education, Youth and Sport (2023) highlights professional standards, career pathways, and competency-based teacher training in the Cambodian TPAP (2024-2030). The CPD Framework (2018) promotes school-based and peer-supported learning, reflecting global best practices. The Strategic Plan for Teacher Education Reform (2024-2030) calls for TEIs to lead pedagogical innovation, particularly in STEM and digital competencies (UNESCO, 2023). Projects like STEPCam (UNESCO, 2023) have strengthened TEIs but also revealed persistent gaps in lecturers and teachers' capacity and localised PD design. Addressing these gaps requires PD that contextualises international STEM approaches, engages teachers in sustained practice, and aligns evaluation with MoEYS CPD indicators. However, Cambodian PD initiatives exist, few have documented systematic evaluation of STEM PD impacts on lecturers and teachers' practices. This study fills that gap by examining how a localised STEM PD affects competencies, pedagogical mindset, and collaboration within the PTEC ecosystem.

The effective professional development for STEM lecturers and teachers necessitates a thoughtful strategy that addresses both content knowledge and pedagogical skills. According to Banh (2025) suggests that high-quality STEM professional development should: 1) Ground programmes in the principles of constructivism, perceiving learning as an active and constructive endeavour where student motivation and beliefs play a crucial role in cognitive processes. 2) Offer teachers and lecturers the chance to cultivate ambitious instructional methods that actively involve and assist all students in mastering challenging science and mathematics concepts. 3) Integrate interdisciplinary links and real-world problem-solving through project- or problem-based learning approaches. 4) Promote LPCs that facilitate continuous collaboration and support. Therefore, there is a need for localised STEM PD affects competencies, pedagogical mindset, and collaboration within the teaching routine.

The broad goals of STEM education teaching and learning- such as fostering inquiry, critical thinking, and authentic scientific practices-are well-established (National Research Council, 2012; Cunningham, 2018), teachers require concrete, structured pedagogical models to translate these ambitions into daily classroom practice. The Claim-Evidence-Reasoning (CER) framework serves as one such foundational model (Mcneil, 2021). It deconstructs the complex practice of scientific argumentation into three core, teachable components: making a testable Claim, providing Evidence (data or observations), and developing Reasoning that logically connects the evidence to the claim using scientific principles. Conceptually, CER is more than just a graphic organiser; it is the explicit articulation of the epistemological structure of scientific explanations (Wangmo et al., 2025). It moves students beyond simply reporting results to constructing meaning and justifying conclusions, thereby embodying the "*science as practice*" paradigm (Osborne, 2014; Manz & Renga, 2017). For teachers, mastery of CER is a critical component of Pedagogical Content Knowledge (PCK) in science. It equips them to design lessons that shift from verifying known facts to guiding students through investigative cycles where claims are built from evidence, directly addressing critical thinking (Gacula, 2024). The gaps identified in Cambodian curriculum reforms and implementation (teaching and learning), particularly in science teaching and learning in teacher education. Therefore, this study positions CER as the central pedagogical focus of the STEM professional development programme. The programme hypothesises that to achieve the broader aims of student-centred, inquiry-based STEM education- as called for in Cambodia's Education Strategic Plan (2024-2028) and the global literature- lecturers and teachers must first internalise and become proficient in facilitating this core explanatory practice. The PD intervention is designed not merely to introduce STEM activities, but to use those activities as contexts for deep training in the application of the CER framework with the effectiveness in content-focused, active, sustain, and collaboration. This would support sense of making by providing a significant framework for comprehending how educators and teachers perceive and apply innovations in STEM education. This approach directly targets the documented challenges in Cambodia by providing a clear, scalable method to enhance scientific reasoning and move beyond rote instruction, thereby making the conceptual goals of STEM education actionable for lecturers and teachers.

3. Methodology

3.1 Research design and Approach

This study employs a mixed-methods case study design (Delaney et al., 2017) to investigate the implementation and outcomes of the STEM Professional Development programme at PTEC. The research follows a convergent parallel mixed-methods approach, both quantitative data (pre/post surveys) and qualitative data (focus group discussions) were collected simultaneously during the same phase of the research process. The results were then integrated to provide a comprehensive understanding of changes in participants' competencies and perceptions.

A mixed-methods pre-post design was employed, combining quantitative (survey) and qualitative (focus group) data to assess changes in teacher competencies, self-efficacy, and mindset.

3.2 Participants

The study involved 27 participants, of which 18 PTEC were Science Lecturers (Biology = 6, Chemistry = 5, Physics = 4, Earth Science = 3) and 9 Attached School Teachers which were from Primary and lower-secondary schools. The participants had teaching experience ranging from 3-18 years (M = 9.4 years). All volunteered to participate and consented to data collection.

3.3 Programme Overview

The six-month PD programme included workshops on inquiry-based STEM pedagogy and adaptation of three units (Interaction, Water Quality, Health in Our Hands). PLC meetings biweekly for lesson planning, peer feedback, and data reflection. Classroom implementations with mentoring and observation and post-implementation reflection through focus groups were conducted. The design drew from Michigan State University's STEM learning activities, localised to Khmer and Cambodian curricula.

3.4 Instruments

Data were collected using two primary instruments: a self-efficacy and pedagogical content knowledge (PCK) survey, and a focus group discussion (FGD) protocol. The Self-Efficacy and PCK Survey: A 30-item, 5-point Likert scale survey (1=Strongly Disagree, 5=Strongly Agree) was developed by the research team. The instrument was structured around the core constructs of the PD:

- Self-Efficacy in CER: Items assessing confidence in personal ability to identify claims, select evidence, and articulate reasoning (e.g., *"I am confident in identifying the main claim..."*).
- Pedagogical Content Knowledge (PCK) in CER: Items assessing ability to integrate CER into lesson planning and student activities (e.g., *"My lesson plans include activities for students to collect data to support their claims"*).
- Understanding of Modelling: Items assessing knowledge and confidence in using scientific models.

The survey was developed based on a comprehensive literature review of CER and teacher self-efficacy instruments. It was translated into Khmer and piloted with a small group of non-participant lecturers to ensure face validity, clarity, and cultural appropriateness. Internal consistency reliability for the survey scales, as measured by Cronbach's Alpha, was calculated on the pre-test data and found to be high ($\alpha > 0.89$ for all major constructs).

Focus Group Discussion (FGD) Protocol: A semi-structured interview protocol was used to guide discussions with the 10 randomly selected participants. The protocol explored themes of mindset change, perceived benefits of the PD, challenges in implementation, and the utility of PLC support. This instrument provided the qualitative depth to complement and contextualise the quantitative survey data.

Table 1

The Summary of Two Primary Instruments

Instrument	Purpose	Description
Teacher PD Survey (pre/post)	Assess teacher self-efficacy, PCK toward STEM teaching	30 Likert items (1–5 scale); $\alpha = 0.89$
Focus Group Discussion	Explore mindset change and perceived benefits	Two 90-minute sessions; recorded and thematically analysed

3.5 Data Collection

The researchers gathered data by means of pre-survey as well as using the results from the post survey that was prepared by researchers. The pre-survey was administered to the respondents prior to the intervention programme to establish baseline data before the workshop and the post-survey was conducted after the reflection phase to assess teacher self-efficacy, PCK toward STEM teaching. The focus group discussion (FGD) was conducted with 10 randomly selected participants (6 lecturers, 4 teachers) to explore mindset change and perceived benefits. The structured classroom observations were conducted by the research team during the implementation phase. The observations served a formative, supportive role, providing real-time feedback to participants and informing the consultations within the PD model. The observational data contributed to the research team's holistic understanding of implementation fidelity and challenges, which informed the development of the FGD protocol.

3.6 Data Analysis

The quantitative data collected were analysed using SPSS. Descriptive statistics (mean, standard deviation) summarised all items. Paired-sample t-tests were conducted to determine the statistical significance of score changes between pre- and post-tests for the composite constructs (Self-Efficacy, PCK, Modelling). The effect sizes (Cohen's d) were calculated to assess the practical magnitude of the changes. While the qualitative data collected was analysed qualitatively using thematic analysis, which involved systematically identifying, analysing, and reporting patterns within the data collected from FGD. Initially, meaningful segments of the qualitative data were coded, and the codes were grouped into broader themes (Braun and Clarke, 2006) to identify recurring patterns from focus group transcripts. The final process was the integration in which the triangulation was used to link statistical gains with qualitative narratives.

4. Results

4.1 Quantitative Findings

The professional development (PD) programme led to substantial and statistically significant improvements in participants' overall competencies. To quantitatively assess the impact of the STEM professional development programme, pre- and post-test surveys were administered to 27 participants. Analysis revealed a profound and statistically significant increase in all measured competencies following.

As shown in Table 1, the overall mean score across all items increased from 2.87 (SD = 0.81) to 4.26 (SD = 0.49), representing a large and significant gain ($t(26) = 11.42$, $p < .001$). The effect size, calculated using Cohen's d, was 2.20, which is exceptionally large and underscores the practical significance of the programme's impact. This overall improvement was driven by substantial gains in both Self-Efficacy in using the CER framework and Pedagogical Content Knowledge for integrating it into lesson planning, both with effect sizes exceeding 1.98.

The results indicate a highly significant increase in scores from pre-test to post-test across all measures. The effect sizes (Cohen's $d > 2.09$) are exceptionally large, suggesting a powerful impact of the professional development programme on both lecturers and teachers' personal understanding of scientific concepts (Self-Efficacy) and their ability to translate this understanding into effective lesson planning (PCK).

Table 2

Changes in Teacher Competencies and Self-Efficacy (N = 27)

Dimension	Pre-Test Mean (SD)	Post-Test Mean (SD)	Mean Gain	t (26)	p value	Effect size (d)
Total Score (All Items)	2.87 (0.81)	4.26 (0.49)	+1.39	11.42	< .001	2.20
Self-Efficacy (CER)	2.83 (0.88)	4.30 (0.52)	+1.47	10.26	< .001	2.09
Pedagogical Content Knowledge (PCK)	2.91 (0.80)	4.22 (0.51)	+1.31	10.27	< .001	1.98

Note: SD = Standard Deviation. Cohen's d interpreted as: Small (0.2), Medium (0.5), Large (0.8).

An item-by-item analysis (Table 3) confirmed that these improvements were consistent across all specific skills. The largest gains were observed in the core "*Claim*" constructs (e.g., "*Importance of specific/relevant claims,*" Mean Gain = +1.59), indicating that participants solidified their foundational understanding of scientific argumentation. Significant gains in PCK items (e.g., "*confidence formulating claims for lessons,*" Mean Gain = +1.34) demonstrate that participants successfully translated their enhanced understanding into teaching confidence and practical planning skills. The following table provides a detailed breakdown of the changes for each survey item, categorised by competency.

Table 3

Item-by-Item of Pre-Post Test Analysis (N=27)

Item Category & Description	Pre-Test Mean	Post-Test Mean	Mean Gain	p-value
A. SELF-EFFICACY IN SCIENTIFIC EXPLANATION (CER)	2.85	4.41	+1.56	< .001
A1. Claim				
1. Confident identifying main claims				
2. Formulate clear claims from data	2.81	4.37	+1.56	< .001
3. Formulate concise claims from data	2.78	4.33	+1.55	< .001
4. Differentiate claim from supporting details	2.74	4.30	+1.56	< .001
5. Importance of specific/relevant claims	2.85	4.44	+1.59	< .001
A2. Evidence				
6. Select data to support a claim	2.81	4.33	+1.52	< .001
7. Select observations to support a claim	2.70	4.26	+1.56	< .001
8. Evaluate sufficiency of evidence	2.74	4.30	+1.56	< .001
9. Distinguish relevant/irrelevant evidence	2.74	4.30	+1.56	< .001
10. Confident collecting reliable evidence	2.85	4.37	+1.52	< .001
11. Link evidence to claim using principles	2.85	4.37	+1.52	< .001
A3. Reasoning				
12. Explain reasoning connecting evidence/claim	2.81	4.33	+1.52	< .001
13. Articulate why evidence supports a claim	2.78	4.30	+1.52	< .001
14. Understand role of reasoning	2.89	4.37	+1.48	< .001
B. PEDAGOGICAL CONTENT KNOWLEDGE (PCK)				
B1. Integrating CER into Teaching				
15. Confident formulating claims for lessons	2.96	4.30	+1.34	< .001
16. Include statements aligned with goals	2.96	4.26	+1.30	< .001
17. Include claims aligned with goals	2.96	4.26	+1.30	< .001
18. Easy to design activities for student claims	2.85	4.19	+1.34	< .001
19. Easy to design activities for articulation	2.85	4.19	+1.34	< .001
20. Incorporate strategies for gathering evidence	2.96	4.22	+1.26	< .001
21. Lesson plans include data collection	2.96	4.22	+1.26	< .001
22. Lesson plans include data analysis	3.00	4.22	+1.22	< .001
23. Guide students on credible evidence sources	3.04	4.26	+1.22	< .001
24. Confident explaining evidence-claim links	3.07	4.26	+1.19	< .001
B2. Applying the CER Framework				
25. Provide examples of reasoning connections	3.07	4.19	+1.12	< .001
26. Include exercises for linking evidence/claim	3.11	4.19	+1.08	< .001
27. Adapt CER to various topics	3.15	4.22	+1.07	< .001
28. CER improved inquiry-based lesson planning	3.19	4.26	+1.07	< .001
29. Reflect on lessons to enhance CER use	3.19	4.22	+1.03	< .001
30. Improve lessons to enhance CER use	3.22	4.22	+1.00	< .001

Note: All p-values were less than .001, indicating statistical significance for every item.

4.2 Qualitative Findings (Focus Group Themes)

Thematic analysis of the Focus Group Discussions (FGDs) provided in-depth insights into how participants experienced the professional development. The findings are structured below to directly address the study's research questions, detailing the shifts in self-efficacy, pedagogical application, and contextual factors influencing implementation.

4.2.1 Enhanced Self-Efficacy and a Growth Mindset Toward Inquiry

Participants described a fundamental shift in their confidence and identity as educators and teachers, moving from a knowledge-delivery model to embracing the role of a facilitator of inquiry, addressing RQ1. Initial hesitancy about managing open-ended, student-driven lessons was replaced by a sense of capability grounded in the structured Claim-Evidence-Reasoning (CER) framework. One lecturer captured this transformation: *“Before, I felt unsure how to guide students’ discovery without just giving them the answer. The CER steps gave me a clear map. Now I see that letting them question, test, and reason is real teaching, and I feel confident to lead that process.”* (Lecturer #7). This theme directly corresponds to the significant quantitative gains in the "Self-Efficacy in CER" construct, illustrating the personal and professional empowerment fostered by the PD.

4.2.2 Evolving Pedagogical Practice and Observed Student Engagement

The data revealed how increased pedagogical content knowledge (PCK) translated into classroom practice, addressing RQ2. Participants reported concretely redesigning lessons to centre on CER, which in turn ignited higher levels of student engagement. They moved beyond theory to implement activities where students constructed claims based on firsthand evidence, such as testing local water quality. A lecturer noted: *“When we used the water quality module, the CER framework structured the entire investigation. Students weren’t just following steps; they were arguing about what the data meant. Their questions were deeper and more persistent.”* (Lecturer #10). This observed surge in student curiosity and active participation was consistently cited as the most motivating outcome, validating the effort to adopt new pedagogies.

4.2.3 Collaborative Support and Systemic Challenges for Sustainability

The FGDs provided critical context on the enablers and barriers to sustaining these new practices, addressing RQ3. Two interrelated sub-themes emerged:

- The Vital Role of Professional Learning Communities (PLCs): The PLC model was unanimously identified as the most valuable support mechanism. It provided a safe space for collaborative problem-solving, resource sharing, and moral support, which reduced the isolation of pedagogical innovation. *“Our PLC became like a family. We shared experiments, failures, and solutions. It kept me motivated when challenges arose,”* shared one teacher (Teacher #3).
- Concerns Regarding Institutional Structures: Despite strong motivation, participants highlighted systemic difficulties. The primary concerns were a lack of dedicated time for collaborative planning and the absence of formal institutional recognition for PLC work. A pragmatic recommendation emerged: *“If PLC participation and the development of CER-based lessons were formally recognised and counted toward the MoEYS CPD credit system, it would incentivise and sustain this work beyond the project,”* explained one teacher (Teacher #5). This points directly to the need for policy and institutional alignment to ensure long-term impact.

Thus, the qualitative findings demonstrate that the PD programme succeeded in fostering a community of practice where enhanced self-efficacy (RQ1) and pedagogical knowledge (RQ2) were developed through collaborative support (RQ3). The observed positive impact on students served as a powerful reinforcing mechanism. However, the long-term integration of CER-based inquiry depends on addressing the identified systemic challenges (RQ3), particularly through formalising structures that protect collaborative time and recognise innovative teaching within the national framework for lecturers and teachers’ professional growth.

5. Discussion

This study evaluated the impact of a STEM professional development programme centred on the Claim-Evidence-Reasoning (CER) framework for science lecturers and teachers in PTEC. The results demonstrate that the localised, practise-based model led to statistically significant, large-magnitude improvements in participants' self-efficacy and pedagogical content knowledge (PCK). The following discussion interprets these findings by engaging with international STEM PD literature and analysing their specific significance for the Cambodian context.

5.1 The CER Framework as an Accessible Pedagogical Core for Inquiry

The study's primary finding- that explicit training in the CER framework effectively builds lecturers and teachers competency- offers a crucial insight for STEM reform in contexts like Cambodia. Internationally, CER is recognised as a foundational scaffold that makes the complex practice of scientific argumentation explicit and teachable (Lizotte et al., 2004). The results confirm its transferability and power. The dramatic gains in both self-efficacy and PCK (Cohen's d > 2.09) suggest that CER provided lecturers and teachers with a clear, manageable "pedagogical lever" to operationalise the broad goal of inquiry-based learning. This aligns with regional findings from projects in Thailand and Vietnam, where structured pedagogical models helped teachers transition from routine instruction to facilitating student-centred science practices (Buntha et al., 2024; Bui & Khuu, 2020). The qualitative data, where participants described CER as a "clear map" for lesson design, underscore that this framework successfully bridged the gap between theoretical policy aspirations (Ministry of Education, Youth and Sport, 2023) and tangible classroom practice.

5.2 Building Self-Efficacy through Collaborative, Mastery-Oriented PD Design

The extraordinary increase in lecturers and teachers' self-efficacy is a cornerstone finding. This aligns robustly with international meta-analyses showing that effective PD is active, collaborative, and sustained (Darling-Hammond et al., 2017; Desimone, 2009). The programme embodied these principles: it was content focused on CER, engaged lecturers and teachers in hands-on lesson adaptation, and provided continuous support over six months. The qualitative theme of "*Development of Growth Mindset and Instructional Self-Efficacy*" reveals the mechanism behind the quantitative increase. Participants attributed their growing confidence to "*mastery experiences*"- successfully trying and refining CER lessons in their classrooms. This process directly reflects the theory of self-efficacy development of Bandura et al. (2003). Furthermore, the "*Collaboration and PLC Impact*" theme highlights how PLCs fostered collective efficacy, a factor critical for sustaining change (Vescio et al., 2008). This mirrors successful PD approaches in neighbouring education systems, such as Singapore's emphasis on professional learning communities for scaling pedagogical innovation (Hairon and Dimmock, 2012).

5.3 Developing Deep Pedagogical Content Knowledge through Contextualisation

The significant growth in PCK indicates that educators progressed beyond understanding CER to mastering how to teach with it. This involves the transformational blending of content and pedagogy that defines expert teaching (Shulman, 1987). The qualitative findings show this transformation vividly: educators and teachers did not just adopt CER but contextualised it- mapping it onto the 5E model or creating subject-specific applications like particle diagrams in chemistry. This act of contextualisation is the symbol of deep PCK and is consistently identified as a critical success factor for PD in diverse cultural settings (UNESCO, 2023). By adapting Michigan State University's modules into Khmer and linking them to local issues (e.g., community water quality), the programme ensured relevance. This directly addresses the "*curriculum and implementation gaps*" prevalent in Cambodia (Bao et al., 2025) and offers a model for "localising" international STEM resources, a common challenge across Southeast Asia.

5.4 Confronting the Sustainability Challenge: Aligning PD with Systemic Structures

While the PD model proved effective, the qualitative theme of "*Sustainability and Institutional Support*" identifies a universal challenge for educational reform. Participants' concerns about relying on voluntary momentum and their call for formalised PLC time and CPD credit recognition echo findings from PD studies worldwide (Roesken-Winter and Blömeke, 2015). They point to a necessary shift from project-based intervention to system-integrated practice. Cambodia's own CPD Framework (Ministry of Education, Youth and Sport, 2024) and Teacher Policy Action Plan (2024-2030) already advocate for school-based collaboration (Ministry of Education, Youth and Sport, 2023). Therefore, the key implication is not creating new policies but operationalising existing ones. Integrating PLC participation into the national CPD credit system would institutionalise the collaborative culture this study found to be essential, a strategy that has bolstered PD sustainability in systems like the Philippines (Crispino and Rocha, 2021).

The study's limitations highlight pathways for future research. The single-site, pre-post design with self-reported data, though strengthened by qualitative triangulation, necessitates further investigation. Future research should: 1) employ longitudinal designs to assess the retention of PCK and practise over time; 2) incorporate direct classroom observations and student outcome measures to establish causal links between teacher PD and student learning; and 3) expand to multi-site studies across different Cambodian provinces to examine scalability and contextual variation. This would build a more robust evidence base for national policy decisions. However, this study provides compelling evidence that a well-designed, CER-focused PD programme can rapidly and significantly enhance the capacity of Cambodian STEM lecturers and teachers in PTEC. The findings validate core principles of effective international PD while demonstrating a successful model for contextualisation. To sustain and scale this success, policy action should focus on 1) Institutionalising the PD Model: MoEYS should integrate this collaborative, practice-based PD structure into the national in-service and pre-service teacher education frameworks; 2) Resource Development & Support: Develop and disseminate open-access, Khmer-language STEM teaching guides featuring CER-based lessons through formalise PLCs by allocating dedicated collegial time and linking participation to the national CPD credit system; and 3) Strategic Investment and Monitoring: Direct strategic investment, such as the World Bank's STEM funding, toward scaling proven, contextualised PD models. Establish a national monitoring framework to track the long-term impact of PD on teaching practice and student learning outcomes. By enacting these recommendations, Cambodia can transform the powerful proof-of-concept demonstrated at PTEC into a systemic driver of STEM education reform, ensuring that both teachers and students are equipped to thrive in the 21st century.

6. Conclusion

This study demonstrates that a STEM professional development programme centred on the Claim-Evidence-Reasoning (CER) framework effectively empowered Cambodian lecturers and teachers. The statistically significant, large-effect-size gains in self-efficacy and pedagogical content knowledge confirm the success of a model that is collaborative, practice-based, and culturally contextualised. Two primary conclusions can be emerged. First, the PD model is a viable and scalable blueprint for Cambodia, aligning with global best practices for effective lecturer (educator) and teacher learning and national policy goals. Second, by building a foundational capacity for inquiry-based teaching, the programme directly strengthens the human resource development objectives outlined in Cambodia's Rectangular Strategy and Education Strategic Plan, equipping lecturers and teachers to foster the critical thinking and problem-solving skills essential for the future workforce. To translate this evidence into systemic impact, the following steps are critical: 1) Policy Integration: Formalise the PD structure by integrating PLC participation into the national CPD credit system and allocating dedicated collaborative time for lecturers and teachers; 2) Strategic Scaling: Systematically adapt and scale this proven model to other Teacher Education Institutions across Cambodia; and 3) Resource Investment: Continue developing and disseminating high-quality, Khmer-language STEM teaching resources that feature the CER framework and local contexts. Future research should employ longitudinal designs to assess the retention of teaching practices and, crucially, investigate the causal impact of such lecturers and teachers training on student learning outcomes and STEM career interest. In summary, this initiative provides both a proven method and a policy pathway for building a vibrant STEM education ecosystem in Cambodia. Investing in the professional growth of lecturers and teachers is a fundamental investment in the nation's innovative capacity and future competitiveness.

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ENHANCING TEACHER CAPACITY IN STEM THROUGH PROFESSIONAL DEVELOPMENT ACTIVITIES: A CASE STUDY OF THE CER PROGRAMME IN MALAYSIA

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ABSTRACT

This study explores how the Claim Evidence Reasoning (CER) Professional Development (PD) activities support Malaysian pre-service, in-service teachers and matriculation lecturers in implementing integrated STEM, Claim-Evidence-Reasoning (CER), and scientific modelling frameworks. Employing a qualitative case study design, data were collected from 141 participants through post-test surveys containing open-ended responses. Data were analysed using inductive thematic analysis to identify key themes on pedagogical impact and classroom implementation. Findings revealed four major themes demonstrating the impact of PD activities: (1) strengthening pedagogical confidence and practice, (2) structured guidance through lesson design, (3) collaborative reflection and peer learning, and (4) enablers and constraints in classroom integration. The results indicate that CER's PD activities design effectively enhanced teachers' conceptual understanding and practical application of CER and modelling frameworks within STEM teaching. However, barriers such as time constraints, curriculum load, and varying student readiness limited full implementation. The study underscores the need for sustained professional learning communities and contextual adaptation of STEM-CER practices in Malaysian classrooms and context. Implications for teacher education and policy directions are discussed.

Keywords: STEM Education, PD Activities, CER, Modelling, Malaysian Classroom

1. Introduction

Globally, science, technology, engineering, and mathematics (STEM) education has gained increasing attention for its potential to foster innovation, problem-solving, and scientific literacy (National Research Council, 2012; Bybee, 2013). The combination of the Claim-Evidence-Reasoning (CER) approach and modelling within this framework offers structured methods to assist students in engaging in scientific activities that reflect inquiry and argumentation in the actual world. Effective implementation of these approaches, however, depends heavily on teachers' pedagogical content knowledge and confidence (Desimone & Garet, 2015). Higher-order thinking and scientific reasoning are undoubtedly incorporated into STEM curricula, but many teachers still use traditional teaching methods that place more emphasis on content coverage than conceptual reasoning.

Professional Development (PD) initiatives were introduced to address this gap by empowering teachers to incorporate CER approach and modelling as core elements of STEM instruction. This study explores how CER PD activities enhance teachers' capacity to design and implement STEM lessons that promote reasoning, argumentation, and modelling. It also identifies the challenges teachers face in translating the CER framework into practice.

2. Research Background

Professional development (PD) plays a crucial role in teacher change and innovation. Research consistently highlights that effective PD should be sustained, content-focused, and situated within authentic teaching contexts (Guskey, 2002; Desimone & Garet, 2015). The CER PD model aligns with these principles through its three phases: (1) intervention development, (2) implementation and observation, and (3) evaluation and adaptation.

The inclusion of CER and modelling within PD reflects the 3D Learning (Three-Dimensional Learning) framework, which connects disciplinary core ideas, scientific practices, and crosscutting concepts (National Research Council, 2012). While modelling improves conceptual visualisation and problem-solving, CER offers a cognitive framework that helps students articulate and defend scientific assertions.

Teaching and learning in STEM highlight the necessity for contextualised methods that connect theory with practice. Consequently, comprehending how CER facilitates teacher learning and tackles actual classroom challenges provides essential insights for enhancing policies and practices in STEM education.

3. Problem Statement

While professional development programmes are widespread, not all are designed to provide sustained support that fosters deep pedagogical change. Teachers frequently report difficulties transferring learned practices into diverse classroom contexts, particularly when faced with exam-oriented pressures, resource limitations, and varied student readiness levels (Fullan, 2007; Guskey, 2002). Despite continuous reforms aimed at enhancing inquiry-based and reasoning-focused STEM education, educators frequently find it challenging to implement frameworks such as CER and modelling effectively within their classrooms. The difficulties they face include inadequate training, a lack of sufficient support in lesson planning, and a disconnect between curriculum expectations and inquiry-driven teaching approaches.

The CER PD programme represents a structured attempt to bridge this gap through sustained PD that integrates CER and modelling into teacher learning cycles. However, empirical evidence is needed to determine how effectively the programme translates into classroom practice and what factors facilitate or constrain implementation.

Thus, the study addresses the following research questions:

1. How do PD activities within CER framework support participants in implementing STEM learning units and CER and modelling frameworks?
2. What challenges and opportunities do participants experience when applying concepts learned from PD activities to their lesson planning?

4. Methodology

The qualitative case study design was employed to explore how professional development activities supported the implementation of CER and modelling among 141 STEM educators. Purposeful sampling ensured that participants had relevant professional development exposure (Creswell & Guetterman, 2019). These approaches ensure a comprehensive understanding of both measurable impacts and the nuanced factors that contribute to the success of the interventions. This study was structured into three (3) phases of research, namely: Intervention Development, Implementation and Observation, and Evaluation and

Adaptation. In the Intervention Development phase, PD interventions were designed to enhance teachers' capacity in STEM instruction and the application of the CER framework. These interventions included capacity-building workshops, enhanced curriculum modules, and mentor training programmes. The second phase focused on the implementation of these interventions and the evaluation of their effectiveness. Open-ended post-surveys were administered to assess how participants adopted and integrated STEM learning units, CER, and scientific modelling into their teaching practices, as well as to identify challenges encountered. Participants' lesson plans were subjected to thematic coding to capture both instructional successes and implementation challenges. In the final phase, the study evaluated the degree of adoption and integration of STEM learning and the CER approach in classroom instruction among pre-service and in-service teachers. Open-ended survey responses data underwent qualitative thematic analysis to identify commonly emerging themes. A total of 141 individuals participated across all three research phases post-test survey. The study employed a convenience sampling method, a non-probability sampling technique wherein participants are selected based on their availability, proximity, and willingness to participate (Etikan et al., 2016). This method was selected due to practical considerations, such as accessibility to participants and time constraints. While convenience sampling allows for efficient and cost-effective data collection, it poses limitations regarding generalisability and introduces the potential for sampling bias (Creswell & Creswell, 2017). The sample consisted of 70 lecturers from matriculation colleges, 44 primary school teachers, and 27 pre-service teachers, as detailed in Table 1.

Table 1

Samples of the Study

	Pre-test	Post-Test	Survey
Matriculation College lecturers	70	70	70
Pre-service teachers	27	27	27
Primary school teachers	44	44	44
Total	141	141	141

Pre-service teachers are teacher trainees who have not yet entered full-time teaching, while in-service teachers/lecturers are practicing educators currently employed in schools or Matriculation Colleges.

In the Malaysian context, pre-service teachers refer to individuals undergoing formal teacher education prior to employment, while primary school teachers are those currently employed in primary schools. This study also includes lecturers from matriculation colleges also known as pre-university institutions under the Ministry of Education Malaysia, that prepare students for entry into universities, particularly in STEM and related fields. All participants completed the post-test survey instruments, ensuring consistency in the data across the sample. The relatively even distribution of participants across different educational backgrounds, while not equal in number, contributes to a broader understanding of how science and mathematics education practices are perceived and implemented across contexts. Although probability sampling methods such as stratified or random sampling could offer more statistically generalisable results, convenience sampling remains common in educational research where researchers often work within institutional constraints (Bryman, 2016). In this study, the choice of convenience sampling may also reflect the researcher's intention to focus on specific educational settings and groups that are actively involved in teaching science and mathematics, making them relevant and informative contributors to the research aims. Despite its limitations, convenience sampling can still provide useful data when interpreted cautiously. The key to using this method effectively lies in being transparent about the sampling process and clearly defining the characteristics of the sample (Palinkas et al., 2015). The study successfully addressed this by identifying the three distinct participant groups and maintaining consistency in the sample across all phases of data collection.

5. Data Collection and Analysis

Qualitative data collection included open-ended responses, were collected through the post-test survey, targeting participants' reflections on how the PD activities, supports participants in implementing STEM, CER, and Modelling as well as challenges faced.

Table 2

Focus for Open-Ended Responses for Post-Test Survey

Research Question	Measure	No of items	Post-Test Survey
			Open-ended Responses
1	How CER PD activities support STEM units: CER and Modelling.	5	✓
2	Challenges and opportunities.	5	✓
	Total	**10**	

The qualitative data were derived from open-ended survey responses. The primary method used for qualitative data analysis was content analysis Krippendorff (2019) which allowed for the systematic coding and categorisation of data to identify meaningful patterns or themes. The analysis followed several key steps:

- Initially, all text data underwent a thorough review to promote understanding and familiarity, which facilitated the identification of initial concepts and possible coding structures.
- An inductive coding method was utilised, permitting codes to arise organically from the data instead of depending on predetermined classifications, a method especially beneficial in exploratory research.
- The data were then analysed line-by-line, with meaningful text segments assigned descriptive codes. For example, a response such as *"I now feel more confident applying CER in my science lessons"* was coded as "*increased teacher confidence*."
- After initial coding, similar codes were grouped into broader categories and synthesised into overarching themes using thematic grouping techniques (Braun & Clarke, 2021).
- Themes were then reviewed and refined to ensure internal consistency and distinctiveness, followed by interpretation to the study's objectives.

To enhance credibility and dependability, repeated reading, peer debriefing among researchers, and audit trails of coding decisions were employed during thematic analysis.

6. Findings and Discussion

This section presents the findings related to the qualitative content and thematic analysis of data collected from 141 participants. The analysis followed the six-phase thematic process outlined by Braun and Clarke (2021) and was rooted in an inductive coding framework, as detailed in the qualitative methodology.

6.1 How Do CER PD Activities Support Participants in Implementing STEM Learning Units and CER And Modelling Frameworks?

Figure 1 illustrates the four emergent themes derived from thematic analysis.

Figure 1

Four Major Themes on How CER PD Activities Support Participants in Implementing STEM Learning Units, CER and Modelling Frameworks

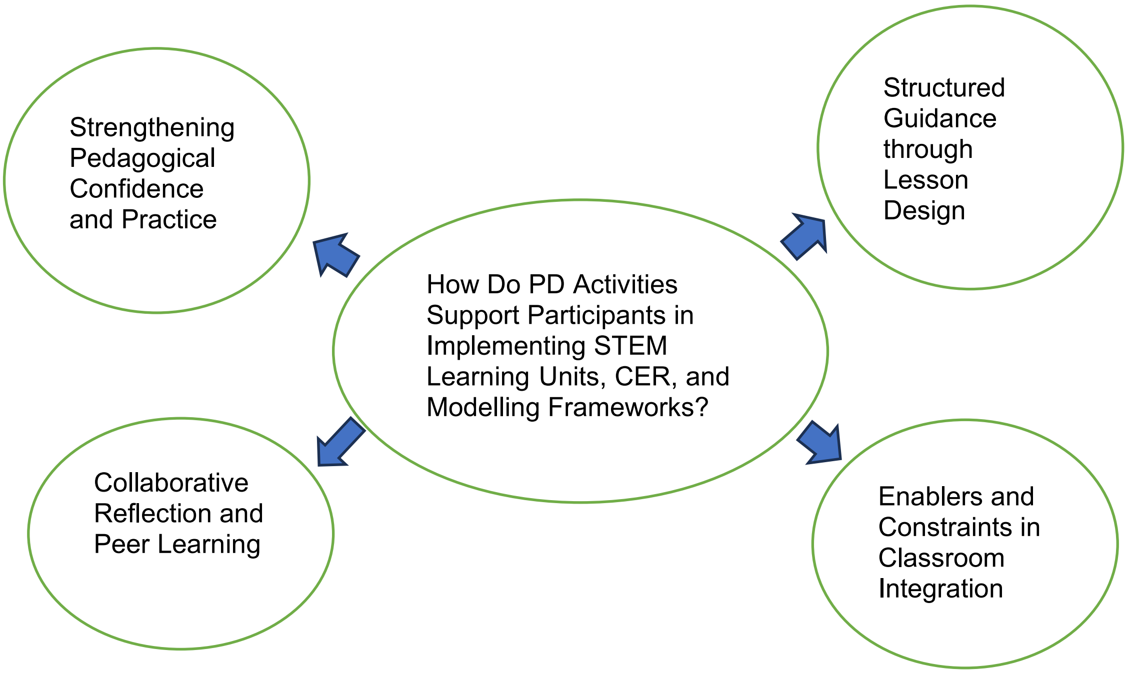

Table 3 below presents the frequency of participants aligned with each theme based on qualitative coding of their narratives.

Table 3

Participant's Frequency by Theme

Theme		No of Participants
Theme 1: Strengthening Pedagogical Confidence		35
Theme 2: Structured Guidance through Lesson Design		38
Theme 3: Collaborative Reflection and Peer Learning		30
Theme 4: Enablers and Constraints in Integration		38
	Total	141

Each theme is discussed in detail below, supported by narrative evidence from participants. Tables embedded in each subsection include the participant, narrative quote, and the associated code derived from content analysis.

6.1.1 Strengthening Pedagogical Confidence and Practice

A significant number of participants described how CER PD activities increased their confidence to implement new pedagogical frameworks, particularly the CER approach and modelling strategies in STEM. They reported a shift in mindset from content transmission to deeper conceptual facilitation and acknowledged the importance of prompting students to reason and argue scientifically. Teachers shifted from content transmission to reasoning-oriented facilitation as described in Table 4.

Table 4

Narrative Evidence for Strengthening Pedagogical Confidence and Practice

Participant	Narrative Quote	Associated Code
P3	*"Before the PD, I had never heard of CER. Now, I use it to help my students explain their science answers."*	Increased teacher confidence
P5	*"I used to just teach content. Now, I ask my students to explain why their answer makes sense using evidence."*	Shift from content to reasoning-based instruction
P12	*"I wasn't afraid to try out new strategies like modelling even though I've never used them before."*	Confidence in experimenting with pedagogy
P17	*"CER was confusing at first, but now I know how to break it down for my students."*	Conceptual clarity through training
P31	*"I can now guide students to reason better in science and maths lessons."*	Improved instructional clarity

This sense of empowerment aligns with previous findings on how high-quality PD can build teacher agency (Desimone & Garet, 2015; Guskey, 2002).

6.1.2 Structured Guidance through Lesson Design

Teachers consistently referred to the usefulness of PD provided scaffold templates, rubrics, and examples that helped them plan CER and modelling-aligned STEM units. Many participants highlighted how structured support allowed them to internalise and apply these frameworks. Structured scaffolding reduced planning anxiety and improved lesson coherence.

Participants highlighted the usefulness of templates, rubrics, and examples as displayed in Table 5.

Table 5

Narrative Evidence for Structured Guidance through Lesson Design

Participant	Narrative Quote	Associated Code
P4	*"I used the CER framework to plan my science lesson on air pollution."*	Use of scaffolded lesson plans.
P6	*"The CER lesson template made it easier to plan lessons. It was like a map."*	Lesson planning guidance.
P7	*"I used the rubric to assess students' reasoning. It helped make expectations clear."*	Assessment alignment with CER.
P13	*"The template from the PD acted like a checklist."*	Template-based structuring.
P29	*"The modelling sample lesson helped me understand how to adapt it for chemistry."*	Transfer of modelling from example.

6.1.3 Misconceptions About Water Clarity and Environmental Health

The PD programme embedded opportunities for sharing, feedback, and co-construction of ideas as displayed in Table 6. Teachers appreciated learning from others' practices and having their lesson plans reviewed by peers. Peer collaboration fostered reflective instructional growth.

Table 6

Narrative Evidence for Collaborative Reflection and Peer Learning

Participant	Narrative Quote	Associated Code
P2	*"One teacher shared how she used cartoons to explain reasoning. That helped me too."*	Peer influence on lesson design.
P10	*"Feedback during the sharing session showed me how to improve CER prompts."*	Constructive peer feedback.
P11	*"Collaborating in lesson planning helped me understand how others applied CER."*	Collaborative co-construction.
P16	*"We discussed and modified our plans in pairs. It helped refine my ideas."*	Dialogic learning.
P27	*"Learning from different strategies was motivating."*	Exposure to diverse practices.

Such interactions fostered communities of practice, which are critical for sustained pedagogical change (Wenger, 1998).

6.1.4 Enablers and Constraints in Classroom Integration

While the PD was largely beneficial, several teachers expressed concerns about time constraints, curriculum coverage pressure, and varying student readiness as indicated in Table 7. These challenges influenced the extent of implementation. Despite challenges, teachers adapted strategies to suit classroom contexts.

Table 7

Narrative Evidence for Enablers and Constraints in Classroom Integration

Participant	Narrative Quote	Associated Code
P1	*"Time is always an issue. CER takes longer than traditional lessons."*	Time constraint.
P8	*"Our school doesn't have enough lab tools, so I used photos instead."*	Resource adaptation.
P9	*"CER is great but difficult with students who have weak language skills."*	Language-based challenge.
P28	*"Hard to cover syllabus and also do full CER."*	Curriculum pressure.
P43	*"Classroom size and noise affect how much reasoning I can promote."*	Classroom management limitation.

Despite these barriers, some teachers adapted strategies to fit their contexts, confirming findings from Fullan (2007) and Guskey (2002) on the importance of local adaptability.

6.2 What challenges and opportunities do participants experience when applying concepts learned from CER PD activities to their lesson planning?

Figure 2 illustrates the four emergent themes derived from thematic analysis.

Figure 2

Four key themes for challenges and opportunities from CER Professional Development activities to their lesson planning

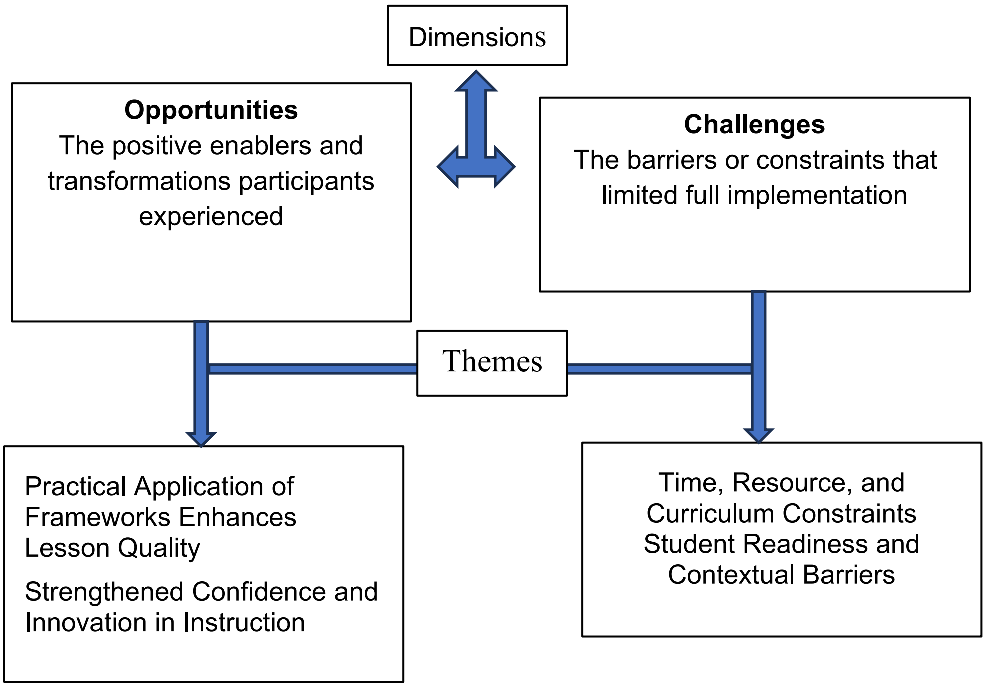

Table 8 displays the frequency of participants by theme. Following are the themes that are supported with narrative data and summarised in tables which include participant, narrative quote, and associated code.

Table 8

Participant's Frequency by Theme

Theme	Frequency (n)
Practical Application of Frameworks	36
Confidence and Innovation in Instruction	34
Time, Resource, and Curriculum Constraints	38
Student Readiness and Contextual Barriers	33
Total	**141**

6.2.1 Theme 1: Practical Application of Frameworks Enhances Lesson Quality (Opportunities)

Many teachers highlighted how the CER PD equipped them with practical tools (e.g., CER templates, Modelling structures) that made lesson planning clearer and more impactful as indicated in Table 9 These frameworks were described as improving lesson coherence and enabling structured scientific thinking.

Table 9

Narrative Evidence for Practical Application of Frameworks

Participant	Narrative Quote	Associated Code
P3	*"I now use the CER structure in most of my lessons. It makes science writing easier to assess."*	CER improves lesson clarity.

P8	*"CER made my students' answers more organised."*	Structured student thinking.
P14	*"Modelling helps students see the concept. It's more than chalk and talk."*	Visualising abstract ideas.
P23	*"Using the templates reduced my time spent planning."*	Efficient lesson planning.
P35	*"I know what to include now – claim, evidence, reasoning and how to build the flow."*	Framework-guided design.

6.2.2 Theme 2: Strengthened Confidence and Innovation in Instruction (Opportunities)

Teachers shared how the CER PD inspired greater experimentation, confidence, and creativity in lesson planning. This sense of empowerment was particularly evident in how participants described using CER and modelling in new ways.

Table 10

Narrative Evidence for Confidence and Innovation in Instructions

Participant	Narrative Quote	Associated Code
P11	*"I now feel confident to try new formats like argumentation tasks."*	Confidence to innovate.
P18	*"Using CER changed how I ask questions in class."*	Instructional transformation.
P29	*"My teaching is more creative now, I combine hands-on and reasoning prompts."*	Creativity in planning.
P41	*"I dared to redesign a full topic using modelling."*	Risk-taking in instructional design.
P53	*"My lesson planning has improved because I now focus more on how students think."*	Metacognitive awareness.

This reflects findings from Desimone and Garet (2015) on how teacher agency grows through meaning.

6.2.3 Theme 3: Time, Resource, and Curriculum Constraints (Challenges)

Participants also identified common implementation challenges, particularly time limitations, resource shortages, and rigid curriculum demand as indicated in Table 11. These barriers affected their ability to apply CER PD concepts consistently.

Table 11

Narrative Evidence for Time, Resource, and Curriculum Constraints

Participant	Narrative Quote	Associated Code
P9	*"I want to use CER more but it takes time that students don't have."*	Time constraint.
P21	*"Limited lab tools make the modelling part difficult."*	Resource limitation.
P34	*"The school timetable doesn't allow enough time for students to finish full CER cycles."*	Scheduling conflict.
P46	*"It's hard to integrate this when we have exams coming up."*	Assessment pressure.

This is consistent with Fullan (2007) and Guskey (2002), who found structural barriers are the most persistent obstacles to sustained instructional reform.

6.2.4 Theme 4: Student Readiness and Contextual Barriers (Challenges)

Some participants pointed out challenges related to students' readiness, language proficiency, and varying classroom dynamics as displayed in Table 12. This theme speaks to the nuanced, adaptive work of lesson planning in real-world classrooms.

Table 12

Narrative Evidence for Student Readiness and Contextual Barriers (Challenges)

Participant	Narrative Quote	Associated Code
P16	*"Students are not used to giving reasons. It takes time."*	Cultural shift in learning.
P22	*"Weak language skills make CER hard for some of my students."*	Language barrier.
P39	*"My students struggle to write explanations even when they have good ideas."*	Expression vs. understanding gap.
P48	*"CER is difficult with ESL learners."*	Second-language learners.
P61	*"Modelling is hard in large classes where students are passive."*	Class size and participation.

Such findings reflect the contextual complexity of implementing reasoning-based instruction (Creswell & Poth, 2016).

The findings demonstrate that CER PD effectively enhances teacher confidence, lesson coherence, and reflective practice. These results support Desimone and Garet's (2015) assertion that sustained, content-focused PD promotes pedagogical change. However, structural constraints remain a major barrier, consistent with Fullan (2007) and Guskey (2002). This indicates that PD effectiveness is strongly influenced by institutional and systemic support

7. Conclusion

This study examined how CER professional development activities support teachers in integrating STEM, CER, and modelling frameworks into classroom instruction. The findings revealed that CER effectively enhances teachers' pedagogical confidence, instructional design capabilities, and reflective practices. Participants demonstrated increased ability to design reasoning-based lessons, employ modelling as a conceptual tool, and collaborate with peers to improve lesson quality.

However, the study also found significant constraints, time limitations, curriculum pressures, and student readiness differences that hinder full integration of CER and modelling. These findings align with prior studies emphasising that sustainable instructional change requires institutional support, ongoing mentoring, and contextual adaptation (Fullan, 2007; Desimone & Garet, 2015).

For teacher education policy and practice, several implications emerge. First, PD should extend beyond one-off workshops to continuous learning cycles supported by peer collaboration. Second, schools and administrators should provide structural support—such as flexible timetabling and resource access to enable inquiry-based practices. Third, pre-service teacher preparation should integrate CER and modelling early in training to normalise reasoning-oriented teaching.

Future research should expand this study through longitudinal and mixed-method designs to measure long-term changes in teacher beliefs and classroom practices. The CER model offers a promising framework for developing teacher professionalism and advancing 3D STEM learning in Malaysia and across Southeast Asia.

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ENHANCING STEM TEACHING THROUGH CER, PBL, AND MODELLING IN TEACHER PROFESSIONAL DEVELOPMENT IN KAZAKHSTAN

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ABSTRACT

This article examines the impact of professional development on the implementation of STEM teaching methodologies among secondary and university educators in Kazakhstan. The study focuses on key approaches such as Claim Evidence Reasoning (CER), Project-Based Learning (PBL), and SageModeler as tools to enhance teachers' instructional practices and student engagement. The purpose of the research is to evaluate how effectively participants integrate these methods into their lessons and to explore the relationship between lesson planning quality and classroom outcomes. A mixed-methods design was used, combining quantitative analysis of pre- and post-course data with qualitative observations and teacher reflections. Statistical tests, including paired t-tests and Spearman correlations, revealed significant improvement in the application of CER ($t = -2.179$, $p = 0.042$) and strong positive correlations between the use of SageModeler and student activity ($\rho = 0.758$, $p < 0.001$). Teachers reported increased confidence and more structured lesson implementation following the training. The findings confirm the effectiveness of short-term professional development focused on practical STEM strategies and digital tools. The study highlights that active modelling and evidence-based reasoning contribute to deeper teacher reflection and higher student engagement. These results demonstrate the potential of STEM-oriented professional training to strengthen teachers' readiness for innovative and technology-enhanced education.

Keywords: STEM Education, Professional Development, Claim Evidence Reasoning (CER), Project-Based Learning (PBL), Modelling, Student Engagement.

1. Introduction

Forecasts by experts in the global labour market indicate that, in the long term, STEM specialists will be even more in demand (Atlas of New Professions, Agency for Strategic Initiatives, (SKOLKOVO, 2014).

Rapid technological development means that in the future, the most in-demand professions will be those related to high technology: IT specialists, big data engineers, programmers.

Today, engineering and entrepreneurial competencies are in high demand in the labour market, offering graduates a competitive advantage and greater chances of success in their chosen fields (Kaliyev,2020).

However, the idea that scientific and technical knowledge alone is not enough is becoming increasingly widespread. Labor market trends are expected to be shaped by two key skill sets:

soft skills and critical thinking. Soft skills are cross-functional abilities that help individuals solve real-life problems and collaborate effectively with others. Research from Harvard University, Stanford University, and the Carnegie Foundation has shown that soft skills account for 85% of a person's professional success, while hard skills contribute only 15%.

Based on the above-mentioned trends in the modern world, there is a growing need to explore new methods and approaches in teaching practice through STEM education. STEM represents a modern educational approach that integrates multiple subject areas as a means to develop critical thinking, research competencies, and teamwork skills (National Research Council, 1995).

Currently, STEM is one of the leading trends in global education. With the rapid advancement of technology, new professions are emerging, and the demand for STEM specialists is rising worldwide. For example, in EU countries, the proportion of employed specialists in this field increased by 12% between 2000 and 2013.

In European countries, the demand for STEM professionals is projected to grow by 8% by 2025, compared to just 3% for other professions. In 2011, among 16 OECD countries analysed, Finland had the highest number of STEM graduates—1,109 per 100,000 people aged 20 to 39. This figure is twice as high as that of Canada and Switzerland (OECD, 2016).

In the USA, there were only 475 STEM graduates per 100,000 people aged 20-39. In other countries, government programmes for the development of mathematical and scientific and technical education have also been adopted.

Finland established an institutional framework for STEM development 13 years ago. In contrast, the United States had only 475 STEM graduates per 100,000 people in the same age group. Other countries have also adopted government programmes aimed at strengthening mathematics, science, and technical education.

For example, the Malaysian Education Development Plan 2013–2025 includes a reform of STEM education. In Australia, the National STEM School Education Strategy 2016–2026 was adopted in 2015. More than 10 European countries have implemented similar national strategies and initiatives, including Austria, Germany, France, Italy, the Netherlands, Norway, the United Kingdom, Ireland, Spain, and others.

STEM projects not only increase students’ interest in engineering fields but also motivate them to pursue careers in science and technology. STEM provides access to emerging technologies and requires the creation of a learning environment that fosters student engagement and active participation.

Therefore, teachers who foster critical thinking in students through research-based activities and the use of modern technologies are one step ahead in preparing them for life in an intellectually advanced society (Hynes, 2017). STEM education is an innovative approach that enables the development of students' skills at a higher level.

The introduction and application of STEAM/STEM technologies is one of the key priorities of modern education in Kazakhstan. This is evidenced by the planned transition to an updated school curriculum within the framework of the State Programme for the Development of Education and Science for 2016–2019. To support the implementation of the new educational policy, it is planned to integrate STEM elements into curricula focused on the development of new technologies, scientific innovations, and mathematical modelling (National Academy of Education named after I. Altynsarin, 2017).

The following initiatives have been introduced:

1. A new interdisciplinary and project-based approach to learning, designed to help students strengthen their research and scientific-technological potential, and to develop skills in critical, innovative, and creative thinking, problem-solving, communication, and teamwork.
2. Since the 2015–2016 academic year, all first-grade students have studied the subject Natural Science, which serves as a foundation for further learning in the natural sciences in higher grades. Additionally, beginning with the 2016–2017 academic year, it was planned to equip all schools with ICT tools, digital educational resources, and internet access.
3. Starting in 2019, natural science and mathematics subjects in senior grades will be taught in English, supporting students in acquiring knowledge in the original language and enabling integration into the global scientific community.
4. A brief review of recent studies on STEM education in Kazakhstan and internationally was conducted to identify the main research constructs and challenges related to teacher professional development. Previous works highlight the growing need for practical, culturally relevant STEM methodologies that bridge theory and classroom application. (Vlast.kz. (n.d.)).
5. The analysis also emphasises the importance of adaptable, context-sensitive approaches such as Claim-Evidence-Reasoning (CER), Project-Based Learning (PBL), and modelling tools like SageModeler for developing teachers' reflective and evidence-based practices. These insights served as the conceptual basis for the present study.

2. Methodology

In the framework of the educational project "*Strengthening Teaching Education Programme*" developed by the 'Caravan of Knowledge' corporate foundation and the 'Southeast Asian Ministers of Education Organization Regional Centre for STEM Education'. 50 teachers and university educators participated in the course. The course was aimed at the successful implementation of STEM education in schools by encouraging teachers to reflect on and revise their own teaching practices through close collaboration with other teachers at both the national and international levels, and by providing educators with the necessary methodological resources for STEM education.

The programme included the theoretical foundations of modern STEAM teaching methods and offered participants the opportunity to apply them in their own practice. The course also featured practical sessions that utilise PBL (Project-Based Learning), CER (Claim, Evidence, Reasoning), and modelling. These approaches are aimed at developing critical thinking, analytical skills, and the ability to solve complex problems.

In developing the Programme, the requirements of the State Compulsory Standards for Higher and Postgraduate Education, approved by Order No. 2 of the Minister of Science and Higher Education of the Republic of Kazakhstan dated July 20, 2022, were taken into account, as well as the State Compulsory Standards for Preschool Education and Training, Primary, Basic Secondary, and General Secondary, Technical and Vocational, and Post-Secondary Education, approved by Order No. 348 of the Minister of Education of the Republic of Kazakhstan dated August 3, 2022.

The Programme was developed based on the Rules for the Development, Coordination, and Approval of Professional Development Courses for Teachers (Annex 1 to the Order of the Minister of Education and Science of the Republic of Kazakhstan No. 175 dated May 4, 2020). The relevance of the Programme is driven by the realities of the modern world and the emerging Society 5.0 strategy, which aims to balance economic progress with the resolution of social issues through systems that closely integrate cyberspace with the physical human environment. Consequently, the education system must quickly adapt to new global trends that focus on developing creative potential through training in digital technologies and the hard sciences.

The aim of the research is to evaluate the changes in teachers' approach to lesson planning and classroom instruction after completing a professional development course on CER, PBL, and modelling tools as a part of the "*Strengthening Teacher Education Programme*" project.

The objectives of the research

a) to analyse the structure and quality of the lesson plans developed by participants after completing the course.
b) to examine the implementation of the newly acquired methods in classroom practice based on the lesson video recordings.
c) to identify the main challenges in applying the methods in teaching practice.
d) to evaluate the overall contribution of the course to the professional growth of the science teachers.

Analysis of teachers' lesson plans was based on such criteria as the clarity of learning objectives, the application of CER and modelling methods, student-teacher interaction, assessment strategies and student engagement.

Analysis of the implementation of the acquired methods in classroom practice based on lesson video recording focusing lesson structure, student engagement, use of SageModeler, teacher reflection.

Preliminary data screening was conducted to ensure validity. The Shapiro–Wilk test indicated that the data were not normally distributed ($p < 0.05$), therefore Spearman's rank correlation was applied. The dataset included 68 valid observations, while 15 cases were excluded due to incomplete entries.

How effectively do participants implement CER and SageModeler strategies in classroom practice, as reflected in the structure of the lesson, student engagement, use of modelling tools, and teacher reflection?

The correlation analysis showed a strong positive relationship between modelling and student engagement (see Table 1).

Table 1

Descriptive Statistics for Lesson Structure, Student Engagement, Use of SageModeler, and Teacher Reflection

Variable	Median	Mean	Std. Deviation
Lesson Structure	2.000	2.244	1.236
Student Engagement	3.000	2.651	1.156
Use of SageModeler	3.000	2.488	1.253
Teacher Reflection	1.000	1.140	1.303

Variables for descriptive analysis - Structure of the Lesson, Student Engagement, Use of SageModeler, Teacher Reflection - Mean, Median, Standard Deviation

Correlation - Does use of SageModeler correlate with stronger teacher reflection? Does strong lesson structure correlate with higher student engagement?

What is the relationship between the quality of lesson plans and the effectiveness of classroom implementation among teachers who completed the course? Additional descriptive data for lesson-planning components are provided in Table 2.

Table 2

Descriptive Statistics for Lesson-Planning Components and Student Engagement

Variable	Median	Mean	Std. Deviation
Clarity of Objectives	5.000	4.809	0.396
CER and Modelling	3.000	3.239	0.955
Interaction	3.000	3.209	0.978
Assessment Strategies	3.000	2.343	1.582
Student Engagement	3.000	3.075	0.990

The descriptive analysis shows moderate variation across most indicators. Student engagement and the use of SageModeler received relatively higher mean values, while teacher reflection demonstrated the lowest scores, indicating potential areas for professional growth.

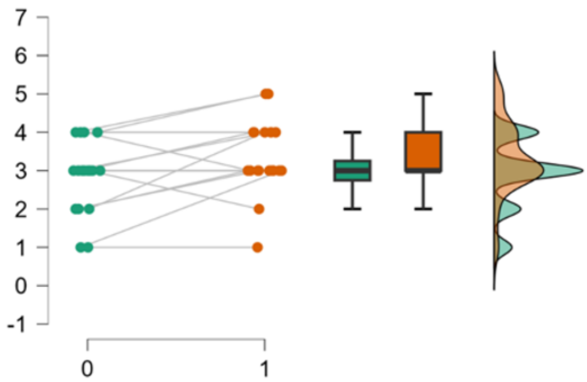
3. Results

3.1 Changes in the Use of CER and SageModeler

Paired t-test results showed a statistically significant improvement in the use of the CER methodology after the completion of the course ($t = –2.179$, $p = 0.042$). This indicates that participants became more confident and systematic in applying CER in their lessons. The Figure 1 below presents the comparison of teachers' self-assessment scores for the application of CER before and after the training, where green dots indicate self-assessment during the first lessons; orange dots indicate self-assessment during subsequent lessons. Each line represents changes in individual teachers' ratings, while the box plots display the overall distribution of scores. Higher values reflect more frequent and consistent use of CER strategies in lesson planning and implementation.

Figure 1

Use of CER Before and After the Course (Self-Assessment)



3.2 Student Activity

According to teachers' self-assessment, student activity significantly increased during subsequent lessons after the course ($t = –2.979$, $p = 0.008$), which may indicate higher student engagement resulting from the implementation of new methods. However, expert assessment did not reveal statistically significant changes ($t = –0.679$, $p = 0.505$), which may be explained by variations in classroom conditions or subjective perception factors.

Figure 2 shows the comparison of student activity according to teachers' and experts' assessments (green – first lessons; orange – subsequent lessons). The differences in teacher-reported scores are presented in Figure 2, while the results based on expert video observations are illustrated in Figure 3.

Figure 2

Student Activity According to Teachers' Assessment

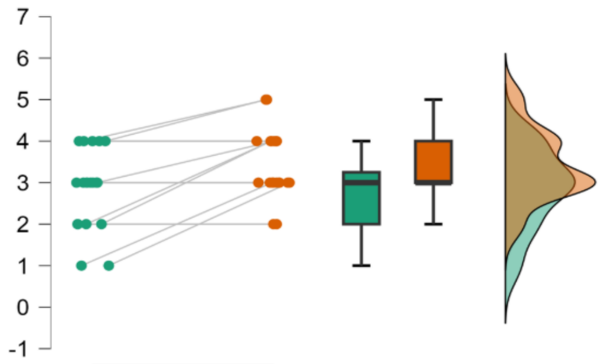
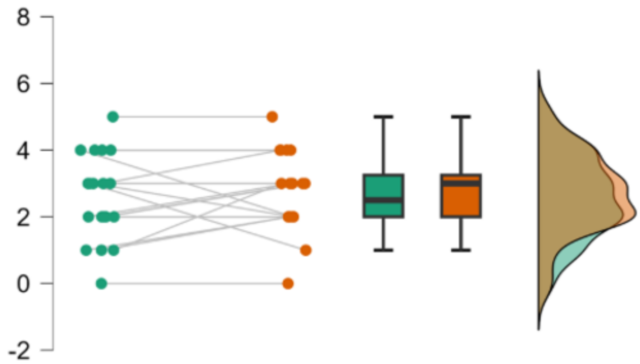


Figure 3

Student Activity According to Experts' Assessment



3.3 Correlation Relationships

A strong positive correlation was found between the use of SageModeler and student activity ($\rho = 0.758$, $p < 0.001$).

A moderate positive correlation was observed between the use of SageModeler and the depth of teacher reflection ($r = 0.29$).

A weak correlation was found between lesson structure and student engagement ($r = 0.16$), which may indicate the influence of external factors.

3.4 Lesson Planning Quality and Implementation Effectiveness

Spearman correlation analysis (see Table 1) showed that such components as interaction ($\rho = 0.838$), the use of CER and modelling ($\rho = 0.728$), and knowledge assessment ($\rho = 0.599$) have a strong positive relationship with student activity. The clarity of learning objectives did not show a significant correlation ($\rho = 0.138$, $p = 0.265$).

Table 3

Correlations Between Lesson Components and Student Activity

Value	Student Activity (ρ)	p-value
Clarity of objectives	0.138	0.265
CER and modelling	0.728	<0.001
Interaction	0.838	<0.001
Knowledge assessment	0.599	<0.001

It was also confirmed that the use of CER improved in subsequent lessons (see above), and that the increase in student engagement, according to teachers, was associated with the implementation of modelling and the interpretation of real-world data in tasks.

The results confirm the effectiveness of short-term professional development courses focused on practice-oriented learning and digital tools. Participants not only mastered the methodologies but also applied them in real classroom settings, particularly in terms of enhancing student engagement. However, the discrepancy between self-assessment and expert evaluation emphasises the importance of data triangulation and the need for classroom observations in authentic contexts. The findings of this study align with the national trends described by Zhumabay et al. (2024), who noted that teacher preparedness and methodological consistency remain key challenges for effective STEM education in Kazakhstan. The results of the current research further support the importance of targeted professional development focused on applied, practice-based approaches such as CER.

4. Discussion

The findings of this study support international research indicating that practice-oriented professional development can enhance teachers' capacity to implement STEM pedagogies effectively. The significant improvement in CER usage suggests that structured scaffolding and repeated application opportunities are essential for developing teachers' inquiry-based reasoning skills, a core element of scientific literacy.

From a theoretical perspective, the results can be interpreted through the lens of constructivist and sociocultural learning theories. CER and PBL align with constructivist principles by positioning learners as active knowledge builders who generate claims, justify them with evidence, and refine understanding through reasoning. Modelling tools such as SageModeler further support this process by enabling external representation of abstract concepts, consistent with cognitive apprenticeship and representational competence frameworks.

The strong association between modelling and student engagement aligns with prior studies emphasising the role of digital tools in supporting conceptual understanding, exploratory learning, and sense-making in STEM classrooms. Modelling activities appear to foster epistemic agency among students, while simultaneously prompting teachers to reflect on instructional decisions and student responses.

The discrepancy between teacher self-assessments and expert evaluations underscores the importance of triangulated data sources in professional development research. This finding suggests that ongoing feedback mechanisms, peer observation, and instructional coaching may be necessary to support accurate self-reflection and sustained pedagogical change.

Limitations of the study include the relatively small sample size, the short duration of the intervention, and reliance on self-reported data, which may limit the generalisability of the findings. Future research should explore longitudinal impacts, incorporate student learning outcomes, and examine how sustained mentoring influences the durability of instructional change.

5. Conclusion

The results of this study demonstrate that the professional development course integrating CER, PBL, and SageModeler methodologies had a meaningful and measurable impact on teachers' instructional practices and their understanding of STEM-oriented pedagogies. The evidence collected from lesson plans, classroom observations, and self- and expert assessments confirm that even short-term, practice-oriented professional development can significantly shift teachers' approaches toward more inquiry-based, evidence-driven, and technology-enhanced instruction.

A key outcome of the programme was the noticeable improvement in teachers' ability to apply the CER framework. Statistical analysis indicated a significant increase in the systematic use of CER strategies in lesson planning and classroom implementation. This suggests that teachers not only acquired theoretical knowledge but were also able to transfer it into practice, creating learning environments where students justify their claims, rely on evidence, and articulate reasoning—core competencies of STEM education.

Furthermore, the study found a strong positive correlation between the use of modelling tools and student engagement. Teachers who actively integrated SageModeler into their lessons observed higher levels of participation, inquiry, and interaction among students. This reinforces the idea that digital modelling tools can transform traditional lessons into dynamic learning experiences where students explore real-world phenomena, test hypotheses and visualise abstract concepts. Importantly, modelling was also associated with deeper teacher reflection, indicating that the use of digital tools supported not only student learning but also teachers' ability to analyse and refine their instructional decisions.

Another key insight of the research concerns lesson planning quality. The correlation analysis showed that interaction, CER application, modelling, and assessment strategies were the strongest predictors of active student engagement. This finding highlights the importance of designing lessons that are not only structured and goal-oriented but also interactive, student-centred, and supported by diverse assessment tools. While clarity of learning objectives remains essential, the results indicate that it is the practical, hands-on aspects of the lesson—rather than the declarative formulation of objectives—that most strongly influence student participation.

Despite the positive outcomes, the study also revealed discrepancies between teachers' self-assessments and expert evaluations, particularly in terms of student activity. This gap suggests the need for ongoing, structured feedback and the inclusion of classroom observations in teacher development processes. Such triangulation helps ensure that professional growth is based on authentic, evidence-based insights rather than subjective impressions.

Overall, the results show that professional development focused on applied STEM practices has significant potential to enhance teacher readiness for innovative instruction in Kazakhstan. By providing educators with accessible tools, collaborative learning environments, and opportunities for practical experimentation, programmes like the "*Strengthening Teacher Education Programme*" can contribute to national efforts to modernise STEM education and align it with global trends. The integration of CER, PBL, and modelling methods supports not only the development of students' scientific literacy and critical thinking but also strengthens teachers' capacity for reflective, technology-rich, and research-informed pedagogy.

In conclusion, the study confirms that well-designed, practice-centred professional development serves as a powerful mechanism for promoting STEM transformation in Kazakhstani schools and universities. Continued investment in such programmes, along with sustained methodological support and opportunities for professional networking, will be essential for scaling innovation and preparing educators for the demands of Society 5.0 and the rapidly evolving global labour market.

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NAVIGATING THE PATH TO REGIONAL COLLABORATION: THE SOUTHEAST ASIAN TEACHER EDUCATION PROGRAMME (SEA-TEP)

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ABSTRACT

This study evaluates the Southeast Asian Teacher Education Programme (SEA-TEP), a collaborative professional development initiative in Cambodia aimed at strengthening pre-service teachers' capacity in inquiry-based STEM pedagogies. Using a mixed-methods, quasi-experimental action research design with 264 participants across three Teacher Education Institutions, the programme centred on the Claim-Evidence-Reasoning (CER) framework and integrated STEM learning units. Results showed a significant improvement in teachers' self-perceived CER understanding (mean scores rising from 56.06 to 97.50, $p < .001$), alongside a marked pedagogical shift toward inquiry-based facilitation. Yet systemic barriers—including resource shortages and curricular pressures—created an "*implementation chasm*," limiting the translation of training into practice. This "*Success Paradox*" highlights the need for systemic coherence, urging policymakers to align curriculum, assessment, and resource allocation with inquiry-based approaches. While grounded in Cambodia, the findings carry broader relevance for Southeast Asia, offering actionable insights for SEAMEO member countries seeking to embed modern STEM pedagogies within diverse and resource-constrained teacher education systems.

Keywords: SEA-TEP, STEM Education, Teacher Professional Development, Inquiry-Based Learning, Claim-Evidence-Reasoning (CER), Cambodia

1. Introduction

Across Southeast Asia, the demand for high-quality science, technology, engineering, and mathematics (STEM) education has intensified as nations strive to cultivate the human capital necessary for 21st-century innovation and economic competitiveness. The Southeast Asian Teacher Education Programme (SEA-TEP), launched by the Southeast Asian Ministers of Education Organization Regional Centre for STEM Education (SEAMEO STEM-ED), represents a strategic response to these needs. The programme seeks to enhance the capacities of teacher education faculty and teacher development personnel across SEAMEO member countries—specifically Cambodia, Indonesia, Kazakhstan, Malaysia, and Thailand—by integrating inquiry-based STEM pedagogies and research collaboration into pre-service and in-service teacher education systems.

In Cambodia, SEA-TEP is jointly implemented by the Department of Research and Innovation (DRI) under the Ministry of Education, Youth and Sport (MoEYS), in partnership with three Teacher Education Institutions (TEIs): the National Institute of Education (NIE), Phnom Penh Teacher Education College (PTEC), and Battambang Teacher Education College (BTEC). The initiative comprises two major components: (1) professional development activities that train educators on inquiry-based STEM learning units—Water Quality, Health in Our Hands, and Interactions—using the Claim–Evidence–Reasoning (CER) and Modelling frameworks; and (2) a research component that evaluates the programme's impact on participants' competencies, teaching practices, and institutional support structures. Within Cambodia's broader educational reform agenda, SEA-TEP aligns with major policy papers, such as the Teacher Career Pathways Framework (Ministry of Education, Youth and Sport, 2021) and the Continuous Professional Development (CPD) Framework (Ministry of Education, Youth and Sport, 2019), which emphasise competency-based teacher growth and inquiry-driven pedagogy.

Despite strong national policy commitments to inquiry-based and competency-oriented teaching, Cambodian teacher education continues to be characterised by predominantly teacher-centred instructional practices that provide limited opportunities for inquiry, problem-solving, and evidence-based reasoning (King, 2018). Within TEIs, pedagogical preparation remains heavily weighted toward theoretical knowledge, while opportunities for sustained, practice-embedded professional development are fragmented and short-term. As a result, both pre-service teachers and teacher educators face persistent challenges in translating policy aspirations for inquiry-based learning into authentic classroom practice.

The SEA-TEP constitutes a strategically significant intervention designed to address this policy–practice gap by introducing structured inquiry-based pedagogical frameworks—specifically CER and scientific modelling—within pre-service teacher education. However, despite SEA-TEP's regional prominence, empirical evidence remains limited regarding how and to what extent such regional professional development initiatives strengthen teacher competencies, reshape classroom practices, and interact with institutional conditions in low-resource teacher education systems such as Cambodia's. Existing studies have tended to emphasise policy alignment or training design, leaving insufficient attention to implementation dynamics, institutional readiness, and the sustainability of pedagogical change. Accordingly, this study systematically examines the outcomes and implementation dynamics of SEA-TEP in Cambodia by investigating changes in pre-service teachers' inquiry-based pedagogical competencies, experiences of classroom transformation, and the institutional conditions that shape the translation of professional development into practice.

1.1 Objectives of the Study

To achieve the stated purpose, this study aimed to evaluate the effectiveness and contextual dynamics of the SEA-TEP professional development programme in strengthening pre-service teachers' competencies in the CER framework and integrated STEM learning units, and to generate evidence-based insights to support the translation and strategic scaling of inquiry-based STEM education in Cambodia. The study aimed to address three research questions.

1. To what extent does participation in the SEA-TEP professional development programme change pre-service teachers' self-perceived competencies in the CER framework and in implementing the three integrated STEM learning units—Water Quality, Health in Our Hands, and Interactions?
2. How do pre-service teachers and teacher educators experience pedagogical transformation through SEA-TEP, particularly with regard to shifts in classroom dynamics and the evolving role of the teacher from instructor to facilitator of inquiry?

3. What systemic, institutional, and practical barriers—including resource availability, curricular pressures, and institutional culture—influence the translation of newly acquired competencies into authentic classroom practice?

2. Literature Review

2.1 Teacher education and professional development in Southeast Asia

Teacher education plays a pivotal role in shaping national competitiveness across Southeast Asia, yet the region continues to face uneven teacher qualifications, limited access to high-quality professional development, and inconsistent adoption of learner-centred pedagogies (Woo et al., 2024; Popova et al., 2022). Regional mechanisms such as SEAMEO have increasingly promoted collaborative learning, joint research, and knowledge exchange to reduce these disparities. Empirical studies show that sustained, practice-embedded professional development—rather than short-term training—produces deeper instructional change (Patfield et al., 2023; Smith & Gillespie, 2023). Programmes that integrate cross-country mentorship and co-developed teaching practices, such as SEA-TEP, offer a promising pathway to enhancing teacher capacity while strengthening regional alignment with SDG 4 (Barrot, 2023; Conallin et al., 2022).

Compared with many inquiry-based STEM professional development initiatives documented in the literature, SEA-TEP exhibits several distinctive features. While widely studied models emphasise sustained, school-based coaching (Darling-Hammond et al., 2017), lesson study and teacher collaboration (Nguyen & Ng, 2022), or curriculum-embedded inquiry cycles (Pedaste et al., 2015), SEA-TEP operates as a regionally coordinated, cross-institutional professional development model embedded within pre-service teacher education systems. Unlike short-term workshop-based interventions that often focus on individual teacher change, SEA-TEP combines structured pedagogical frameworks (CER and modelling), regional knowledge exchange, and an explicit research component aimed at institutional learning. This positioning situates SEA-TEP between classroom-focused professional development and system-oriented reform, making its implementation dynamics and outcomes analytically distinct from existing inquiry-based STEM initiatives.

2.2 Teacher Professional Development and STEM Education in Cambodia

Cambodia's teacher education reforms have progressed from addressing basic workforce shortages to building competency-based, lifelong professional learning systems (Tep, 2024). Key policy milestones include the Policy on Teachers (Ministry of Education, Youth and Sport, 2013), the Teacher Career Pathways Framework (MoEYS, 2018), and the CPD Framework (Ministry of Education, Youth and Sport, 2019), each emphasising reflective practice and instructional improvement. Recent reforms explicitly prioritise STEM and inquiry-based learning as national CPD objectives (Ministry of Education, Youth and Sport, 2023), supported by initiatives such as Strengthening Teacher Education Programme in Cambodia (STEPCam) project, which upgraded TEI infrastructure and digital capability (UNESCO, 2024).

Within this environment, SEA-TEP aligns closely with national aspirations by piloting advanced pedagogical models for pre-service teachers—bridging policy intent with classroom practice and contributing to Cambodia's modernisation of STEM teacher preparation.

2.3 Inquiry-Based Science Education as a Pedagogical Foundation

Inquiry-Based Science Education (IBSE) situated learning as an active process of investigation, evidence-gathering, and explanation-making, distinguishing it from traditional, lecture-based instruction (Pedaste et al., 2015; Duschl & Grandy, 2008). Research consistently shows that IBSE enhances conceptual understanding, motivation, and scientific reasoning (Gillies, 2023; Minner et al., 2010). However, adopting IBSE requires teachers to shift from "*content deliverers*" to facilitators of inquiry—an identity shift that is particularly challenging in hierarchical and exam-oriented educational cultures such as Cambodia's (Thy et al., 2023).

SEA-TEP's professional development model seeks to operationalise IBSE through structured frameworks that support teachers in guiding students' thinking and sense-making.

2.4 Integrated Pedagogical Framework: CER And Modelling

Within IBSE, two mutually reinforcing frameworks—Claim–Evidence–Reasoning (CER) and scientific modelling—provide concrete structures for helping students think and act like scientists.

2.4.1 Claim–Evidence–Reasoning (CER)

The CER framework, widely recognised for strengthening scientific argumentation, guides learners to articulate a claim, support it with empirical evidence, and justify it through scientific reasoning (McNeill & Krajcik, 2012). CER has been shown to improve critical thinking, explanation writing, and teachers' pedagogical content knowledge (Gao et al., 2022; Osborne, 2023). Effective implementation requires teachers to model argumentation, scaffold student reasoning, and assess the quality of claims and evidence—competencies central to inquiry teaching.

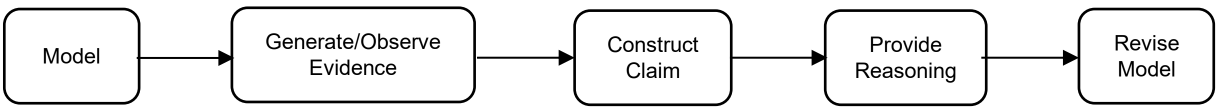
2.4.2 Scientific Modelling and Systems Thinking

Modelling involves constructing representations of phenomena, testing relationships among variables, and revising explanations based on evidence (Chen, 2022; Schwarz et al., 2022). Digital tools such as SageModeler allow learners to visualise causal relationships and engage in computational systems thinking (Kite & Park, 2023; Bowers et al., 2022).

Rather than functioning as isolated techniques, CER and modelling form an iterative inquiry cycle:

Figure 1

Iterative Reasoning Process in Inquiry-Based STEM



This combined approach deepens conceptual understanding, strengthens metacognition, and aligns with contemporary science education standards internationally. SEA-TEP intentionally integrates CER and modelling to enhance pre-service teachers' instructional competencies across the three STEM learning units.

2.5 Systemic Challenges to Implementing Innovative Pedagogies

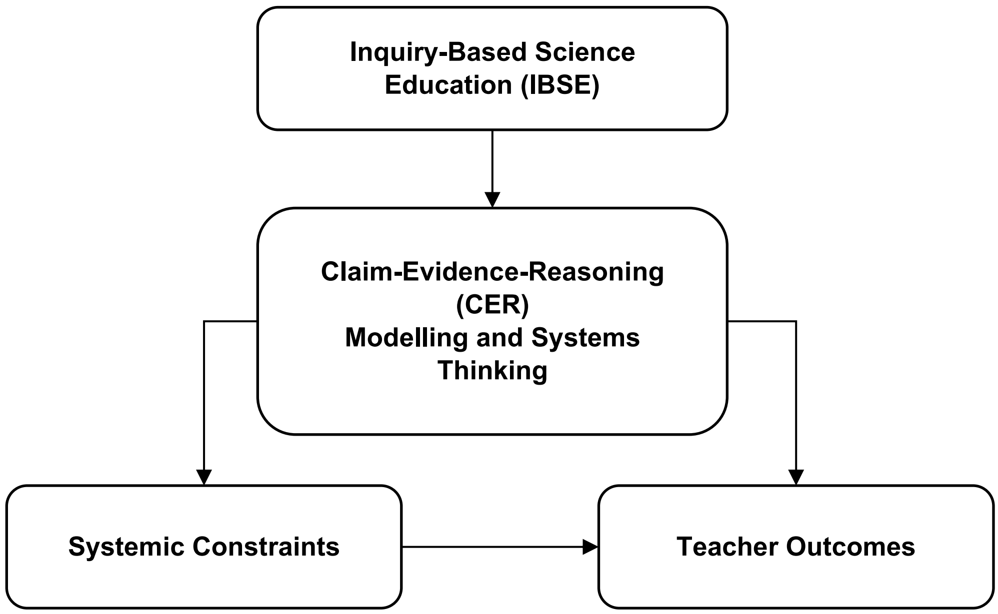
Despite strong policy foundations, implementing inquiry-based approaches in Cambodia is constrained by systemic and institutional barriers. TEIs often face shortages of laboratory resources, digital tools, and reliable internet—limitations that hinder the facilitation of hands-on or modelling-based activities (Phirom et al., 2021; Asian Development Bank, 2022). Teacher educators also report limited prior exposure to contemporary STEM pedagogies and insufficient time within rigid curricula to experiment with inquiry-oriented lessons (Ly, 2023). Additionally, assessment systems still reward memorisation, and hierarchical classroom norms discourage student questioning and collaborative reasoning.

These constraints highlight that sustainable pedagogical reform requires aligned institutional policies, leadership support, and continuous professional learning—not short-term training alone (Guskey, 2016; Fullan, 2015).

2.6 Conceptual Foundation for the Present Study

Figure 2

Conceptual Model of CER–Modelling Pedagogical Integration and Teacher Outcomes



The pedagogical foundation of SEA-TEP is rooted in IBSE, operationalised through two core instructional strategies: the CER framework and modelling and systems thinking. These approaches were central to the PD intervention and served as anchors for both instructional design and teacher facilitation.

As illustrated in Figure 2, the conceptual framework positions IBSE at the top, cascading into CER and systems thinking as parallel pedagogical tools. These, in turn, interact with two critical forces: systemic constraints and teacher outcomes. The left pathway highlights persistent implementation barriers—such as resource shortages, curricular rigidity, and institutional inertia—while the right pathway reflects the pedagogical transformation observed among participating teachers, including improved inquiry facilitation and conceptual clarity. The horizontal bidirectional arrow between systemic constraints and teacher outcomes represents a feedback loop: while effective training can elevate teacher practice, unresolved systemic issues can undermine sustainability.

Importantly, this framework offers broader relevance for Southeast Asian education systems. For SEAMEO member countries navigating similar reform challenges, it provides a scalable model for embedding inquiry-based STEM pedagogies while highlighting the need for systemic coherence across curriculum, assessment, and resource allocation.

The literature points to a clear gap between Cambodia's policy aspirations for inquiry-based STEM education and the realities in TEIs. While IBSE, CER, and modelling provide strong pedagogical foundations, their successful implementation depends on systemic alignment, institutional capacity, and sustained professional development. This study addresses this gap by examining:

1. Pre-service teachers' competency gains in CER and integrated STEM learning units,
2. Their lived experiences of pedagogical transformation, and
3. The systemic and institutional factors shaping implementation.

By integrating quantitative measures with qualitative insights, the study contributes context-specific evidence to inform SEA-TEP's improvement, national STEM teacher preparation, and broader regional collaboration goals.

3. Methodology

3.1 Research Design

This study adopted a mixed-methods, quasi-experimental design grounded in an action research framework to evaluate the effectiveness of the SEA-TEP in Cambodia. A one-group design was utilised because the study aimed to include all three major teacher education institutions in the country, leaving no comparable sites available for a control group. The overall research design comprised two complementary strands: a quantitative component to assess measurable changes in pre-service teachers' competencies, and a qualitative component to generate deeper insights into pedagogical shifts, implementation processes, and contextual factors shaping programme outcomes.

The quantitative strand utilised a pre-test/post-test design to assess pre-service teachers' self-perceived competencies in the CER framework and three integrated STEM learning units (Water Quality, Health in Our Hands, and Interactions). The qualitative strand involved Focus Group Discussions (FGDs), Key Informant Interviews (KIIs), and professional development (PD) workshop observations to explore teacher educators' and pre-service teachers' experiences, challenges, and reflections on pedagogical change. The synthesis of quantitative impact data with qualitative contextual findings occurred at the interpretation stage, generating comprehensive, evidence-based insights, a design aligned with best practices for evaluating complex educational interventions (Creswell & Plano Clark, 2017).

3.2 Research Sites and Participants

The study was conducted at three key TEIs in Cambodia: NIE, PTEC, and BTEC. These TEIs were purposely selected by the Department of Research and Innovation (DRI) of the MoEYS due to their pivotal roles in pre-service teacher training and formal engagement under the SEA-TEP sub-grant agreements. The project involved a total of 594 participants across multiple activity components, comprising 399 pre-service teachers, 126 in-service teachers, and 69 teacher educators and programme coordinators. This figure reflects overall engagement in SEA-TEP training, professional development, and research activities. However, the analytic sample for the quantitative study was smaller. Of the 399 pre-service teachers, only 264 (66%) completed both the pre-test and post-test surveys. Pre-service teachers who completed only one survey (either the pre-test or the post-test) were excluded from the quantitative analysis due to incomplete paired data requirements. Consequently, the quantitative findings reported in this study are based on responses from these 264 participants.

3.3 Instruments and Measures

3.3.1 Quantitative Instrument

A structured questionnaire was developed to measure participants' self-perceived competencies in two domains, each comprising 25 items rated on a 5-point Likert scale (1 = Very Poor to 5 = Excellent). The CER Framework Competency instrument covered five subdomains: Foundational knowledge of CER, Pedagogical content knowledge for teaching CER, Skills in designing and facilitating CER, Skills in assessment and differentiation, and Beliefs about CER's impact and application. The STEM Learning Unit Competency instrument assessed competence in inquiry-, project-, and design-based learning; application of instructional frameworks and tools; classroom facilitation and management; and holistic integration and contextualisation. The instrument was developed in Khmer, pilot-tested with 84 in-service teachers, and refined for clarity and accuracy. Internal consistency was excellent (Cronbach's alpha = .981), and item-total correlations exceeded .765, confirming reliability and meaningful contribution of all items (Hair et al., 2018).

3.3.2 Qualitative Instruments

Three qualitative tools were employed: a FGD Guide to capture pre-service teachers' experiences with inquiry-based pedagogy and classroom application; a KII Protocol to elicit institutional perspectives from TEI leaders and project staff on implementation challenges, support, and sustainability; and a Workshop Observation Checklist to record evidence of pedagogical practices, engagement patterns, and resource use during PD sessions. All instruments were reviewed by the SEA-TEP research committee to ensure content validity and contextual appropriateness.

3.4 Data Collection Procedures

Data collection occurred in three sequential phases during the 2024–2025 academic year. Phase I focused on Instrument Development and Validation, where the competency instrument was collaboratively designed and piloted with 84 in-service teachers; feedback was incorporated to refine items for the main study. Phase II, Quantitative Data Collection, involved pre-service teachers completing the digital pre-test survey via Google Forms before the SEA-TEP training and the post-test survey immediately after, with data automatically captured and anonymised. Phase III, Qualitative Data Collection, included conducting FGDs and KIIs at each TEI, facilitated in Khmer language, recorded with consent, and transcribed for analysis. Direct observations of PD workshops provided necessary triangulation to verify self-reported findings, ensuring methodological rigor and depth of understanding.

While this study relies on self-perceived competency measures, which may be influenced by response bias or participants' confidence rather than direct observation of instructional practice, such measures are widely used in professional development research to capture changes in teachers' pedagogical understanding and readiness to implement new approaches. In the context of this study, self-assessment was appropriate given the scale of the intervention across multiple Teacher Education Institutions and the focus on early-stage pedagogical change following professional development. To mitigate the limitations of self-reported data, the quantitative findings were triangulated with qualitative evidence from focus group discussions, key informant interviews, and workshop observations, allowing for a more robust interpretation of competency development and implementation dynamics.

3.5 Data Analysis

3.5.1 Quantitative Analysis

Quantitative data were analysed using IBM SPSS Statistics (Version 27). Analytical procedures included descriptive statistics (mean, standard deviation) to summarise competency levels, paired-sample t-tests to assess significant changes between pre- and post-test scores, and comparative analyses by institution and learning unit. All analyses were conducted at a 95% confidence level ($p < .05$) and visualised using tables and graphs.

3.5.2 Qualitative Analysis

Transcripts from FGDs, KIIs, and observation notes were analysed using thematic analysis following Braun and Clarke's (2006) six-step approach (Familiarisation, Coding, Identification of themes, Review/refinement, Definition/naming, and Integration). Inter-coder reliability was ensured through collaborative coding sessions. Themes were grouped around four core dimensions: (1) Pedagogical transformation, (2) Shifts in classroom dynamics, (3) Systemic constraints, and (4) Emerging best practices. The resulting qualitative insights were cross-referenced with quantitative outcomes to ensure validity through data triangulation.

3.6 Ethical Considerations

This study was conducted in accordance with ethical standards for educational research. Institutional approval was obtained through the DRI of the MoEYS prior to data collection. Participation was voluntary, and informed consent was obtained from all participants before the administration of surveys, focus group discussions, interviews, and workshop observations. Participants were informed of the purpose of the study, the use of data for research purposes only, and their right to withdraw at any stage without penalty. To ensure confidentiality, all data were anonymised, and no personally identifiable information was included in the analysis or reporting.

4. Findings

4.1 Overview

This section presents the key findings from the mixed-methods evaluation of the SEA-TEP in Cambodia. Quantitative results from the pre-test and post-test surveys provide evidence of changes in pre-service teachers' competencies, while qualitative findings derived from FGDs, KIIs, and PD workshop observations capture the lived experiences, perceived transformations, and implementation challenges among participating stakeholders.

4.2 Quantitative Findings

4.2.1 Participant Profile

The quantitative phase included 264 pre-service teachers across the three TEIs: BTEC, PTEC, and NIE. The sample comprised 70.8% female and 29.2% male participants, representing the typical gender distribution in pre-service teacher cohorts in Cambodia. Participants specialised in biology, chemistry, and physics and were enrolled in programmes that integrated the SEA-TEP professional development components.

4.2.2 Impact on CER Competencies

Self-perceived competencies in the CER framework were assessed across five domains using a five-point Likert scale (1 = Very Poor to 5 = Excellent). Post-intervention results indicate a broadly consistent pattern of competency development across all domains, suggesting that participants developed a coherent understanding of both the conceptual foundations and pedagogical applications of CER. In particular, the findings point to strengthened confidence in designing and facilitating CER-aligned learning activities, as well as in recognising the role of CER in promoting student inquiry and scientific reasoning. Together, these patterns suggest that the SEA-TEP intervention supported not only domain-specific knowledge but also an integrated pedagogical orientation toward inquiry-based instruction.

Table 1

Descriptive Statistics on Post-Intervention CER Competencies (N = 264)

CER Competency	Mean	SD	Interpretation
Foundational Knowledge of CER	3.92	0.46	Good
Pedagogical Content Knowledge for Teaching CER	3.86	0.45	Good
Skill in Designing and Facilitating CER	3.86	0.50	Good
Skill in Assessment and Differentiation	3.75	0.55	Good
Beliefs about CER's Impact and Application	4.02	0.48	Strong

4.2.3 Pre- and Post-Test Comparison

A paired-samples t-test showed a significant increase in overall CER competency scores from pre- to post-intervention ($t(263) = 34.60$, $p < .001$). Beyond statistical significance, the observed change suggests substantial practical gains in participants' capacity to design, facilitate, and assess CER-aligned inquiry activities. Beyond statistical significance, this improvement represents a substantial practical shift in participants' readiness to design, facilitate, and assess inquiry-based learning using the CER framework. The marked increase and reduced variability in post-test scores suggest not only overall competency gains but also greater consistency in participants' understanding and application of CER practices following professional development.

4.2.4 Competency Gains by STEM Learning Unit

Separate analyses were conducted for each of the three integrated STEM learning units. All units demonstrated significant improvement between pre- and post-test scores ($p < .001$).

Table 2

Pre- and Post-Test Results for STEM Learning Units

STEM Learning Unit	Pre-test M (SD)	Post-test M (SD)	t(df)	p	Interpretation
Water Quality (Chemistry)	59.02 (18.14)	95.11 (11.92)	–17.70 (92)	< .001	Significant Gain
Interactions (Physics)	60.29 (17.48)	90.81 (15.63)	–13.31 (84)	< .001	Significant Gain
Health in Our Hands (Biology)	59.33 (17.24)	94.77 (13.30)	–18.31 (85)	< .001	Significant Gain

These results confirm that SEA-TEP's professional development activities produced substantial increases in participants' self-assessed competencies across all disciplinary areas, reinforcing the programme's overall effectiveness.

Beyond statistical significance, these gains indicate that participants were able to transfer inquiry-based pedagogical principles across disciplinary contexts rather than developing unit-specific or isolated competencies. The consistently large increases observed in chemistry (Water Quality), physics (Interactions), and biology (Health in Our Hands) suggest that SEA-TEP's PD model effectively supported adaptable inquiry-based teaching practices applicable across STEM domains. This cross-disciplinary improvement underscores the practical value of the programme in preparing pre-service teachers to implement inquiry-oriented instruction in diverse subject areas within teacher education curricula.

4.3 Qualitative Findings

Qualitative data from FGDs, KIIs, and workshop observations enriched the quantitative findings by revealing participants' perspectives on pedagogical change, contextual barriers, and emerging best practices. Four major themes emerged from the thematic analysis.

Theme 1: Pedagogical Transformation through Inquiry-Based Approaches

Participants consistently reported a profound conceptual shift from teacher-centred to student-centred, inquiry-based teaching. The CER and Modelling frameworks were viewed as transformative tools that enabled learners to think like scientists rather than passive recipients of knowledge.

"The CER framework is like inquiry-based learning—simple but powerful for helping students explain phenomena with logic and evidence." (Pre-service teacher, BTEC)

Educators emphasised that SEA-TEP allowed them to internalise the logic of inquiry—understanding how claims, evidence, and reasoning interconnect—and to guide students through hands-on experiments, data analysis, and scientific argumentation. Many described the approach as "*a new way of teaching science that connects to real life*."

Theme 2: Shifts in Classroom Dynamics and Learner Engagement

The implementation of inquiry-based strategies brought visible changes in classroom interactions. Teachers observed that students became more active, communicative, and analytical, contrasting sharply with prior lecture-based routines.

"When I used CER activities, students were excited to share ideas, test their thinking, and draw conclusions. The class became more alive." (Teacher Educator, NIE)

Teachers also reported that group collaboration fostered peer learning and critical discussion. Comparatively, control-group observations (where traditional instruction persisted) revealed low student participation and surface-level understanding, underscoring the added value of SEA-TEP pedagogies.

Theme 3: Systemic Constraints and Implementation Challenges

Despite the programme's success, participants identified several barriers that constrained implementation fidelity. These include:

1. Resource limitations — inadequate laboratory materials, limited ICT access, and unreliable internet connectivity, particularly in provincial TEIs.
2. Time constraints — difficulty balancing curriculum coverage with inquiry-based activities during tight academic schedules.
3. Human capital and institutional factors — large classes, language barriers, and teacher resistance to shifting from traditional methods.

"We lack equipment and materials for experiments, and some teachers still prefer lecturing—it's hard to change old habits." (Teacher Educator, PTEC)

These challenges highlight the need for systemic alignment between professional development, curriculum design, and institutional support mechanisms.

Theme 4: Emerging Best Practices and Conditions for Sustainability

Participants proposed key strategies for sustaining SEA-TEP's impact beyond the project period:

1. Continuous professional learning — establishing regular refresher training and peer-mentoring systems for teacher educators.
2. Integration into national policy and curricula — embedding CER and Modelling frameworks within the MoEYS teacher education standards.
3. Institutional collaboration — fostering networks among TEIs for joint resource sharing and research.
4. Material and technical support — ensuring access to essential teaching resources, digital platforms, and localised training materials.

"*SEA-TEP should be continued and included in the national teacher curriculum. All science teachers need this kind of training."* (Pre-service teacher, PTEC)

5. Discussion

The findings of this study present a compelling, albeit complex, narrative of the SEA-TEP implementation in Cambodia. The quantitative data provides unequivocal evidence of the programme's success in enhancing the pedagogical competencies of pre-service teachers, while the qualitative data offers a nuanced and critical perspective on the systemic realities that mediate the translation of these new competencies into practice. This discussion synthesises these two data streams to interpret the core dynamics at play, organised around four central themes: the paradox of potent training within a constraining environment; the profound nature of the required pedagogical shift; the diagnostic significance of specific competency gaps; and the emergent mandate for systemic coherence between policy, curriculum, and pedagogy.

5.1 The "Success Paradox": Strong Training within a Constraining Reality

The central finding of this study is the contrast between SEA-TEP's effectiveness in strengthening individual pedagogical capacity and the systemic conditions that constrain its classroom enactment. Quantitative evidence demonstrates substantial gains in pre-service teachers' competencies in the CER framework, reflecting enhanced pedagogical knowledge, confidence, and readiness to implement inquiry-based STEM instruction (Guskey, 2016; Darling-Hammond et al., 2017). These gains were consistently observed across chemistry, physics, and biology learning units, indicating that the professional development model fostered transferable inquiry-oriented practices rather than content-specific skills (Pedaste et al., 2015).

At the same time, qualitative findings reveal that this individual-level success unfolds within a context of persistent systemic constraints. Across all Teacher Education Institutions, participants described a pronounced "*implementation chasm*" between professional development settings and classroom realities. Cambodia-specific factors—including chronic shortages of laboratory materials, limited digital infrastructure, and uneven institutional resources—were repeatedly identified as barriers that directly undermine inquiry-based pedagogy, which depends on students' opportunities to generate and analyse empirical evidence. Similar constraints have been widely documented in low-resource education systems, where material and infrastructural limitations present persistent barriers to the enactment of inquiry-based STEM reforms (Nicol, 2021). In exam-oriented systems, such constraints are further compounded by accountability pressures that encourage a reversion to transmission-oriented teaching despite teachers' positive orientations toward reform.

This tension constitutes the Success Paradox: SEA-TEP effectively builds human capital, yet the educational system remains insufficiently prepared to absorb and sustain these gains. While the specific resource and governance constraints identified reflect the Cambodian teacher education context, the broader dynamic—where pedagogical innovation outpaces systemic adaptation—mirrors patterns documented across other low-resource and assessment-driven education systems (Rundgren, 2018). The findings therefore suggest that scaling professional development in isolation, without parallel investment in inquiry-supportive learning environments and systemic alignment, is unlikely to produce durable instructional change.

5.2 From Knowledge Transmission to Inquiry Facilitation

Beyond measurable competency gains, SEA-TEP catalysed a substantive reorientation of teachers' professional roles and identities. Participants consistently contrasted the programme's student-centred, inquiry-based ethos with prevailing teacher-centred practices in Cambodian classrooms (Song, 2015). These traditional practices are commonly associated with passive learning and rote memorisation—patterns widely documented in systems shaped by content-heavy curricula and transmission-oriented pedagogy. The shift from teacher as "*knowledge transmitter*" to "*inquiry facilitator*" was widely regarded as pedagogically desirable but professionally demanding (Penuel et al., 2011).

Qualitative evidence revealed significant "*instructional vulnerability*," characterised by uncertainty and resistance when managing open-ended inquiry, facilitating dialogic interactions, and tolerating instructional ambiguity. Such responses should not be interpreted as a localised reluctance to change; rather, they signal a transferable psychological barrier documented in global studies of inquiry-oriented reform (Fullan, 2015). This identity transformation is particularly acute in exam-oriented, hierarchical cultures like Cambodia's, where assessment systems reward memorisation and classroom norms often discourage student questioning and collaborative reasoning.

While the depth of this identity shift is a universal finding, the specific intensity of the struggle in Cambodia is a context-specific reflection of its centralised system and the uneven resource distribution across provincial Teacher Education Institutions. Consistent with international literature, these findings indicate that inquiry-based pedagogy requires sustained professional support beyond initial training (Windschitl et al., 2011). Within the context of the "*Success Paradox*", these results underscore that for regional initiatives like SEA-TEP to be sustainable, they must move beyond individual training to foster Professional Learning Communities—such as peer-mentoring systems and institutional collaboration—to support teachers as they navigate complex instructional change.

5.3 Assessment and Differentiation as a Diagnostic Challenge

While overall competency gains were statistically significant, assessment and differentiation emerged as relative areas of uncertainty, reflecting a common "*diagnostic gap*" in professional development. This finding is significant because these practices represent the most advanced dimensions of inquiry-based teaching. Unlike traditional summative assessment, which remains the norm in Cambodia's exam-oriented culture, inquiry-oriented classrooms require teachers to evaluate complex reasoning processes, provide real-time formative feedback, and adapt instruction dynamically.

Lower confidence in this domain suggests that while participants internalised the theoretical value of the CER framework, they felt less equipped to manage its practical complexity in diverse, large-scale classrooms. This gap represents a transferable implementation challenge; globally, teachers often struggle to move beyond the "*surface features*" of inquiry toward the sophisticated task of differentiating instruction based on student evidence (Windschitl et al., 2011).

In the Cambodian context, this challenge is a context-specific reflection of systemic misalignment. The lack of curriculum flexibility and the persistence of assessment systems that reward memorisation create a high-stakes environment where formative, inquiry-based assessment is perceived as a professional risk (Black & Wiliam, 2018; Remillard, 2005). Consequently, the findings point to a clear mandate for future SEA-TEP iterations: professional development must move beyond pedagogical theory to include targeted, practice-based training in formative assessment and differentiation. Without parallel systemic reform to national assessment standards, these advanced competencies are likely to remain aspirational rather than operational.

5.4 The Need for Systemic Coherence

The final theme underscores participants' recognition that pedagogical change cannot be sustained in isolation from systemic reform. Qualitative data reveal persistent misalignment between inquiry-based pedagogy and curriculum pacing, assessment practices, and institutional expectations. Participants framed this tension not as an insurmountable barrier, but as a call for policy alignment, advocating for the formal integration of CER and inquiry-based approaches into national curricula and teacher education standards. While some constraints identified—such as limited resources and exam-oriented pressures—are common across many low- and middle-income education systems, others are specific to Cambodia, including the centralised role of the MoEYS and uneven resource distribution across Teacher Education Institutions.

Resolving the Success Paradox identified in this study requires systemic coherence. As stated in previous literature, without alignment between professional development, curriculum frameworks, assessment systems, and resource provision, inquiry-based teaching is likely to remain marginalised (National Research Council, 2007). The findings therefore offer a clear message to policymakers: pedagogical innovation and systemic reform must proceed in tandem to achieve sustainable transformation in STEM education.

6. Implications

The findings of this study generate distinct and complementary implications for research, policy, and practice, with relevance extending beyond Cambodia to the broader SEAMEO region.

6.1 Implications for Research

This study provides foundational evidence of the effectiveness of inquiry-based professional development in pre-service STEM teacher education. Future research should build on this work by examining classroom enactment and student learning outcomes through observational and longitudinal designs. Multi-country or comparative studies within the SEAMEO region would be particularly valuable for assessing the transferability and contextual adaptability of the SEA-TEP model across diverse institutional and policy environments.

6.2 Implications for Policy

At the policy level, the findings highlight the importance of systemic coherence. While SEA-TEP successfully builds teacher capacity, its impact is constrained by misalignment among curriculum demands, assessment practices, and resource availability. For Cambodia and other SEAMEO member states, this suggests that inquiry-based pedagogy must be embedded within national teacher standards, curricula, and assessment frameworks to ensure sustainability. SEA-TEP thus offers evidence to support policy shifts from stand-alone training projects toward integrated, system-level reform strategies.

6.3 Implications for Practice

For TEI and PD providers, the study underscores the limitations of one-off training models. Sustainable pedagogical change requires continuous support mechanisms such as mentoring, professional learning communities, and practice-focused coaching. Embedding SEA-TEP principles within core pre-service curriculum—rather than treating them as external interventions—emerges as a critical strategy for institutionalisation. These practice-oriented implications are highly relevant for TEIs across the SEAMEO region seeking scalable approaches to inquiry-based STEM education.

Collectively, these implications position SEA-TEP not only as a national capacity-building initiative, but also as a regionally relevant model aligned with SEAMEO's mandate to strengthen teacher education and STEM learning across Southeast Asia.

7. Conclusion

This study confirms that SEA-TEP is a powerful and effective mechanism for advancing inquiry-based STEM pedagogy within Cambodian Teacher Education Institutions. Through mixed-methods evidence, the research demonstrates that structured professional development centred on frameworks such as CER and Scientific Modelling significantly enhances pre-service teachers' competencies and readiness to implement student-centred learning.

At the same time, the study makes clear that the long-term success of SEA-TEP depends on the broader educational ecosystem in which trained teachers operate. The central challenge has shifted from proving the effectiveness of inquiry-based professional development to ensuring that supportive policies, curricula, assessments, and resources are in place to sustain and scale its impact.

Viewed through a regional lens, SEA-TEP represents more than a successful national intervention. It offers SEAMEO and its member states a tested, adaptable framework for strengthening STEM teacher education in contexts facing similar systemic constraints. With sustained policy commitment, institutional ownership, and regional collaboration, SEA-TEP has the potential to contribute meaningfully to long-term STEM education reform in Cambodia and across Southeast Asia.

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INTEGRATING STEM LEARNING UNITS INTO LESSON PLANNING: A STUDY OF IN-SERVICE TEACHERS IN MALAYSIA'S SEA-TEP PROGRAMME

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ABSTRACT

This study examines how participants in the Southeast Asian Teacher Education Programme in Malaysia incorporate integrated STEM learning units into their lesson planning and instructional practices. Grounded in constructivist and situated learning perspectives, the research investigates teachers' instructional readiness, pedagogical enactment, and contextual factors influencing implementation. Data were collected from 141 teacher participants using a multi-domain survey instrument with strong internal reliability, complemented by classroom observation data to contextualise self-reported practices. Descriptive and inferential analyses indicated consistently high levels of teacher self-efficacy, intentional planning, inquiry-oriented instructional strategies, assessment literacy, and engagement-focused pedagogies. Effect size analysis showed that mean responses across domains were substantially above the neutral midpoint, suggesting practically meaningful levels of STEM integration readiness and enactment. Participants frequently reported using hands-on learning, technology-supported instruction, real-world problem solving, formative assessment, and reflective practice, all core features of high-quality integrated STEM education. Despite this strong pedagogical foundation, structural constraints, including curriculum alignment demands, time limitations, and assessment pressures, emerged as ongoing implementation challenges. The findings highlight that teacher competence alone is insufficient for sustained STEM reform; systemic coherence across professional development, curriculum policy, and school structures is required. This study contributes regionally grounded empirical evidence from Southeast Asia, a context underrepresented in STEM education research, and demonstrates how structured teacher education initiatives can strengthen classroom-level STEM integration. The results offer implications for scaling mentoring models, curriculum design, and institutional support to advance sustainable STEM education reform.

Keywords: STEM Education, STEM Learning Units, Lesson Planning, SEA-TEP

1. Introduction

The Southeast Asian Teacher Education Programme (SEA-TEP) plays a key role in strengthening teacher capacity and promoting pedagogical innovation across Southeast Asia, including Malaysia. In response to the demands of the Fourth Industrial Revolution, Malaysian educators are increasingly expected to integrate Science, Technology, Engineering, and Mathematics (STEM) learning into classroom instruction to foster problem-solving, inquiry, collaboration, and creative thinking (Zainil et al., 2024). This integration aligns with national priorities to enhance higher-order thinking skills and prepare learners for future workforce challenges (Noufal, 2022). Despite strong policy emphasis and institutional support, the incorporation of STEM learning units into lesson planning remains uneven among pre-service and in-service teachers.

This study addresses the following research question:

"How do SEA-TEP participants in Malaysia incorporate STEM learning units into their lesson planning teaching practices?"

Although STEM education has attracted growing attention in Malaysian education reform, existing research indicates that educators frequently face challenges stemming from limited STEM pedagogical content knowledge, insufficient interdisciplinary preparation, and constrained instructional resources (Mao et al., 2024). Consequently, STEM implementation often remains at a superficial level, characterised by fragmented activities rather than coherent, inquiry-driven learning units. While prior studies have examined teachers' perceptions of STEM education or systemic implementation issues, there is limited empirical evidence on how teacher education programme participants operationalise STEM learning units during lesson planning, particularly within regional initiatives such as SEA-TEP in Southeast Asia. This gap is significant, as lesson planning is a critical stage at which pedagogical knowledge is translated into classroom practice. SEA-TEP aims to enhance teacher education through collaborative learning, mentoring, and innovation-oriented instructional strategies across Southeast Asia.

In Malaysia, the programme supports pre-service teachers and teacher educators by promoting inquiry-based pedagogy, reflective practice, and evidence-informed instructional design, in line with national reforms that advocate student-centred and technology-enhanced learning (Choy et al., 2021; Dinham et al., 2020). Participants are introduced to curriculum design frameworks that foster active learning and problem-solving. However, translating these frameworks into classroom-ready lesson plans remains challenging, particularly in contexts where sustained mentoring, authentic teaching experiences, and school-based support systems are still developing (Romera et al., 2023; Backhouse, 2020).

STEM learning units are structured instructional modules that integrate interdisciplinary knowledge and real-world problem-solving across science, technology, engineering, and mathematics (Alrwaished, 2024; Liew & Teoh, 2023). Effective STEM lesson planning requires coherent alignment of learning objectives with inquiry-based instructional strategies, interdisciplinary connections, and formative assessment practices (Kuo, 2024; Su, 2022; Li et al., 2019). Although SEA-TEP participants show growing awareness of STEM pedagogy, many struggle to design integrated learning units that transcend traditional subject boundaries and support sustained inquiry. This challenge reflects broader national trends in Malaysia, where teachers often adopt surface-level STEM approaches because of limited confidence, experience, and structured guidance (Jamaluddin et al., 2023; Karpudewan et al., 2022).

Research consistently shows that the quality of lesson planning strongly influences classroom implementation and student engagement, particularly in inquiry-based STEM contexts (Großmann & Krüger, 2023; Ong et al., 2023). Although SEA-TEP participants are exposed to instructional models such as project-based learning, the 5E instructional model, and design-thinking frameworks, evidence indicates a persistent gap between theoretical understanding and practical enactment. International studies likewise emphasise the importance of guided practice and mentoring in helping pre-service teachers translate STEM pedagogical principles into effective, classroom-ready lesson plans (Ribeirinha & Correia, 2025; Yilmaz, 2022).

This research advances STEM education scholarship by bridging policy-driven STEM reform and classroom-level instructional planning in teacher education. By examining how SEA-TEP participants in Malaysia operationalise STEM learning units in lesson planning, the study provides empirical, context-specific evidence from a region that remains underrepresented in global STEM education research. The findings extend existing literature by shifting the focus from teachers' perceptions of STEM integration to their pedagogical enactment in instructional design. Furthermore, the study offers theoretically and practically grounded insights to inform the development of scalable mentoring structures, curriculum frameworks, and professional learning models that strengthen sustainable STEM integration across teacher education systems in Southeast Asia.

2. Literature Review

2.1 SEA-TEP and Practice-Oriented Teacher Preparation

The Southeast Asian Teacher Education Programme (SEA-TEP) aims to strengthen teacher preparation by promoting reflective practice, collaborative learning, and pedagogical innovation across participating countries, including Malaysia. Malaysia's participation in SEA-TEP aligns with national priorities to modernise teacher education and prepare educators to deliver future-ready learning experiences (Kamarudin & Noor, 2024; Pandian et al., 2022). Research on teacher education reform in Malaysia consistently shows that programmes emphasising mentorship, reflective cycles, and authentic teaching experiences yield greater improvements in instructional competence than theory-driven training alone (Pazilah et al., 2024; Choy et al., 2021).

SEA-TEP's emphasis on collaborative lesson design, experimentation with innovative pedagogies, and evidence-based reflection aligns with global shifts towards experiential and inquiry-oriented teacher development. However, synthesising regional and international studies indicates that the effectiveness of such programmes depends heavily on institutional coherence, sustained coaching, and supportive school environments that enable teachers to enact newly acquired pedagogical approaches beyond formal training contexts (Wang & Chen, 2022; Patfield et al., 2021). These findings suggest that examining how SEA-TEP participants translate programme principles into concrete lesson-planning practices is essential to understanding the programme's pedagogical impact in Malaysia.

2.2 STEM Learning Units and Integrated Instruction

STEM education has become a central focus of educational reform in Malaysia, driven by concerns about declining student participation in science-related pathways and the need to develop a technologically skilled workforce (Liew & Teoh, 2023; Ismail et al., 2019). STEM learning units are a primary means of achieving these goals, integrating science, technology, engineering, and mathematics through real-world problem-solving, hands-on inquiry, and collaborative learning (Marzuki et al., 2024; Roehrig et al., 2021).

Across international contexts, integrated STEM instruction has been shown to enhance students' conceptual understanding, creativity, and motivation when implemented coherently and authentically (Hällström & Ankiewicz, 2023; Roehrig et al., 2021). However, studies in Malaysia reveal persistent implementation challenges. Despite strong policy advocacy, many teachers continue to adopt discipline-based or activity-focused approaches rather than fully integrated STEM units, largely due to limited training, low confidence in interdisciplinary teaching, and insufficient instructional resources (Yreck, 2024; Zakeri et al., 2022).

Synthesised findings indicate that effective STEM unit implementation requires more than subject-matter knowledge; teachers must also possess competencies in engineering design processes, technological integration, and facilitating student-led inquiry (Smith et al., 2022; Meester et al., 2021). Additionally, examination-oriented school cultures often constrain the adoption of open-ended STEM activities, underscoring the need for alignment among curriculum, pedagogy, and assessment practices (Golegou et al., 2025; Jusoh et al., 2024). These challenges directly inform the study's focus on how SEA-TEP participants incorporate STEM learning units into lesson planning, rather than examining STEM implementation solely at the classroom level.

2.3 STEM Lesson Planning as a Mediating Practice

Lesson planning is a critical mediating process that translates STEM frameworks into classroom instruction. Effective STEM lesson plans typically articulate clear learning objectives, incorporate inquiry-based strategies, scaffold learning tasks, and integrate formative assessments aligned with real-world problem contexts (Nipyrakis et al., 2024; Ong et al., 2024). Pedagogical models such as the 5E instructional cycle, project-based learning, and design-thinking approaches are widely recognised as effective structures for integrated STEM instruction (Golegou et al., 2025).

Research into pre-service teacher development consistently shows that structured lesson planning, together with guided practice, peer collaboration, and reflective feedback, significantly enhances instructional quality and pedagogical coherence (Kidd et al., 2025; Ribeirinha & Correia, 2025). In Malaysia, however, studies indicate that pre-service teachers often struggle to design STEM lesson plans that move beyond isolated activities towards sustained inquiry and problem-based learning (Choy et al., 2021; Tee et al., 2018). This gap has been attributed to limited exposure to exemplary STEM lesson plans, insufficient modelling of interdisciplinary teaching practices, and weak collaboration across subject areas during the planning process (Lin et al., 2025).

Assessment design poses an additional challenge in STEM lesson planning. Early-career and pre-service teachers often report low confidence in developing authentic assessments that capture students' problem-solving, design thinking, and collaborative learning outcomes (Ribeirinha & Correia, 2025; Nipyrakis et al., 2024). These findings underscore the importance of assessment literacy as an integral component of STEM lesson planning, rather than a separate pedagogical skill.

2.4 Link to the Present Study and Survey Variables

Synthesising the literature reveals a persistent gap between policy aspirations for integrated STEM education and teachers' capacity to implement STEM learning units through coherent lesson planning. Although SEA-TEP provides structured exposure to inquiry-based pedagogy and collaborative design, limited empirical research has examined how programme participants operationalise these units during lesson planning in the Malaysian context.

Guided by these insights, the present study focuses on key constructs identified in the literature: (a) the integration of STEM learning units into lesson planning, (b) the use of inquiry-based and interdisciplinary instructional strategies, (c) perceived challenges related to resources, confidence, and institutional support, and (d) assessment practices within STEM lesson design. These constructs informed the development of the survey instrument used in this study, enabling a systematic examination of how SEA-TEP participants translate STEM pedagogical principles into lesson planning practices and the challenges they encounter in doing so.

3. Theoretical Framework

This study is guided by an integrated theoretical framework, grounded primarily in constructivist learning theory and complemented by situated learning theory and theories of educational change. Together, these perspectives provide a coherent lens for examining how SEA-TEP participants incorporate STEM learning units into their lesson planning, the challenges they encounter, and the conditions that support or constrain effective pedagogical enactment.

3.1 Constructivism as the Foundation for STEM Lesson Planning

Constructivist learning theory conceptualises learning as an active process in which knowledge is constructed through inquiry, social interaction, and reflection, rather than transmitted passively (Mahn & John-Steiner, 2012; Piaget, 1964). From this perspective, effective instruction requires learning environments that engage learners in problem-solving, evidence-based reasoning, and the integration of prior knowledge with new experiences. These principles underpin contemporary STEM pedagogies and directly inform expectations for high-quality STEM lesson planning.

In this study, constructivism provides the foundational rationale for examining how teachers design STEM learning units that emphasise inquiry, collaboration, and conceptual coherence. Lesson planning is a critical site where constructivist principles are either enacted or diluted, depending on teachers' pedagogical understanding, confidence, and contextual constraints. Accordingly, the survey instrument includes items that capture participants' use of inquiry-based strategies, interdisciplinary integration, and alignment among learning objectives, activities, and assessments.

3.2 CER, Scientific Modelling, and 3D Learning as Pedagogical Enactments

The Claim–Evidence–Reasoning (CER) framework operationalises constructivist principles by scaffolding students' development of scientific explanations through structured argumentation (Prain et al., 2022; Toulmin, 2003). By requiring learners to articulate claims, justify them with evidence, and connect reasoning to scientific concepts, CER promotes higher-order thinking, epistemic engagement, and scientific discourse (Osborne et al., 2016). In lesson planning, CER serves as a concrete indicator of teachers' capacity to design instruction that supports reasoning and sense-making rather than rote learning.

Similarly, scientific modelling embodies constructivist learning through iterative cycles of representation, testing, and revision, enabling learners to engage in authentic scientific practices and deepen conceptual understanding (Gilbert & Justi, 2016; Schwarz et al., 2009). Modelling requires teachers to plan learning sequences that foster student agency, provide feedback, and support the refinement of ideas, making it a demanding yet powerful component of integrated STEM instruction.

The Next Generation Science Standards (NGSS) framework, with its emphasis on three-dimensional (3D) learning that integrates Disciplinary Core Ideas (DCIs), Science and Engineering Practices (SEPs), and Crosscutting Concepts (CCCs), further extends constructivist principles by treating knowledge, practice, and reasoning as inseparable components of learning. In this study, CER, modelling, and 3D learning are treated not as isolated pedagogical strategies but as interconnected indicators of teachers' ability to design coherent, inquiry-driven STEM learning units. Survey items on instructional strategies and pedagogical alignment are grounded in these constructs.

3.3 Situated Learning, Teacher Self-Efficacy, and Professional Practice

While constructivism explains how meaningful STEM learning should occur, situated learning theory offers insight into how teachers develop the capacity to design and implement such experiences. Situated learning emphasises that professional knowledge is constructed through participation in authentic, collaborative, and contextually embedded practices (Kim & Hannafin, 2008). From this perspective, teacher confidence and pedagogical competence emerge through engagement in real-world instructional design, reflection, and peer interaction.

SEA-TEP's professional development model aligns with situated learning by engaging participants in collaborative lesson planning, experimenting with STEM pedagogies, and reflecting on their practice. However, the extent to which participants internalise and enact these practices varies, thereby influencing their self-efficacy in designing STEM learning units. This theoretical lens informs the inclusion of survey variables measuring perceived confidence, instructional challenges, and institutional support, which are critical mediators of the relationship between professional development experiences and lesson planning outcomes (Darling-Hammond et al., 2017).

3.4 Educational Change, Sustainability, and Systemic Constraints

Finally, Fullan's (2018) theory of educational change offers a macro-level perspective on the sustainability and scalability of instructional innovations, including CER, modelling, and 3D learning. Fullan emphasises teacher ownership, coherence across system levels, and responsiveness to local contexts as essential conditions for meaningful change. In the Malaysian and Southeast Asian context, these factors shape teachers' ability to integrate STEM learning units consistently into lesson planning, particularly in examination-oriented systems and resource-constrained environments.

This perspective guides the study's focus on systemic and contextual challenges reported by SEA-TEP participants, including time constraints, assessment demands, and school-level support. Corresponding survey items capture these enabling and constraining conditions, allowing analysis of how broader systemic factors intersect with individual pedagogical practices.

3.5 Integrated Framework and Link to the Present Study

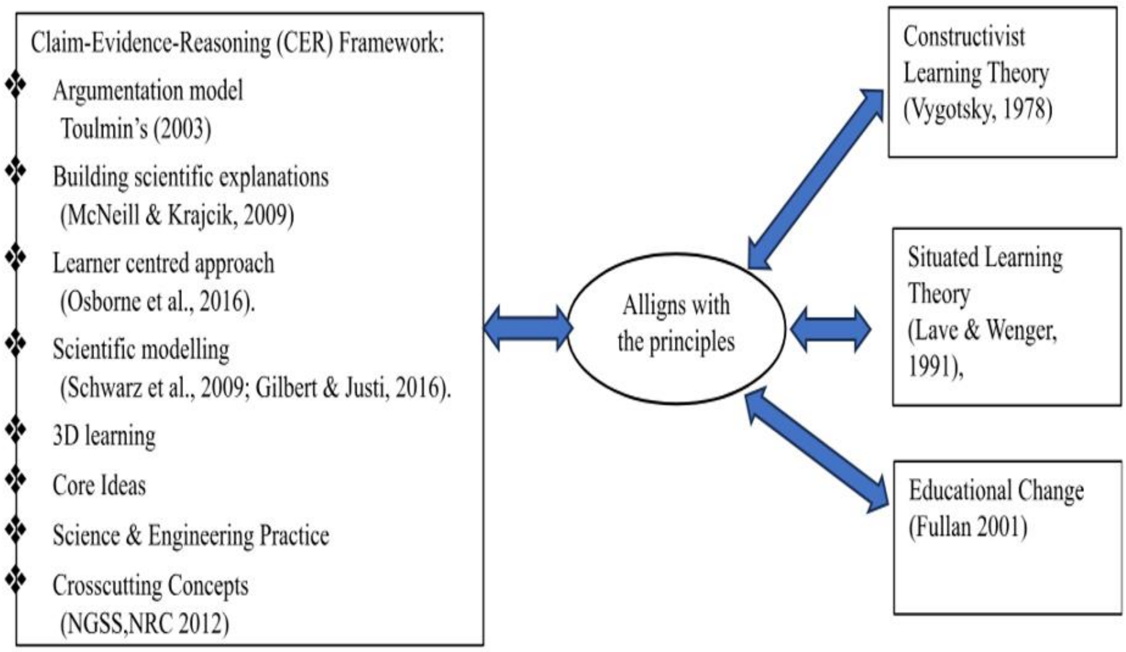
Together, constructivist learning theory, situated learning theory, and educational change theory form an integrated framework for analysing STEM lesson-planning practices among SEA-TEP participants. The integrated theoretical framework underpinning this study is presented in Figure 1.

As illustrated in Figure 1, the framework conceptualises STEM lesson planning as a mediating practice shaped by pedagogical knowledge (CER, modelling, 3D learning), professional learning experiences, teacher confidence, and systemic conditions. This framework directly informs the study's survey design, which examines (a) the incorporation of STEM learning units, (b) the use of inquiry-based and interdisciplinary strategies, (c) perceived confidence and challenges, and (d) assessment practices within lesson planning.

By grounding the analysis in this integrated theoretical framework, the study provides a coherent basis for interpreting how teacher education initiatives, such as SEA-TEP, support or constrain the enactment of constructivist STEM pedagogies within real-world instructional planning contexts.

Figure 1

Contextual Grounded Theoretical framework



4. Methodology

This study adopted a quantitative research design to examine the extent to which participants integrated STEM learning units into their instructional planning and to identify the challenges encountered during implementation. A survey approach was selected because it allows a systematic examination of pedagogical patterns, perceived competencies, and implementation constraints across a defined teacher population engaged in a common professional development context.

4.1 Instrument Development and Validation Student Assessment Results: Conceptual Gains Through MER Implementation

A structured survey instrument was developed to align closely with the study's research question and theoretical framework. The instrument comprised five primary constructs: (a) Understanding and Confidence, (b) Planning and Preparation, (c) Instructional Practices, (d) Assessment and Reflection, and (e) Engagement and Motivation. These constructs reflect key dimensions of STEM pedagogical enactment identified in the literature, including inquiry-based lesson planning, interdisciplinary integration, teacher self-efficacy, and assessment practices in STEM contexts.

Survey items were adapted from established research on STEM pedagogy, inquiry-based science instruction, CER-based reasoning, and 3D learning, with modifications to suit the Malaysian SEA-TEP context. Items on inquiry strategies and instructional practices drew on frameworks associated with constructivist and STEM-aligned pedagogies, while confidence-related items were informed by teacher self-efficacy research in science education. Assessment items reflected the literature on formative assessment and authentic evaluation in STEM learning environments. All items were reviewed by experts in science education and teacher professional development for content relevance and clarity to establish content validity.

Each construct was operationalised using multiple Likert-scale items on a four-point agreement scale (1 = Strongly Disagree to 4 = Strongly Agree). The absence of a neutral midpoint was intentional, encouraging respondents to indicate a directional stance on their practices and perceptions, a feature common in studies of pedagogical beliefs and instructional behaviours. Internal consistency reliability was assessed using Cronbach's alpha for each construct before inferential analysis.

4.2 Participants and Sampling

The study involved 141 in-service science teachers from public primary and secondary schools across Malaysia. Participants represented diverse school contexts, including urban, suburban, and rural settings, and were actively teaching in classrooms at the time of data collection. All participants were enrolled in SEA-TEP, a structured professional development programme designed to strengthen science pedagogy through CER, scientific modelling, and 3D learning approaches.

Purposive sampling was used to ensure that respondents had direct experience of SEA-TEP-related instructional approaches. Inclusion criteria required participants to:

1) be currently teaching science at the primary or secondary level;
2) serve in government schools;
3) be participating in SEA-TEP; and
4) consent to engage in reflective and evaluative activities associated with the programme.

This sampling strategy ensured that participants could provide informed responses about the practical integration of STEM learning units. The sample was heterogeneous in terms of teaching experience, academic preparation, and prior professional development, allowing analysis across varied instructional backgrounds (Palinkas et al., 2015).

4.3 Data Analysis

Descriptive statistics were computed first to summarise overall response patterns across constructs. To determine whether participants' reported practices and perceptions differed significantly from a baseline, one-sample t-tests were conducted using the scale midpoint as the reference value. This approach is appropriate for assessing whether mean responses indicate endorsement at a level beyond a minimally acceptable level of practice or confidence. The midpoint serves as a theoretical threshold separating lower and higher levels of agreement, enabling interpretation of whether STEM-related practices are meaningfully integrated rather than merely present.

In addition to statistical significance (p-values), effect sizes (Cohen's d) were calculated to assess the magnitude of differences between observed means and the reference value. Effect sizes were interpreted using conventional benchmarks (small ≈ .20, medium ≈ .50, large > .80) to gauge the practical significance of findings, ensuring that results were evaluated not only on statistical significance but also on their educational relevance.

4.4 Ethical Considerations

Ethical procedures were strictly followed throughout the study. Institutional approval was obtained before data collection, and participation was voluntary. All respondents provided informed consent and were assured that their responses would remain confidential and be used solely for research purposes. Data were anonymised during analysis to protect participants' identities, and no school or individual identifiers were reported.

5. Results

The findings for the research question are displayed in Table 1.

Table 1

Participants Incorporation of STEM Learning Units into Their Lesson Planning Teaching Practices

Section / Item	Cronbach's Alpha value	Mean	SD	t-Statistics	Cohen d	p-value
1.Understanding and Confidence						
"I am aware of resources available to help me implement STEM concepts in my lessons	0.87	3.21	0.48	17.81	1.48	< .001
"I am comfortable using technology as a tool to enhance STEM learning in my classroom"		3.29	0.50	18.76	1.58	< .001
"I believe I can positively influence my students' attitudes toward STEM subjects."		3.25	0.48	18.49	1.56	< .001
2. Planning and Preparation						
"I set clear objectives when incorporating STEM activities into my teaching."	0.87	3.19	0.45	18.42	1.53	< .001
"I feel confident in my ability to teach STEM content effectively."		3.09	0.53	13.17	1.11	< .001
"I can use mathematics / science thinking in my STEM instruction."		3.19	0.48	17.22	1.44	< .001
3. Instructional Practices						
"I use hands-on STEM activities to enhance student learning."	0.85	3.19	0.49	16.70	1.41	< .001
"I regularly integrate technology tools to facilitate STEM instruction in my classroom."		3.13	0.50	15.20	1.26	< .001
"I implement real-world problem-solving scenarios to enhance STEM learning."		3.15	0.49	15.67	1.33	< .001
4. Assessment and Reflection						
"I assess student understanding of STEM concepts through formative assessments."	0.88	3.14	0.46	16.70	1.39	< .001
"I reflect on the effectiveness of STEM learning activities after each lesson."		3.09	0.49	14.32	1.20	< .001
"I regularly use performance-based assessments to evaluate students' application of STEM concepts."		3.11	0.46	15.71	1.33	< .001
5. Engagement and Motivation						
"I believe that integrating real-world STEM applications increases student motivation."	0.84	3.23	0.47	18.44	1.55	< .001
"I encourage students to ask questions during STEM lessons."		3.26	0.50	18.03	1.52	< .001
"I feel confident in my ability to motivate students to learn STEM concepts.		3.13	0.53	14.00	1.19	< .001

The internal consistency across all subscales was high, indicating reliable measurement of the targeted constructs: Understanding and Confidence (α = .87), Planning and Preparation (α = .87), Instructional Practices (α = .85), Assessment and Reflection (α = .88), and Engagement and Motivation (α = .84). These values indicate strong coherence among items within each domain.

One-sample t-tests were conducted to assess whether mean scores differed significantly from the theoretical midpoint (2.5). Across all constructs, mean scores ranged from 3.09 to 3.29, indicating consistent agreement with statements describing STEM-related competencies and practices. All comparisons were statistically significant ($p < .001$). Importantly, effect sizes (Cohen's d) were uniformly large (all $d > 0.80$; see Table X), indicating substantial practical significance beyond statistical significance.

5.1 Understanding and Confidence

Participants reported high levels of confidence and awareness in STEM teaching. Mean scores across items in this construct exceeded 3.20, with very large effect sizes ($d \approx 1.5$–1.7). These findings indicate that teachers felt well informed about STEM resources, comfortable using technology, and capable of positively influencing students' attitudes towards STEM. This domain represents a strong foundation for STEM implementation, suggesting that perceived self-efficacy is not a primary barrier.

5.2 Planning and Preparation

Teachers also reported strong competence in STEM lesson planning. Mean scores for setting objectives and integrating mathematical/scientific thinking exceeded 3.15, with large effect sizes. Confidence in teaching STEM content had the lowest mean in this domain ($M = 3.09$) and a comparatively smaller, though still large, effect size ($d \approx 1.1$), suggesting that while teachers generally feel capable, content-specific confidence may be a comparatively weaker area requiring further professional support.

5.3 Instructional Practices

Results indicate that participants actively apply STEM pedagogies in classroom practice. High mean scores ($M \approx 3.13$–3.19) and large effect sizes confirm the frequent use of hands-on learning, technology integration, and real-world problem-solving. These findings suggest that SEA-TEP participation is associated with a shift from theoretical awareness to pedagogical enactment.

5.4 Assessment and Reflection

Assessment-related practices also showed significant positive deviation from the midpoint, with means above 3.09 and large effect sizes. Teachers reported regular use of formative assessment, reflective practice, and performance-based assessment. However, compared with other domains, this construct showed slightly lower effect sizes, suggesting that although assessment practices are established, they may be less robust than instructional enactment, an observation consistent with literature identifying assessment as a persistent challenge in STEM reform.

5.5 Engagement and Motivation

Participants strongly endorsed practices that support student engagement. High means ($M \approx$ 3.13–3.26) and very large effect sizes indicate strong belief in the motivational value of real-world STEM contexts, frequent encouragement of student questioning, and confidence in motivating learners. These findings highlight teachers' alignment with inquiry-oriented and student-centred STEM pedagogies.

5.6 Overall Pattern

Taken together, the results indicate that participants demonstrate well-established STEM-related confidence, planning competence, instructional enactment, and student engagement, with assessment practices slightly less pronounced yet still strong. The consistently large effect sizes suggest that SEA-TEP participants' practices are not merely above average but represent substantial practical adoption of STEM pedagogical principles.

6. Discussion

6.1 Teacher Self-Efficacy as a Foundation for Instructional Change

Participants reported high levels of confidence in their ability to implement STEM instruction, consistent with Bandura's theory that self-efficacy influences teachers' willingness to adopt and sustain innovative practices. In the SEA-TEP context, this is particularly significant, as confidence in using technology, accessing STEM resources, and influencing students' attitudes suggests that participants view themselves as capable agents of instructional change rather than passive recipients of reform initiatives. This implies that SEA-TEP's emphasis on experiential learning, collaborative design, and reflective practice may be strengthening teachers' professional agency. From a regional perspective, teacher self-efficacy is a critical enabler of reform across Southeast Asia, where systemic constraints such as examination pressures and uneven resource distribution often limit pedagogical innovation. Teachers who believe in their instructional capacity are more likely to adapt STEM approaches to local contexts rather than discontinue them when challenges arise.

6.2 From Planning Intentions to Pedagogical Enactment

The findings indicate that STEM integration extends beyond conceptual awareness into intentional lesson design and classroom enactment. Teachers reported aligning objectives with STEM activities, incorporating disciplinary reasoning, and employing hands-on, technology-supported, and real-world problem-solving strategies. This alignment reflects constructivist and inquiry-based pedagogies central to international STEM frameworks. The consistency between planning and enactment suggests that SEA-TEP may be supporting coherence between professional development experiences and classroom practice, an area where many teacher education initiatives encounter difficulty. When planning practices, instructional strategies, and engagement approaches converge, the likelihood of sustained instructional change increases. For teacher education systems in Southeast Asia, this underscores the importance of professional development models that integrate theory, design, practice, and classroom application rather than treating these components as separate.

6.3 Assessment as the Remaining Challenge

Although assessment practices were reported positively, they appeared less pronounced than instructional enactment. This pattern reflects a well-documented challenge in STEM reform, where teachers often adopt inquiry-based instruction more readily than authentic assessment approaches. Designing formative and performance-based assessments requires specialised pedagogical content knowledge and assessment literacy, which are frequently underemphasised in teacher preparation. For SEA-TEP and similar regional programmes, this highlights a strategic area for enhancement. Strengthening teachers' capacity to design and interpret authentic assessments may help ensure that evaluation practices align with inquiry-based STEM goals rather than defaulting to traditional recall-oriented methods that can undermine reform efforts.

6.4 Engagement and Student-Centred Pedagogy

Participants strongly endorsed practices that promote student engagement, including real-world relevance and inquiry through questioning. These practices align with research showing that contextualised and dialogic learning environments foster motivation, deeper understanding, and sustained interest in STEM pathways. Teachers' confidence in motivating students further reinforces the link between self-efficacy and student-centred instruction.

At a regional level, this emphasis on engagement is particularly important in Southeast Asia, where increasing participation in STEM fields is a shared policy priority. Teachers' capacity to connect STEM learning to students' lived experiences may play a pivotal role in broadening access and sustaining interest among diverse learner populations.

6.5 Implications for SEA-TEP and Teacher Education in Southeast Asia

The findings suggest that professional development models emphasising experiential learning, collaborative lesson design, and reflective practice support the translation of STEM principles into both planning and classroom enactment. Such approaches should remain central to programme design. A greater emphasis on assessment literacy in STEM contexts is needed to strengthen coherence between instructional innovation and evaluation practices. Building teacher confidence and professional ownership can help educators navigate systemic constraints common in the region. Institutional supports, such as collaborative planning time, mentoring structures, and access to high-quality resources, are essential to sustaining the practices cultivated through professional development initiatives.

6.6 Limitations

Several limitations should be considered when interpreting these findings. Although classroom observations were conducted, they were used to provide contextual understanding rather than systematic observational measurement using a validated observation protocol. As a result, the study relies primarily on self-reported survey data, which may better reflect teachers' perceptions and professional beliefs than their day-to-day practices. Self-report measures in educational research are also susceptible to social desirability bias, particularly when participants are involved in a professional development programme that promotes specific pedagogical approaches.

In addition, the study employed a cross-sectional design, capturing instructional practices at a single phase of programme implementation. This limits the ability to determine the long-term sustainability of reported practices or to establish causal relationships between SEA-TEP participation and changes in teaching behaviour. Teaching practices may fluctuate over time in response to institutional demands, curriculum pacing pressures, or resource availability. The sample, while diverse in teaching experience and school contexts, consisted exclusively of in-service science teachers enrolled in SEA-TEP and drawn from government schools. This purposive sample strengthens relevance to the programme context but may limit generalisability to teachers outside structured professional development initiatives or to other national systems in Southeast Asia operating under different curricular and policy conditions.

Finally, the quantitative survey design captures breadth across multiple domains of practice but does not provide the depth of insight into how teachers interpret, adapt, or negotiate STEM pedagogies within specific classroom and cultural contexts. Future research incorporating longitudinal designs, systematic observation protocols, teacher interviews, and classroom artefact analysis would provide a richer understanding of how integrated STEM practices evolve and are sustained over time.

7. Recommendations

The findings indicate that SEA-TEP has established a strong foundation for building teachers' confidence and readiness to implement integrated STEM learning units, but the programme needs refinement to address persistent implementation barriers. Professional development should become more explicitly practice-embedded, with structured opportunities for teachers to co-design, trial, and refine STEM units over time. Incorporating mentoring cycles, lesson study structures, and iterative design workshops would support deeper pedagogical transfer from training settings to classroom practice. Such models can help teachers address challenges related to curriculum alignment, assessment design, and instructional pacing, while strengthening coherence between professional learning and classroom enactment.

System-level conditions must also align with instructional innovation. Time constraints, scheduling rigidity, and curriculum demands remain structural obstacles that limit the depth of STEM integration. School leaders and policymakers should provide protected planning time, encourage interdisciplinary collaboration, and offer clearer curriculum guidance that legitimises integrated STEM approaches. When institutional structures, assessment expectations, and curriculum policies signal support for interdisciplinary teaching, teachers are more likely to sustain reform-oriented practices.

Assessment capacity is another priority area for programme enhancement. Although formative and performance-based assessment practices are in place, teachers continue to struggle to evaluate complex STEM learning outcomes. SEA-TEP should therefore strengthen training in assessment design aligned with inquiry, modelling, and three-dimensional learning goals. Greater emphasis on designing authentic tasks linked to real-world and community contexts would also support student engagement and relevance, areas identified as ongoing concerns.

Further investigation is needed to understand how STEM instructional practices develop and stabilise over time. Longitudinal studies could examine whether reported practices are sustained beyond the immediate period of professional development and how institutional contexts influence the durability of change. Future research should also incorporate more systematic classroom observation protocols and qualitative methods, such as interviews and analysis of lesson artefacts, to examine how teachers interpret and adapt STEM pedagogies across diverse classroom settings.

Comparative studies across Southeast Asian education systems would provide insight into how policy environments, curriculum structures, and resource conditions shape STEM implementation. In addition, research on student learning outcomes, motivation, and identity development in response to integrated STEM units would extend understanding beyond teacher practice and strengthen the evidence base for programme impact. Together, these lines of inquiry would support more context-responsive and scalable models of STEM teacher education.

8. Conclusion

This study examined how participants in SEA-TEP in Malaysia incorporate STEM learning units into lesson planning and identified the pedagogical and structural factors that shape their implementation. Grounded in constructivist, situated learning, and educational change perspectives, the findings indicate that teachers have a strong foundation for integrated STEM instruction, as evidenced by high instructional confidence, intentional planning, and consistent use of inquiry-oriented, technology-supported, and real-world-connected pedagogies. These patterns suggest that SEA-TEP has been effective in developing the professional dispositions and pedagogical orientations associated with meaningful STEM integration.

At the same time, the study highlights systemic constraints that shape the depth and sustainability of implementation. Challenges in curriculum alignment, time allocation, scheduling structures, and assessment demands show that STEM reform is not solely a matter of teacher competence but of institutional coherence. The results, therefore, reinforce the importance of aligning professional development with supportive school conditions and policy frameworks, so that innovative practices can be enacted consistently rather than episodically.

The study contributes regionally and academically in several ways. Empirically, it provides one of the few large-scale, programme-linked analyses of STEM instructional planning within Southeast Asian teacher education, a context that remains underrepresented in international STEM education literature. Conceptually, it demonstrates how integrating constructivist learning theory, situated professional learning, and system-level change perspectives offers a coherent lens for understanding how teachers translate reform-oriented STEM principles into classroom practice. In practice, it provides evidence to inform the design of scalable professional learning structures that connect teacher preparation, curriculum design, and institutional support.

Overall, SEA-TEP is a promising model for strengthening teachers' capacity to design integrated STEM learning experiences. However, the long-term impact of such programmes depends on sustained structural support and ongoing research that tracks how practices evolve over time and influence student learning. Strengthening this alignment across teacher education, school systems, and policy environments is central to advancing high-quality STEM education in Malaysia and the broader Southeast Asian region.

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SCIENTIFIC ARGUMENTATION SKILLS OF STUDENTS IN STEM PROJECT-BASED LEARNING ON WATER QUALITY

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ABSTRACT

Scientific argumentation is a crucial competency for fostering scientific literacy and higher-order thinking skills in 21st century science education. Nevertheless, many students in Southeast Asia continue to face challenges in constructing scientific explanations supported by valid evidence and coherent reasoning as revealed in PISA's science literacy score. In response to this challenge, the Southeast Asian Teacher Education Programme (SEA-TEP) initiated by SEAMEO STEM-ED emphasises the development of innovative STEM-based pedagogical approaches that have been initiated in five countries, including Indonesia. The Programme adopted the 3D Learning framework with focusing on Claim–Evidence–Reasoning (CER) on three topics, one of them is Water Quality. This study was conducted to investigate the effectiveness of the STEM-Project-based Learning (STEM-PjBL) on Water Quality Lesson, in enhancing junior high school students' scientific argumentation skills in Surakarta, Indonesia. The unit lesson that has been adopted and modified to match the Indonesia science curriculum and local water quality issue, was implemented in two private Islamic schools in Surakarta and Sukoharjo. The schools were purposely selected because their science teachers have participated in the SEA-TEP Professional Development Training and had agreed to serve as respondents. Improvements were observed across all CER elements with the most substantial gains occurring in the students' ability to formulate scientific claims. Findings also reveal that the lesson enhances student engagement, collaboration, and awareness of the real-world relevance of water quality issues. These highlight the potential of STEM-PjBL integrated with CER as an effective instructional approach to support inquiry-oriented STEM learning in science class and its potential to be adapted for teacher professional development, both pre-service and in-service for advancement of STEM education initiatives in Southeast Asia.

Keywords: Scientific Argumentation, CER, STEM, Project-Based Learning, Water Quality

1. Introduction

Scientific argumentation has become an essential skill in contemporary science education, particularly as societies strive to develop scientifically literate citizens capable of making informed decisions in a rapidly evolving technological landscape. In line with the global science education framework, such as the Next Generation Science Standards (NGSS), argumentation is positioned as a core scientific practice that enables students to construct, justify, and critique knowledge claims using evidence and reasoning (McNeill & Krajcik, 2012).

Scientific argumentation is closely related to scientific explanation, which plays a vital role in developing scientific literacy, critical thinking, problem-solving skills and risk analysis required in the 21st century (Chan & Erduran, 2023; Driver et al., 2000; Jiménez-Aleixandre & Erduran, 2007; Lobczowski et al., 2020; McNeill, 2011; Schenk et al., 2021). The ability to argue scientifically supports critical thinking, problem-solving, communication, and the development of metacognitive awareness. These competencies are essential for addressing real-world environmental issues, including water pollution, which remains a major societal challenge in many Southeast Asian communities (Henderson, et al., 2014; Osborne et al., 2004).

Despite its importance, numerous studies have shown that students often struggle to develop coherent scientific arguments (Berland & McNeill, 2010; Osborne et al., 2016; Simon et al., 2006). Students frequently provide descriptive or opinion-based responses rather than scientifically justified explanations, often having difficulty linking empirical data with relevant scientific concepts, resulting in arguments that lack logical coherence and evidential support. International assessments of ASEAN countries' students' science literacy, including Indonesia in Programme for International Student Assessment (PISA) 2022 reported low. Only about 34% of Indonesian 15-year-old students reached Level 2 or higher in science, which reflects the ability to recognise correct scientific explanations and relate data to conclusions, below the OECD average of 76% (OECD, 2023). These results indicate that many ASEAN students face challenges in applying scientific knowledge meaningfully, especially in contexts requiring reasoning and argumentation. This issue is particularly prominent in Indonesian science classrooms, where learning remains strongly teacher-centred, emphasising factual recall rather than inquiry, reasoning, or critical discussion (Paramita et al., 2025).

The framework of the Next Generation Science Standards (NGSS) introduces three-dimensional learning (3D Learning) which is emphasised as a core instructional approach that integrates Science and Engineering Practices (SEPs), Crosscutting Concepts (CCCs), and Disciplinary Core Ideas (DCIs) to promote deep conceptual understanding and authentic scientific engagement (National Research Council, 2012; National Research Council, 2013). Within this framework, engaging in argumentation from evidence is identified as a central scientific practice, requiring students to construct explanations and justify claims using empirical data and scientific principles (National Research Council, 2013).

The CER framework operationalises this practice by explicitly guiding students to formulate claims, select relevant evidence, and connect evidence to scientific concepts through logical reasoning, thereby aligning closely with Science and Engineering Practices dimension of 3D Learning (Krajcik & Czerniak, 2018; McNeill & Krajcik, 2012). By providing a structured pathway, CER helps students move beyond rote descriptions toward scientifically grounded explanations (Han et.al, 2015; Kelley & Knowles, 2016). Through this alignment, CER serves as a practical pedagogical scaffold that supports the enactment of three-dimensional science learning in classroom contexts.

However, CER alone is not sufficient. Learning must also be contextual, engaging, and connected to real-world phenomena. Project-Based Learning offers a promising platform for embedding CER within meaningful investigations (Capraro & Slough, 2013; Han et al., 2015). Through hands-on activities, students explore authentic problems, collect data, design solutions, and present their findings (McNeill & Krajcik, 2012).

Previous research indicates that while individual instructional approaches such as STEM Project-based Learning can improve students' higher-order thinking skills, including problem-solving, scientific literacy, and creativity, their effects are not always consistent across contexts when applied in isolation. For example, studies on PjBL alone have shown positive gains in critical thinking and science learning outcomes (Afriana, 2022; Diani et al., 2025), but some designs using only PjBL or STEM have not demonstrated significantly stronger outcomes compared to conventional approaches (Afriana, 2022; Bandjar et al., 2024).

Similarly, comparative research suggests that integrated STEM-PjBL approaches yield greater improvements in creative and cognitive learning outcomes than traditional PjBL alone, likely because STEM integration provides additional opportunities for interdisciplinary application and deeper engagement with scientific concepts (Syamra & Suryadi, 2025). These studies tend to focus on general thinking skills or creativity rather than explicitly targeting students' scientific argumentation structured through CER.

When combined with STEM integration, PjBL becomes a powerful approach that encourages students to engage in interdisciplinary thinking, creativity, collaboration, and problem-solving (Capraro & Slough, 2013; English, 2016). Integrating PjBL with STEM education further strengthens learning by connecting science concepts with technology, engineering design, and mathematical reasoning (Bybee, 2013; Dare et al., 2018; Kelley & Knowles, 2016). Previous studies have reported that STEM-PjBL can enhance students' scientific reasoning, explanation, and argumentation skills across various educational contexts (Chen & Lin, 2019).

Although previous studies have reported positive effects of STEM PjBL on students' conceptual understanding and engagement, empirical research examining its integration with structured scientific argumentation frameworks such as CER remains limited, particularly in Southeast Asian educational contexts. Moreover, few studies have explicitly explored how STEM-PjBL supports the development of students' scientific argumentation skills in sociocentric issues such as water quality.

The SEA-TEP by SEAMEO STEM-ED seeks to address these systemic gaps by strengthening both pre-service and in-service teacher capacity, fostering curriculum innovation, and supporting collaborative professional learning across five countries (including Indonesia, Malaysia, Thailand, Cambodia, and Kazakhstan) to build instructional expertise in STEM teaching that emphasises inquiry, evidence-based reasoning, and problem solving (SEAMEO STEM-ED, 2025). Three universities in Indonesia have been involved in the project, one of them is Universitas Sebelas Maret (Surakarta). The team has adapted the SEA-TEP professional development (PD) curricula and lesson plans for implementation in local junior and senior secondary schools.

One of the lesson units developed under this initiative addresses water quality—an issue highly relevant to community well-being and sustainability within the Southeast Asian context. The SEA-TEP explicitly promotes the development of contextualised, phenomenon-based STEM learning units that integrate three-dimensional learning principles and CER to strengthen students' scientific literacy and evidence-based reasoning (SEAMEO STEM-ED, 2025). All participating teachers are trained through structured professional development to design STEM-integrated lessons that engage students with authentic socio-scientific issues relevant to their local communities, including environmental sustainability and water quality management.

Water quality is positioned as a meaningful instructional context because it enables students to analyse real environmental problems, interpret empirical data, and justify scientific claims using evidence derived from hands-on investigations and testing activities. Through engagement with phenomena related to acidity, pH, ecosystem health, and pollution, students experience authentic scientific inquiry while practising scientific argumentation grounded in empirical findings, aligning with international recommendations for environmental health education (World Health Organization, 2017).

This study evaluates the impact of a STEM-PjBL curriculum integrated with CER scaffolding. The detail objectives of this study are:

1. To analyse the impact of the STEM-PjBL on students' scientific argumentation skills.
2. To describe students' argumentation profiles based on CER.
3. To explore teacher and student reflections on the implementation of the STEM-PjBL approach in the context of water quality.

2. Methods

2.1 Research Design

This study employed a quasi-experimental design with a non-equivalent control group to examine the effectiveness of a STEM-PjBL lesson plan with explicit CER scaffolding in enhancing students' scientific argumentation skills. The learning intervention employed a STEM-PjBL approach emphasises interdisciplinary integration, authentic problem-solving, and design-based learning experiences (Capraro & Slough., 2013; Dare et al., 2018).

To address potential selection bias arising from non-random assignment, we conducted equivalence testing on demographic variables (age, prior science achievement, socioeconomic background) and pretest scores. Statistical analyses confirmed no significant differences between groups at baseline, supporting the assumption of group comparability. Additionally, both groups were taught by teachers who had participated in the same SEA-TEP professional development programme, ensuring consistency in pedagogical preparation and reducing instructor-related confounding effects.

The research design also incorporated important ethical considerations. All participating students, regardless of group assignment, received high-quality instruction aligned with national curriculum standards. To control for teacher variability, both the experimental and control classes in each school were taught by the same teacher. The control group received conventional instruction on water quality that met learning objectives, ensuring that no students were disadvantaged by participation in the study. Upon the completion of the study, the validated STEM-PjBL lesson materials were fully integrated into the teachers' instructional repertoire for implementation in subsequent academic terms, ensuring broader access to the pedagogical innovation.

2.2 Research Setting and Participants

The research was conducted during the second semester of the 2024/2025 academic year in two private Islamic junior secondary schools in Indonesia: SMP Muhammadiyah 7 Surakarta, a private Islamic junior high school under the Muhammadiyah Foundation, and SMP Islam Al-Hadi, an Islamic private junior high school under Amal Fatimah Foundation, in Sukoharjo Regency. The schools were selected using a purposive sampling technique based on several criteria, including comparable curriculum characteristics, availability of science facilities, and similar student academic backgrounds. In addition, the science teachers at both schools had previously participated in the SEA-TEP Professional Development Training organised by Universitas Sebelas Maret prior to the implementation of the lesson plan.

Table 1

Distribution of Research Subjects

School	Group	Class	Number of Students
SMP Muhammadiyah 7	Experiment	VIII-D	28
SMP Muhammadiyah 7	Control	VIII-C	28

SMP Islam Al-Hadi	Experiment	IX-B	24
SMP Islam Al-Hadi	Control	IX-C	26
Total			106

The study involved 56 students from SMP 7 Muhammadiyah and 50 from SMP Al Hadi. Using purposive sampling, two classes were selected from Grade 8 at SMP 7 Muhammadiyah and two from Grade 9 at SMP Al Hadi. One class in each school serves as the experimental group and the other as the control (see Table 1). The variation in grade levels is due to the "*Acid-Base*" topic being taught at different stages in each school's curriculum.

2.3 Instruments

2.3.1 The Water Quality Lesson Plan

The Water Quality lesson plan used in this study was adapted from the Water Quality Learning Unit developed by Ann M. Novak and published by the CREATE Institute for STEM at Michigan State University (Novak, 2019; Novak & Krajcik, 2019). This lesson plan is grounded in 3D learning and inquiry-based science instruction. Adaptation of the original lesson plan was designed to align with the objectives of the SEA-TEP programme and to align with Indonesia science curriculum, and the local water quality issue. The adaptation is to support the development of students' scientific argumentation skills through the integration of Science and Engineering Practices (SEP), Disciplinary Core Ideas (DCI), Crosscutting Concepts (CCC), and the Claim–Evidence–Reasoning (CER) framework.

The instructional unit focused on the topic of water quality and water pollution, with the main driving question: "*Is the water around us safe for consumption?*" This unit is implemented in Grade 8 or 9 junior secondary school over five meetings (four weeks), with each meeting lasting 45 minutes. The learning sequence was structured to progressively guide students from problem identification to investigation, data analysis, explanation, and solution design.

Across the four instructional meetings, students engaged with a sequence of sub-driving questions that focused on local water conditions, criteria for potable water, experimental analysis of water quality based on pH, and the design of solutions to produce safe drinking water. Several adaptations were made to Novak's unit lesson, including the use of a locally relevant water issue-safe drinking water in Surakarta- as the anchoring phenomenon, a narrowed focus on water quality parameters limited to pH measurement, and a redesigned final problem-solving phase in which students discussed innovative solutions for providing safe drinking water for the community. As one alternative solution, students were introduced to the concept of bubble water as an innovative approach to improving drinking water safety.

The lesson plan explicitly incorporated Science and Engineering Practices, including asking questions, developing and using models, planning and carrying out investigations, analysing and interpreting data, and constructing explanations from evidence. The Disciplinary Core Ideas centred on the physical and chemical properties of water, water quality parameters (particularly pH), and the environmental impacts of water pollution. In addition, Crosscutting Concepts, particularly cause and effect and patterns, were emphasised to support students' understanding of relationships between human activities, water quality changes, and environmental consequences (see Table 2).

Table 2

Adaptation of the Water Quality Lesson Plan for the Experimental Class

Meeting	Science and Engineering Practices (SEP)	Disciplinary Core Ideas (DCI)	Crosscutting Concepts
1	Asking questions; Developing and using models	Physical and chemical properties of water	Cause and effect
2	Developing and using models; Constructing explanations; Obtaining and evaluating information	Criteria for potable water; pH concept	Cause and effect
3	Planning and carrying out investigations; Analysing and interpreting data; Applying CER	Measurement of water quality parameters (pH)	Patterns
4	Constructing explanations; Communicating solutions; Designing prototypes	Environmental impact of water quality and water treatment	Cause and effect; Systems

2.3.2 CER-Based Scientific Argumentation Test

Students' scientific argumentation skills were assessed using a CER rubric adapted from McNeill & Krajcik (2012), which has been widely used to evaluate students' ability to construct scientifically coherent explanations. Students were required to provide scientific explanations related to water quality, including pH or acidity, natural indicators, and pollution impacts. Each response was scored using a 1–3 rubric for Claim, Evidence, and Reasoning, with a maximum total score of 9 (see Table 3). The test was in the form of open-ended questions using the CER framework. Each item required students to answer context-based questions related to water quality, including pH, natural indicators, and pollution impacts. The total score was then categorised into three levels of scientific argumentation ability: low (1–3), medium (4–6), and high (7–9).

Table 3

Scientific Argumentation Using the Framework of CER Assessment Rubrics

Element	Score		
	Score 1	**Score 2**	**Score 3**
Claim	The student presents an unclear, incomplete, or incorrect claim that is not directly related to the question posed	The student provides a claim that is relevant to the question but lacks clarity, precision, or completeness	The student presents a clear, accurate, and complete claim that directly addresses the question
Evidence	The student provides little or no evidence, or the evidence presented is irrelevant, inaccurate, or not based on observations or scientific data	The student provides some relevant observational data or scientific information; however, the evidence is incomplete or not sufficiently detailed to fully support the claim	The student provides accurate, relevant, and sufficient observational data or scientific evidence that clearly supports the claim

Reasoning	The student fails to connect the evidence to the claim, or the reasoning is illogical and does not refer to scientific principles	The student attempts to link the evidence to the claim using scientific concepts, but the explanation is partially developed or contains minor misconceptions	The student logically and coherently connects the evidence to the claim using appropriate and correct scientific principles

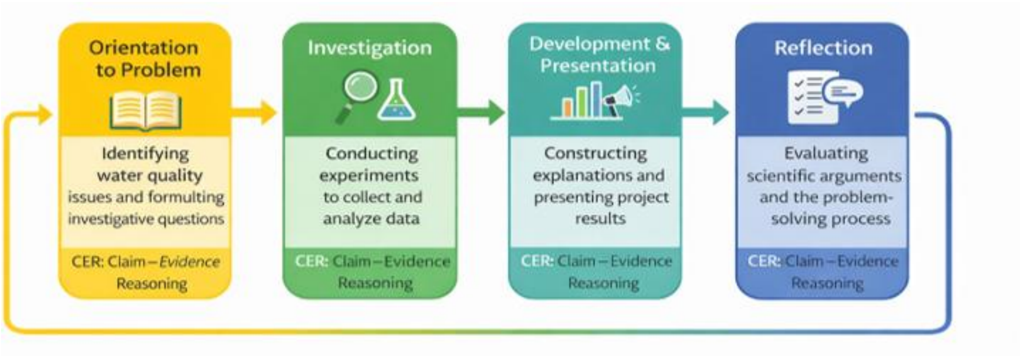
At the final stage of the intervention, both students and teachers completed a structured reflection questionnaire to capture their perceptions of the STEM-PjBL implementation, including student engagement, clarity of scientific concepts, collaboration, and perceived learning benefits. The questionnaire was administered after the completion of all learning units.

2.4 Procedures

In each participating school, the same teachers were assigned to both groups to maintain instructional consistency. The control classes received instruction using the teachers' conventional lesson plans, whereas the experimental classes were taught using an adapted water quality instructional unit grounded in STEM-oriented Project-Based Learning (PjBL) and supported by the Claim–Evidence–Reasoning (CER) framework. Instruction in both control and experimental groups was conducted over five sessions, each with a duration of 45 minutes (see Table 5). A visual overview of the STEM-PjBL learning implementation integrated with the CER framework is presented in Figure 1.

Figure 1

Overview of the STEM-PjBL Learning Implementation Supported by the CER Framework.



Detailed descriptions of the learning progression and the alignment of Science and Engineering Practices (SEP), Crosscutting Concepts (CCC), and Disciplinary Core Ideas (DCI) are provided in Table 4.

Table 4

STEM-PjBL with 3D Learning Framework Instructional Design

Meeting (Time)	Science Engineering Practices (SEP)	Crosscutting Concept (CCC)	Discipline Core Ideas (DCI)
1 (45 minutes)	Asking Questions and Defining Problems: Students observe water samples, identify problems related to water quality, and formulate investigative questions for the project.	Patterns Cause and Effect	Water Quality: -Physical parameters (colour, turbidity, odour)- Chemical parameter (pH) -Indicators of contamination
2 (45 minutes)	Developing and Using Models: Students develop a model for water quality testing, identify variables, and create a procedural diagram.	Systems and System Models	Water Testing Processes: -pH testing -Physical observations -Relationship between water quality and living organisms
3 (45 minutes)	Planning and Carrying Out Investigations Students carry out the water quality experiment using pH indicators and record data systematically.	Energy and Matter Cause and Effect	Interactions of substances: - pH changes -Factors causing contamination -Environmental impacts
4 (45 minutes)	Analysing and Interpreting Data Students compare results across water types, identify data patterns, and draw conclusions.	Patterns	Data Interpretation: -Reading pH results -Connecting parameters with water quality
5 (45 minutes)	Constructing Explanations and Communicating Students develop scientific arguments using the CER framework, conclude their project findings, and present them.	Stability and Change	Scientific Argumentation and Water Quality: -Claim, Evidence, Reasoning - Recommendations for improving water safety

2.5 Data Analysis

The development of students' scientific argumentation skills was quantitatively assessed through the application of Hake's normalized gain (N-Gain) scores, which provided a standardised measure of improvement from pre-test to post-test. Prior to inferential analysis, the dataset was subjected to Shapiro-Wilk and Levene's tests to verify the assumptions of normality and homogeneity of variance, respectively. As the results indicated that the data did not conform to a normal distribution, the non-parametric Mann–Whitney U test was employed to evaluate significant differences between the experimental and control cohorts. All statistical tests were conducted with a significant threshold established at $p < 0.05$.

Qualitative data derived from student and teacher reflections were analysed using a descriptive thematic approach. This process involved an iterative coding strategy to identify and categorise recurring themes related to student engagement levels, the perceived effectiveness of the intervention, and the specific pedagogical challenges encountered throughout the instructional process. The systematic analysis facilitates a deeper understanding of the contextual factors that influenced the development of argumentation skills during the learning intervention.

2.6 Data Validity and Reliability

The Instrument validity was examined through rigorous expert validation and reliability assessment. Content validity was quantified using the Content Validity Index (CVI), yielding a score of 0.92, which signifies a high level of representativeness and relevance. Instrument reliability was further evaluated through interrater agreement, resulting in a coefficient of 0.87, categorised as high reliability. Additionally, the consistency of the scoring process for scientific argumentation was assessed using Cohen's Kappa; the resulting value of 0.81 indicates substantial interrater agreement and stable scoring consistency.

3. Results and Discussion

3.1 Scientific Argumentation Skills Test Results

The results of this study present the empirical findings on students' scientific argumentation skills following the implementation of the STEM-Integrated Project-Based Learning (STEM-PjBL) supported by the Claim–Evidence–Reasoning (CER) framework.

Table 5

The Mean Scores for Pre-Test, Post-Test, and N-Gain Across Both Groups

Group	N*	Pre-Test	Post-Test	N-Gain	Category
		Mean ± SD	Mean ± SD		
Experiment					
SMP 7 Muhammadiyah	20	64.78 ±12.07	87.00±10.08	0.67	Mid
SMP Al Hadi	17	65.49±13.07	92.29±10.86	0.79	Mid
Control					
SMP 7 Muhammadiyah	20	57.11±5.71	61.11±4.73	0.15	Low
SMP Al Hadi	20	50.89±9.50	53.78±9.29	0.054	Low

N is the number of students who completely attended the five meetings and filled in the pre- and post-test*

The quantitative analysis shows that students in the experimental group experienced a higher improvement in scientific argumentation skills compared to those in the control group. The Mann–Whitney U test indicated a statistically significant difference between the two groups, confirming the effectiveness of the STEM-PjBL with CER framework intervention (see Table 5).

3.2 Argumentation Skills Profile

Further analysis was conducted to examine students' scientific argumentation profiles based on CER levels. This classification follows McNeill and Krajcik (2012), ranging from Level 1 (claim only) to Level 5 (complete CER structure). Table 6 presents the distribution of students across these levels.

Table 6

Distribution by Argumentation Level

Level	Description	Percentage of Students (%, Experiment)	Percentage of Students (%, Control)
Level 1	Claim without evidence and reasoning	5.7	15.4
Level 2	Claim with simple evidence	17.3	35.9
Level 3	Claim and evidence with weak reasoning	19.4	27.3
Level 4	Logical Claim, Evidence, and Reasoning	33.6	14.8
Level 5	Complete Claim, Evidence, and Reasoning	24.0	6.6

These results reveal that 57.6% of students in the experimental group reached Levels 4 and 5, which reflect complete and logically structured CER-based arguments. In contrast, the control group was dominated by Levels 2 and 3 (63.2%), indicating limited ability to provide reasoning supported by evidence. Qualitative examination of students' written responses further illustrates these differences in argumentation quality. Based on those questions, the students provide different scientific arguments, which were varied between low level CER and high-level CER (see Table 7).

Table 7

Example of Student's CER

Question	High-Level CER (Level 5)	Low-level CER (Level 2)
Is the water sample suitable for consumption? **(Answer: Yes/No) – Claim**	Sample A is suitable for consumption, whereas Samples B and C are not suitable for consumption	Sample A is suitable, whereas Samples B and C are not suitable
Based on the data in the table, what evidence supports your claim? – Evidence	The physical and chemical parameters of Sample A meet the requirements for potable water, whereas Samples B and C do not meet the consumption standards.	Because sample A shows the water's consumptions characteristic whereas samples B and C aren't.

Provide reasoning that supports your claim and evidence! – Reasoning	Physically, Sample A is colourless, odourless, and tasteless. Chemically, the total dissolved solids (TDS) value is below the maximum limit of 500 mg/L, and the pH value ranges between 6.5 and 8.5. These results are consistent with the observational data presented in the table above, indicating that Sample A meets clean water quality standards, while Samples B and C do not.	Shows in the table above

A high-level response (Level 4–5) demonstrates a complete CER structure, in which the student clearly states a claim regarding water suitability, supports it with relevant observational and measurement data, and justifies the claim using established water quality standards, including pH range and total dissolved solids limits.

In contrast, a low-level response (Level 2) is characterised by a simple and descriptive claim supported by limited evidence and the absence of scientific reasoning. The student relies primarily on superficial physical appearance, such as water clarity, without connecting observations to empirical data or underlying scientific concepts. This comparison highlights that students who participated in STEM-PjBL supported by explicit CER scaffolding were more capable of constructing mature, data-driven, and logically coherent scientific arguments.

3.3 Reflections from Students and Teachers

To further confirm the quantitative findings, reflection questionnaires from students and teachers were analysed qualitatively. Table 8 summarises student responses.

Table 8

Student Reflection Results on STEM-PjBL

Reflection Aspects	Percentage of students' agreement (%)
Learning made concepts easier to understand	87
Project activities were interesting and enjoyable	84
Improved collaboration skills	80
Encouraged scientific and argumentative thinking	78
Helped connect science to real-life contexts	82

Students stated that the "*Safety Drinks*" project provided a new, challenging learning experience in which they directly measured water pH, identified acidity levels, and connected results to acid-base theory.

Teacher reflections reinforced the student feedback. Teachers observed that STEM-PjBL encouraged students to think critically, work collaboratively, and construct arguments grounded in evidence. Examples of teacher statements:

- *"This model makes students more confident in expressing opinions because they have real data as the basis for their arguments."* (Science Teacher, SMP Muhammadiyah 7 Surakarta)
- *"The project activities greatly support the development of conceptual understanding and scientific attitudes."* (Science Teacher, SMP Islam Al-Hadi),

4. Discussion

The results of this study present the empirical findings on students' scientific argumentation skills following the implementation of the STEM-PjBL supported by the CER framework. The strongest improvement was observed in the Claim element, which is consistent with previous research indicating that students generally find it easier to articulate claims than to justify them with evidence and scientific reasoning (Berland & McNeill, 2010; McNeill & Krajcik, 2012). This pattern aligns with theoretical perspectives on scientific argumentation, particularly Toulmin's argumentation model, which highlights claims as the most accessible element of an argument when explicit scaffolding is provided.

In contrast, the Reasoning element showed comparatively lower gains, a finding that mirrors international studies reporting that students often struggle to connect evidence to underlying scientific principles and to articulate causal mechanisms (Sampson & Clark, 2008; Osborne et al., 2016). Reasoning requires higher-order cognitive processes, including conceptual understanding, abstraction, and the ability to integrate data with disciplinary knowledge, which develop more gradually and require sustained instructional support.

Within the context of inquiry-based STEM learning, STEM-PjBL offers authentic problem situations that promote data collection, analysis, and justification; however, developing robust scientific reasoning remains a pedagogical challenge that necessitates repeated opportunities for guided reflection, modelling, and explicit reasoning prompts (McNeill et al., 2016). Overall, the observed improvements across the CER elements support the role of structured scaffolding within STEM-PjBL in strengthening students' scientific argumentation, while also highlighting the need for continued emphasis on reasoning development.

The results demonstrate that students instructed using the STEM-PjBL achieved higher gains in scientific argumentation skills compared to those receiving conventional instruction. This finding is consistent with previous studies indicating that STEM-integrated PjBL enhances scientific explanation and reasoning skills (Chen & Lin, 2019; Han et al., 2015; Kurniawan et al., 2025). Improvements across CER components suggest that structured CER scaffolding within authentic STEM projects supports deeper conceptual understanding and evidence-based reasoning (Osborne et al., 2016; Sampson et al., 2011).

Students in the experimental group demonstrated increased engagement, collaboration, and motivation during learning activities related to water quality investigations. This heightened engagement likely resulted from the authentic, problem-based nature of the STEM-Integrated Project-Based Learning (STEM-PjBL) tasks, which have been shown to foster sustained student interest and intrinsic motivation when learners perceive activities as meaningful and relevant to real-world contexts (Hidi & Renninger, 2006; Thomas, 2000). In addition, the integration of CER scaffolding provided clear cognitive support that enabled students to participate more confidently in collaborative discussions, reducing cognitive load and facilitating shared sense-making among peers (Osborne et al., 2016; Sampson & Clark, 2008).

Teachers also reported more active classroom interactions and improved student participation during project discussions. Teachers themselves may have been more engaged because the STEM-PjBL model encourages instructional autonomy and reflective practice, which have been associated with higher teacher motivation and professional fulfilment in the literature (Kelchtermans & Ballet, 2002). The combination of student-centred tasks, collaborative inquiry, and structured reasoning support thus contributed to the observed increases in engagement for both students and teachers within the experimental group.

Furthermore, this study demonstrates that contextualization of the Southeast Asian Teacher Education Programme (SEA-TEP) professional development training—through its alignment with national curricula, local phenomena, and socio-scientific issues—is highly feasible across diverse regional contexts. Consequently, the systematic implementation of this pedagogical framework represents a viable strategy for enhancing students' scientific argumentation skills. Such improvements are critical for elevating scientific literacy performance in international assessments, such as the PISA, particularly within the Southeast Asian region.

Despite these promising findings, this study has several limitations. The research was conducted in a limited number of schools and focused on short-term learning outcomes. Future studies are encouraged to involve larger and more diverse samples, as well as longitudinal designs, to examine the sustained impact of STEM-PjBL integrated with CER on students' scientific argumentation skills.

5. Conclusion

The results of this study highlight important implications for classroom practice, teacher professional development, and STEM education initiatives in Southeast Asia. Teachers are encouraged to integrate explicit CER scaffolding within STEM-PjBL to support students in constructing coherent and evidence-based scientific arguments. For teacher education programmes such as SEA-TEP, this study provides empirical evidence to inform the design of instructional modules that promote scientific literacy and higher-order thinking skills. At a broader level, the findings contribute to ongoing efforts to strengthen STEM education through contextually relevant and inquiry-driven learning approaches in the region.

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EVALUATING THE EFFECTIVENESS OF THE SOUTHEAST ASIAN TEACHER EDUCATION PROGRAMME (SEA-TEP) IN THAILAND

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ABSTRACT

This study examined the effectiveness of the SEA-TEP professional development workshop in supporting Thai teachers' adoption of Claim–Evidence–Reasoning (CER) and modelling using a mixed-methods approach. Quantitative data were analysed using independent-samples t-tests with propensity score matching to control for background characteristics. Results indicated no statistically significant differences between the experimental and control groups in teachers' self-efficacy in applying reasoning-focused instructional approaches or in their knowledge of CER and modelling. In contrast, qualitative findings from interviews and focus groups revealed that teachers perceived the workshop as highly beneficial. Participants expressed strong willingness to implement CER and modelling in their classrooms and reported positive impacts on students, including enhanced collaboration, improved scientific questioning and hypothesising, development of 21st-century skills, and increased engagement. However, teachers also identified several challenges that constrained effective implementation. Overall, the findings highlight the need for sustained professional development, curriculum alignment, administrative and resource support, and scaffolded instructional designs to strengthen the integration of CER and modelling in the Thai educational context.

Keywords: Claim–Evidence–Reasoning (CER), Modelling-Based Inquiry, Professional Development, STEM Education, Teacher Self-Efficacy, STEM Pedagogical Knowledge

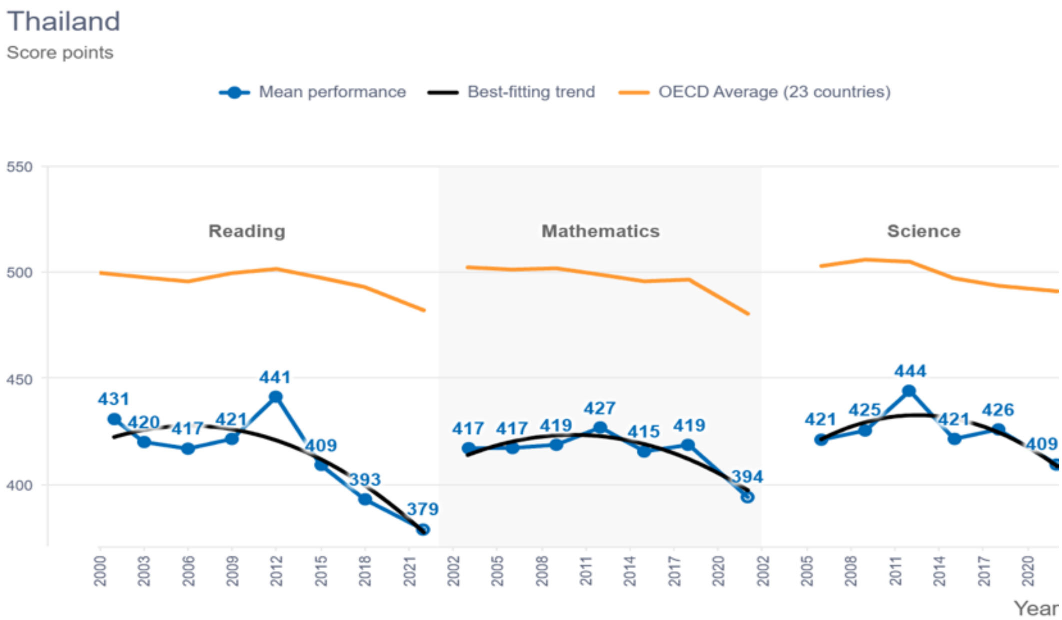
1. Introduction

Science education has been a cornerstone of educational development, as advancements in science and technology are widely regarded as key drivers of economic growth, national development, and international competitiveness. Countries with strong capabilities in science and technology are better positioned to succeed in the global arena and reap greater benefits. Therefore, not only have significant investments been made in science education, but science instruction has also been continually refined and monitored to support development goals.

Thailand is among the countries that need to improve science education at the primary and secondary school levels, as international assessments—such as the programme for International Student Assessment (PISA)—have highlighted weaknesses in science instruction. For example, Figure 1 shows that Thailand's average PISA science score in 2022 was 409, which is below the international average. Additionally, PISA results reveal a declining trend in science performance, with scores gradually decreasing from 2006 to 2022.

Figure 1

Thailand's performance in reading, mathematics, and science



Source: https://www.oecd.org/en/publications/pisa-2022-results-volume-i-and-ii-country-notes_ed6fbcc5-en/thailand_6138f4af-en.html

Thailand has implemented a variety of strategies to address inefficiencies in science education. At the macro level, efforts have included the consolidation of science-related institutions. One notable example is the establishment of the Ministry of Higher Education, Science, Research and Innovation—a new government body tasked with promoting science education at the tertiary level. This ministry encourages strong collaboration between universities and industries to develop a high-quality workforce. At the primary and secondary levels, the Ministry of Education has introduced several initiatives aimed at improving science instruction. One such initiative is the creation of "*innovative educational areas,*" or sandbox zones, which grant selected provinces greater autonomy in managing their educational practices. These areas are designed to reduce centralised control and allow for locally tailored approaches to science education. Another movement at the country level is the requirements in the new curriculum that emphasise more student competencies than test scores or grades.

At the school and classroom level, there have been suggestions by educators and scholars to change science practices in classrooms by introducing higher-order teaching strategies that require students to think critically and put more effort in their learning. For example, science teachers are encouraged to use active learning strategies in their classrooms to reduce inactive lessons. Some advanced digital technology tools are introduced to teachers using a traditional method called teacher training programmes. Teachers are also required to collaborate with other teachers within a school by means of sharing teaching practices and discussions. This is usually called a professional learning community (PLC).

One significant development in science education, both in Thailand and globally, is the adoption of STEM education, which is believed to address various challenges in science instruction. STEM stands for Science, Technology, Engineering, and Mathematics, and it represents a strategic approach to teaching science. Integrated in a holistic manner, integrative STEM education applies technology and engineering design-based methods to intentionally teach the content and practices of science and mathematics alongside those of technology and engineering (McComas & Burgin, 2020). In Thailand, the national curriculum incorporates STEM education, with an emphasis on design-based learning and computational thinking (Ladachart et al., 2024). As a relatively recent initiative, STEM education in Thailand has shown both successes and limitations. For instance, research by Ladachart et al. (2024) found significant gender differences in STEM performance, although there were no statistically significant differences in interest and recognition between male and female students.

Given the limitations of STEM education in Thailand, there has been a growing call for stronger collaboration between schools and science teacher development institutes to enhance teachers' ability to implement STEM instruction effectively. For example, the Institute for the Promotion of Teaching Science and Technology (IPST) has developed STEM workshops and instructional materials specifically designed for teachers. Additionally, the Southeast Asian Ministers of Education Organization (SEAMEO), particularly the SEAMEO Regional Centre for STEM Education (SEAMEO STEM-ED) with the collaboration with the private sector—particularly Chevron—has supported the development of science and STEM education in Thailand and other Asian countries, including Malaysia, Cambodia, Kazakhstan, Vietnam, and Indonesia.

One recent initiative programme supported by the SEAMEO and Chevron partnership is the Southeast Asian Teacher Education programme (SEA-TEP) which introduces the Claim-Evidence-Reasoning (CER) framework and modelling approaches in science classrooms. The CER framework is a widely used instructional method that helps students develop scientific argumentation. In this approach, students make a claim, support it with evidence, and provide reasoning to explain the connection between the two (Nussbaum et al., 2024). This method not only enhances students' scientific thinking but also makes their thought processes more visible. When combined with other instructional strategies, CER and modelling can produce greater learning outcomes than when used in isolation.

This study aims to evaluate the effectiveness of the Southeast Asian Teacher Education programme (SEA-TEP) in Thailand. With collaboration with SEAMEO STEM-ED, three universities in Thailand, Chulalongkorn University, Naresuan University, and King Mongkut's University of Technology Thonburi, provided professional development (PD) workshops on the application of Claim-Evidence-Reasoning (CER) framework and modelling approaches to science teachers. The findings could offer insights into the extent to which this instructional approach is effective, as well as the factors that influence its success or failure. The results will be beneficial not only for science teachers in Thailand but also for educators in other countries seeking to enhance the quality of science education.

1.1 Research Questions

This study aims to address the following research questions:

1. How effective was the implementation of the Southeast Asian Teacher Education Programme (SEA-TEP) in Thailand?
2. What are impacts of the SEA-TEP on participations' understanding and application of CER and modelling?
3. How did participants adopt and integrate STEM learning units and/or CER and modelling into teaching practices?
4. What are challenges encountered by participants when adopting and integrating STEM learning units and/or CER and modelling into teaching practices?

1.2 Research Objectives

Given the research questions, the objectives of this study aim to:

1. Examine the effectiveness of the implementation of SEA-TEP in Thailand.
2. Assess the impact of SEA-TEP on participants' understanding and application of CER and modelling.
3. Explore how participants adopt and integrate STEM learning units and/or CER and modelling into their teaching practices.
4. Identify the challenges encountered by participants when adopting and integrating STEM learning units and/or CER and modelling.

2. Literature Review

2.1 Claim-Evidence-Reasoning (CER) and Modelling-Based Inquiry in Science Education

As science education moves toward inquiry-based and student-centred learning, instructional strategies such as Claim-Evidence-Reasoning (CER) and Modelling-Based Inquiry (MBI) have gained widespread attention for their effectiveness in promoting scientific thinking and deep conceptual understanding. Both approaches encourage active engagement, critical thinking, and communication, which are essential components of 21st-century science classrooms (e.g., Gotwals & Songer, 2010; McNeill & Krajcik, 2008; National Research Council, 2012; Windschitl et al., 2008).

2.1.1 Claim-Evidence-Reasoning (CER): Definition and Purpose

The Claim-Evidence-Reasoning (CER) framework is an instructional model designed to help students construct scientific explanations and develop argumentation skills. A claim is a statement or conclusion that answers a question or problem. Evidence consists of scientific data that support the claim. Reasoning provides a justification that connects the evidence to the claim using scientific principles or theories (McNeill & Krajcik, 2012). The CER framework draws heavily from the work of Toulmin's Argument Pattern (TAP), which outlines how claims are supported by data and justified through warrants (Toulmin, 1958). Adapted for science education, CER simplifies argumentation into a three-part structure that is accessible to students from elementary through high school levels. It aligns well with the next Generation Science Standards (NGSS), which emphasise scientific explanation and argumentation as core practices.

2.1.2 Modelling-Based Inquiry: Definition and Background

Modelling-Based Inquiry (MBI) is a teaching approach where students actively build, use, test, and refine models to represent and explain scientific phenomena. Rather than treating models as static visuals or textbook tools, MBI engages students in model-based reasoning, emphasising the iterative and dynamic nature of scientific modelling (Windschitl et al., 2008). Models can be diagrams, physical objects, simulations, or mathematical representations that help students visualise complex concepts. Model-based reasoning originated from the modelling instruction programme developed by David Hestenes and colleagues in the 1990s, primarily for physics education (Hestenes, 1992). The approach has since expanded into other science disciplines, including biology and chemistry, and has been integrated into many professional development programmes worldwide. The method is grounded in constructivist learning theory, which posits that learners build understanding through active exploration and social interaction.

2.2 Using Propensity Score Matching to Evaluate the Effectiveness of CER- and Modelling-Based Inquiry in Thailand

Evaluating the impact of educational interventions, such as CER and modelling-based inquiry, requires careful consideration of potential biases in observational data. In educational contexts, it is often impractical or unethical to randomly assign participants to treatment and control groups. Instead, individuals—such as teachers participating in a professional development programme—self-select into the intervention or are selected based on contextual factors. This self-selection introduces selection bias, where differences in outcomes may be attributed to pre-existing characteristics rather than the intervention itself. To address this issue, Propensity Score Matching (PSM) offers a rigorous statistical technique that approximates a randomised experimental design using observational data. Originating from the Rubin Causal Model (RCM), the method was formalised by Donald Rubin and Paul Rosenbaum in the early 1980s (Rosenbaum & Rubin, 1983). It is based on the notion of counterfactual inference—that is, estimating what would have happened to participants in the treatment group had they not received the treatment. According to Rubin (1974), the fundamental problem of causal inference is that we can never observe both outcomes (treated and untreated) for the same individual. PSM attempts to resolve this by pairing treated and untreated individuals with similar characteristics to simulate a fair comparison. The PSM process involves several key steps. First, propensity scores are estimated, typically using logistic regression, where the dependent variable is binary (e.g., 1 = received CER- and modelling-based inquiry, 0 = did not). The predictor variables, or confounders, are selected based on their influence on both the likelihood of treatment and the expected outcomes. In the context of science education in Thailand, relevant covariates might include gender, age, teaching experience, prior participation in STEM training, school size, class size, workload, geographic location, and access to teaching resources. After estimating the propensity scores, individuals are grouped using various matching techniques. A commonly recommended approach by Rosenbaum and Rubin (1983) is to stratify individuals into five equal-sized strata or quintiles based on their propensity scores. This stratification helps ensure balance in covariates across treatment and control groups within each stratum. Within each quintile, outcomes—such as changes in teachers' self-efficacy or STEM instructional knowledge—are compared, and the average treatment effect on the treated (ATT) is calculated. These results are then aggregated to provide an overall estimate of the programme's effectiveness.

PSM is particularly valuable for evaluating the CER- and modelling-based inquiry initiative in Thailand because it allows for causal inference in non-experimental settings. Applying PSM to the evaluation of CER- and modelling-based inquiry in Thailand can reveal not only whether the instructional method is effective, but also which groups of teachers benefit most, such as those in rural vs. urban schools or novice vs. experienced educators. It enables researchers to draw more robust conclusions about the intervention's impact, ultimately guiding policy decisions and the design of future teacher development programmes.

3. Research Method

This research is a mixed research method aiming at investigating whether or not the CER and modelling-based inquiry is effective and exploring whether or not there are successful factors and barriers in applying this instruction in science classrooms. In order to address these issues. We carried out the investigation as presented below.

3.1 Objective 1: Examine the effectiveness of the implementation of the SEA-TEP in Thailand.

For this research objective, a quantitative research method called propensity score analysis was used to determine the effectiveness of the SEA-TEP in Thailand. The effectiveness in this study was evaluated by two aspects including participations' understanding and application of CER and modelling. Participants' understanding was measured by participants' knowledge in CER and modelling while the application of CER and modelling was measured by participants' self-efficacy in applying CER and modelling in classrooms.

3.1.1 Participants

Participants were teachers participating in the SEA-TEP in Thailand. Three SEA-TEP programmes have been conducted by researchers from Chulalongkorn University, Naresuan University, and King Mongkut's University of Technology Thonburi. The teachers involved in one of these programmes are selected as the experimental group that received the CER-and modelling-based inquiry. This study also included teachers who did not participate in the intervention and they were chosen in a way to be similar to those in the experimental groups in terms of gender, education, school location and experiences in professional development. This group of included teachers was used as the control group which did not receive the CER- and modelling-based inquiry.

3.1.2 Instrument

Self-efficacy in applying the instructional approach that focuses on students' reasoning and thinking, adapted from Dong et al. (2019), was measured by 6 rating scale questions (ranging from 1 to 5). For example, I am confident to design a good effective classroom that focuses on students' reasoning, I know the way to handle the problems when I design my classroom that focuses on students' reasoning, I think it is not difficult to deliver a classroom that focuses on students' reasoning , I am confident about handling the difficulties of a thinking classroom, I know how to conduct a thinking classroom in my school, and my past teaching experience can provide a suitable solution for thinking and reasoning classroom. The Cronbach's Alpha coefficient for this scale was .891. Questions used to measure teachers' knowledge in CER and modelling were adapted from Lin, and Williams (2016). There are three items to measure teachers' knowledge in CER and modelling and include 1) I am familiar with knowledge in CER, 2) I am familiar with knowledge in science modelling, and I am familiar with knowledge in tools/materials used to teach CER and modelling. The Cronbach's Alpha coefficient for this scale was .849. Data was collected through the online survey.

3.1.3 Data Analysis

Propensity score analysis was used to analyse data to reveal if the intervention was effective. The outcome variables included teachers' self-efficacy in applying the instructional approach that focuses on students' reasoning and thinking and teachers' knowledge in CER and modelling. The independent variable was the professional development programme (1= experimental group and 0 = control group). The confounding variables included gender, school location, education, and experiences in professional development (e.g., time spent on reading books and journals, and the number of training in CER and modelling). Logistic regression was used to predict the intervention group (1= experimental group and 0=control group) by including aforementioned confounding variables as predictors. Propensity scores from the logistic regression were used to match participants in the experimental group with those in the control group. Based on the matching using the propensity score, twenty-four participants (twelve participants from each group) were identified. The matched participants were thought to be equivalent in terms of background variables and were used for comparisons to reduce biases when the independent samples t-test was conducted to compare scores on self-efficacy and knowledge between the two groups.

3.2 Objectives 2-4

Objective 2: What are impacts of the SEA-TEP on participations' understanding and application of CER and modelling?

Objective 3: How did participants adopt and integrate STEM learning units and/or CER and modelling into teaching practices?

Objective 4: What are challenges encountered by participants when adopting and integrating STEM learning units and/or CER and modelling into teaching practices?

Assess the impact and explore CER and modelling adoption, as well as the challenges encountered by teachers when adopting and integrating STEM learning units and/or CER and modelling.

These objectives are set forth to explore additional information regarding the effectiveness of the SEA-TEP programme and how CER and modelling workshops influenced teachers 'understanding and application of CER and modelling. A group of 10 participants participated in workshops conducted by Chulalongkorn University, Naresuan University, and King Mongkut's University of Technology Thonburi were selected. Data regarding the impacts, teacher's adoption, challenges, and supports as a result of teacher participation in the professional workshop in CER and modelling were collected by interview and focus groups. Interview and focus group data was analysed by content analysis.

4. Results

4.1 Demographic Variables of Matched Participants from the Experimental and Control Group

There were 187 participants in the control group and 15 participants in the experimental group. Due to substantial differences in background characteristics between the two groups, direct comparison of outcomes would have been problematic for assessing the effectiveness of the professional development programme. Therefore, propensity scores were estimated using logistic regression by using gender, region, education, and prior professional development experiences as predictors and the dummy variable that indicates whether or not the participants participated in the professional workshop was the dependent variable. Then the estimated propensity scores obtained from the logistic regression were used to match participants across groups. Participants with divergent background characteristics who could not be successfully matched were excluded from subsequent analyses. After matching using propensity scores, a total of 24 participants were successfully matched, including 12 participants from the experimental group and 12 from the control group. According to table 1, for the dummy variables experience reading CER-related materials (ReadCER) and experience attending thinking/reasoning workshops (Train), the mean represents the proportion of participants with prior experience. Approximately 67% of the control group and 58% of the experimental group reported experience reading CER-related materials, while workshop attendance was low in both groups (17% and 8%, respectively). In overall, the control and experimental groups are comparable in terms of gender, region, education, and prior professional development experiences. This is supported by the approximately identical distributions of estimated propensity scores of the two groups in figure 1.

Table 1

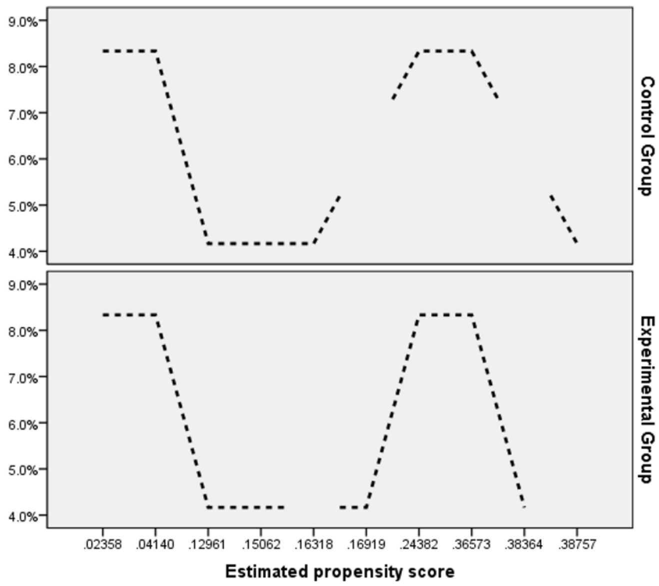
Demographic Characteristics of Matched Participants from the Experimental and Control Group

Variable		**Control Group**				**Experimental Group**			
		n	percent	*M*	*SD*	*n*	percent	*M*	*SD*
Gender	Male	2	16.7	.17	.39	2	16.7	.17	.39
	Other	10	83.3			10	83.3		
Region	Urban	1	8.3	.08	.29	2	16.7	.17	.39
	Other	11	91.7			10	83.3		
Education	Graduate Degree	1	8.3	.08	.29	2	83.3	.17	.39
	Other	11	91.7			10	16.7		
ReadCER				.67	.49			.58	.51
Train				.17	.39			.08	.29
Read				2.67	.89			2.83	.21

Note: ReadCER = experiences in reading books and materials in CER and modelling (1=yes, 0 = no), Train = experiences in attending thinking and reasoning classroom workshops (1=yes, 0 = no), and Read = the frequency in reading books and research in teaching development (1= Not at all, 5 = Everyday).

Figure 1

The Distributions of Propensity Scores Between the Treatment and Control Group



4.2 Effectiveness of the Implementation of SEA-TEP in Thailand

Independent samples t-test was used to compare the self-efficacy in applying the instructional approach that focuses on students' reasoning and thinking and the knowledge in CER and modelling between the experimental and control groups by using data from the matched participants. Figure 2 shows averages of self-efficacy and knowledge as measured to compare the extent of differences among participants in the experimental and control groups. Even though figure 2 show somewhat different between the experimental and control groups in terms of self-efficacy in applying the instructional approach that focuses on students' reasoning and thinking and the knowledge in CER and modelling, table 2 reveals that, after backgrounds were controlled using the propensity scores, 1) scores on self-efficacy in applying the instructional approach that focuses on students' reasoning between the experimental and control groups were not statistically different *($M_E = 3.64$, $M_C = 3.69$, $t = .224$, $p = .825$)*. Similarly, the independent samples t-test reveals that the difference in teachers' knowledge in CER and modelling between the two groups was not statistically significant *($M_E = 3.67$, $M_C = 3.22$, $t = -1.456$, $p = .159$).*

Figure 2

Participant's Self-Efficacy and Knowledge

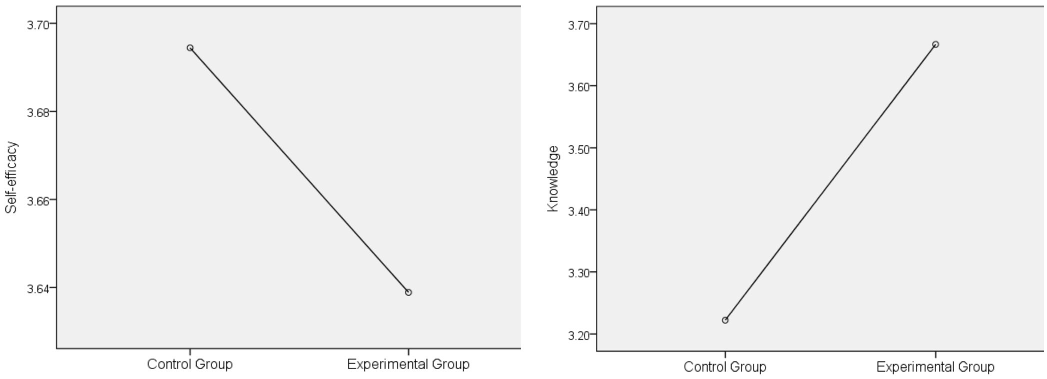


Table 2

Comparisons of Self-Efficacy and Knowledge between the Experimental and Control Group

		M	***SD***	**Levene's Test**		***t-test* for Equality of Means**		
				F	*p*	*t*	*df*	*p*
Self-efficacy	Experimental Group	3.64	.59	.78	.39	.224	22	.825
	Control Group	3.69	.62					
Knowledge	Experimental Group	3.67	.82	.34	.57	-1.456	22	.159
	Control Group	3.22	.67					

4.3 Qualitative Data Analysis Results

Qualitative data were collected through focus groups and interviews to examine teachers' adoption of CER and modelling, their perceived impacts, and the challenges encountered when adopting and integrating STEM learning units and/or CER and modelling. The data analysis revealed several key themes.

After participants completed the workshops, they returned to their schools and expressed willingness to adopt CER and modelling in their instruction. However, based on their responses, the current Thai curriculum was not well aligned with CER and modelling. To integrate these approaches into their classrooms, participants selected instructional content that they believed aligned with CER and modelling. For example, water quality testing was identified as suitable content because it allowed students to propose hypotheses, design experiments, collect data, analyse and interpret results, and draw conclusions. In addition to alignment, participants considered the adequacy and availability of teaching materials when planning tentative student projects. They indicated that many laboratory tools required for integrating CER and modelling were not available in their schools. As a result, students were often unable to freely choose hands-on activities due to these limitations. However, some participants allowed students to design and conduct their own experiments when laboratory tools were provided through university support and when activities were supervised by faculty members from the universities that offered the professional development workshops.

Regarding the impact of participation in the professional development programme and the adoption of CER and modelling, all participants reported that the programme was highly useful. They described various positive impacts on students, including increased collaboration, improved scientific questioning and hypothesising, development of 21st-century skills, and greater student engagement. Participants also expressed positive attitudes toward working with CER and modelling and indicated that they intended to continue using these approaches in the future.

Based on the interviews and focus group discussions, participants identified several challenges related to adopting and integrating STEM learning units and/or CER and modelling. The first challenge was the limited availability of learning resources and experimental equipment required for STEM education. The second challenge was a lack of self-confidence in implementing CER and modelling in real classroom settings. Because CER and modelling are complex instructional approaches, participants were sometimes uncertain whether their instructional practices were appropriate. As a result, they expressed a need for additional examples and support structures, such as professional learning communities, to facilitate discussion and shared learning. The third challenge was the misalignment between the existing curriculum and CER and modelling. Finally, participants identified insufficient instructional time as a major challenge, as integrating CER and modelling requires extended time for hands-on activities and for students to construct and refine explanations using modelling tools, with which many students were unfamiliar.

5. Conclusion and Discussion

This study examined the effectiveness of the SEA-TEP professional development workshop in Thailand using a mixed-methods approach. Quantitative results from independent samples t-tests indicated that, after controlling for background characteristics through propensity score matching, there were no statistically significant differences between the experimental and control groups in teachers' self-efficacy in applying reasoning-focused instructional approaches or in their knowledge of CER and modelling. Although descriptive statistics suggested slightly higher knowledge scores for the experimental group, these differences did not reach statistical significance.

In contrast, qualitative findings revealed that participants perceived the workshop as highly beneficial. Teachers expressed strong willingness to adopt CER and modelling in their classrooms and reported positive impacts on students, including increased collaboration, improved scientific questioning and hypothesising, enhanced 21st-century skills, and higher engagement. However, teachers also reported multiple challenges that constrained effective classroom implementation, including misalignment with the national curriculum, limited availability of laboratory resources, lack of instructional time, and low confidence in implementing complex instructional approaches such as CER and modelling without continued support.

According to the research findings, several issues warrant discussion, as presented below.

5.1 Effectiveness of the SEA-TEP Workshop

The quantitative findings suggest that participation in the SEA-TEP workshop did not result in statistically significant gains in teachers' self-efficacy or knowledge of CER and modelling when compared with the control group. This result may indicate that short-term professional development alone is insufficient to produce measurable changes in these constructs, particularly when teachers face systemic constraints in their teaching contexts. However, the qualitative findings present a more nuanced picture of effectiveness. Teachers consistently described the workshop as useful and motivating, and they reported meaningful changes in their instructional intentions and perceptions of student learning. This divergence between quantitative and qualitative results suggests that the workshop may have been effective in shaping teachers' beliefs, attitudes, and intentions, even if these changes were not immediately reflected in standardised self-report measures. Such findings align with prior research indicating that changes in instructional practice and self-efficacy often require sustained support and extended implementation periods before becoming measurable (Dong et al., 2019).

5.2 Challenges in Integrating CER and Modelling

Several interrelated challenges limited the effective implementation of CER and modelling in Thai classrooms. First, resource constraints were a major barrier. Many schools lacked the laboratory equipment necessary to support hands-on, inquiry-based STEM activities. As a result, teachers were often unable to allow students to design and conduct experiments independently, limiting the depth of CER and modelling practices. Second, teachers reported low confidence in implementing CER and modelling, particularly in authentic classroom settings. Because these approaches require sophisticated pedagogical knowledge, teachers were often uncertain whether their instructional decisions were appropriate. This finding highlights the need for continued pedagogical scaffolding beyond initial workshops. Third, curricular misalignment emerged as a systemic challenge. The current Thai curriculum was perceived as not well aligned with CER and modelling, making it difficult for teachers to integrate these approaches without selectively adapting or omitting prescribed content. Finally, time constraints significantly hindered implementation. CER and modelling require extended instructional time for experimentation, discussion, and refinement of explanations, which conflicted with existing instructional schedules and content coverage expectation.

5.3 Strengthening the Quality of CER and Modelling Integration in Thailand

To strengthen the quality and sustainability of CER and modelling integration in the Thai context, several actions are recommended. First, professional development should move beyond one-time workshops toward long-term, sustained support, including follow-up coaching, classroom observations, and iterative feedback. Establishing professional learning communities (PLCs) would allow teachers to share experiences, troubleshoot challenges, and build confidence collaboratively and thus could support teachers' professional growth (Mao et al., 2024). Second, curriculum alignment should be addressed at the policy level. Explicit integration of CER and modelling into national curriculum standards and assessments would legitimise these approaches and reduce teachers' need to adapt content independently. Third, resource support is essential. Partnerships between schools and universities—shown to be effective in this study—should be expanded to provide access to laboratory equipment, modelling tools, and instructional materials. In addition, administration support should be considered as it can enhance teachers' self-efficacy (Dong et al., 2019). Finally, instructional designs should include scaffolded CER and modelling activities that gradually build teachers' and students' competencies, particularly in contexts where prior exposure to modelling tools is limited, to ensure the success of STEM education (McComas & Burgin, 2020).

6. Limitations and Future Research

Several limitations should be acknowledged. The sample size was relatively small, which may have limited the statistical power to detect significant differences between groups. Additionally, the reliance on self-reported measures may not fully capture changes in actual classroom practice. The study also examined short-term outcomes following the workshop, which may not reflect longer-term effects of professional development on teacher practice and student learning. Future studies should employ larger samples and longitudinal designs to examine how teachers' self-efficacy, knowledge, and instructional practices evolve over time. Classroom observations and analysis of instructional artifacts would provide richer evidence of implementation quality. Further research should also explore how curriculum reform, assessment policies, and school-level support structures interact with professional development to influence the successful integration of CER and modelling in Thailand.

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DEVELOPING CLAIM-EVIDENCE-REASONING SKILLS THROUGH STEM BASED PROBLEM-BASED LEARNING: A STUDY OF WATER QUALITY IN JUNIOR ISLAMIC SCHOOLS

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ABSTRACT

The development of scientific argumentation skills is a critical objective of science education; however, many Indonesian students continue to experience difficulties in constructing evidence-based claims and coherent reasoning. This study investigated junior Islamic school students' Claim–Evidence–Reasoning (CER) skills through the implementation of STEM-based Problem-Based Learning in a water quality investigation context. A quasi-experimental pre-test–post-test design was employed involving 130 eighth-grade students from two Islamic junior secondary schools in Palembang. Experimental groups received explicit CER instruction integrated within STEM-based Problem-Based Learning, while control groups were taught using conventional instructional approaches. Quantitative data were collected using a rubric-based CER assessment and analysed through normalised gain scores, while qualitative data from classroom observations, student work, and interviews examined students' reasoning development. The results showed that students in the experimental groups achieved higher learning gains ($g = 0.618$ and 0.724) compared to those in the control groups ($g = 0.231$ and 0.454). Most students in the experimental classes were able to formulate specific scientific claims, utilise empirical evidence, and establish logical connections between evidence and scientific principles. Qualitative findings indicated that instructional quality, consistency of teacher scaffolding, and the richness of classroom discourse played a key role in supporting CER development. The locally relevant water quality context further enhanced students' engagement and reasoning. These findings demonstrate that STEM-based Problem-Based Learning can effectively strengthen scientific argumentation skills in Islamic school settings when implemented with deliberate pedagogical support and structured feedback, offering implications for wider adoption in Indonesian madrasah science education.

Keywords: Claim-Evidence-Reasoning, Islamic Schools, STEM-Based Problem-Based Learning, STEM Education, Water Quality

1. Introduction

The 21st century has witnessed growing emphasis on developing students' scientific literacy and critical thinking skills, particularly in addressing real-world environmental challenges (National Research Council, 2012). Water quality issues have become increasingly pressing concerns globally, with significant implications for public health and environmental sustainability (Ariza et al., 2021; Li & Wu, 2019; Tella et al., 2025). In Indonesia's urban areas, water quality management remains a critical challenge requiring scientifically literate citizens capable of analysing environmental data and proposing evidence-based solutions (Marselina et al., 2022; Wulandari et al., 2024). Integrating authentic environmental issues into science education provides meaningful contexts for students to develop essential scientific practices, including the ability to construct scientific arguments (Chowdhury, 2016; Hermawan et al., 2024), creating opportunities to simultaneously address environmental concerns while cultivating higher-order thinking skills.

Science, Technology, Engineering, and Mathematics (STEM) education has emerged as a prominent pedagogical approach fostering integrated learning through problem-based contexts that enable students to apply scientific knowledge across disciplinary boundaries (Dare et al., 2021; Taconis & Bekker, 2023). In Indonesia, particularly within Islamic schools (Madrasah Tsanawiyah), there has been growing awareness of modernising science education while upholding cultural and religious values (Kusaeri & Ridho, 2019; Raisah et al., 2023). Despite serving a substantial portion of Indonesia's student population, research on innovative science pedagogies in these settings remains limited (Irwanto et al., 2017; Maison et al., 2021). Water quality, as a tangible and locally relevant issue, provides an ideal context for implementing STEM-based learning that aligns with Islamic principles of environmental stewardship while developing students' scientific competencies.

Despite the recognised importance of scientific argumentation, many Indonesian students show limited abilities in constructing claims, identifying appropriate evidence, and articulating reasoning that connects evidence to claims (Handayani et al., 2018). The Claim-Evidence-Reasoning (CER) framework provides a structured approach to scientific argumentation (Lizotte et al., 2004), yet its implementation in Indonesian Islamic schools remains underexplored. Traditional science instruction continues to emphasise rote memorisation rather than developing argumentation skills essential for scientific literacy (Uthaikanchanakul, 2025; Verawati & Wahyudi, 2024), with students often struggling to distinguish between opinions and evidence-based arguments (Osborne et al., 2016). Understanding how students develop CER skills within culturally specific educational contexts is essential for designing culturally responsive science instruction.

This research is underscored by Indonesia's commitment to improving science education quality and achieving sustainable development goals related to clean water and sanitation (Arora & Mishra, 2019; Lee et al., 2016). Madrasah Tsanawiyah students represent a significant yet understudied population despite educating millions of Indonesian youths (Martin & Faisal, 2019), highlighting the critical need to examine how STEM-based instruction centred on local environmental issues can develop students' scientific argumentation skills in these contexts (Permanasari et al., 2021; Kumar & Choudhary, 2025). Without empirical evidence on how students develop CER skills through contextualised STEM learning, educators lack guidance for effective learning design.

Previous research has demonstrated the effectiveness of the CER framework in developing students' scientific argumentation across various contexts (Clark et al., 2012; McNeil, 2021; Novak et al., 2016), and STEM-integrated approaches can enhance students' engagement and conceptual understanding when addressing real-world problems (English, 2016; Laksono et al., 2024). Explicit teaching of argument structure, combined with opportunities for practice and feedback, significantly improves students' argumentation quality (McDonald, 2017; Osborne et al., 2016). However, most existing studies have been conducted in Western educational contexts with limited attention to Indonesian or Islamic school settings (Handayani et al., 2018), and few have specifically examined how STEM-based water quality instruction develops scientific argumentation skills (Schall, 2015; Sulistiowati et al., 2019). This study extends previous research by investigating CER skill development within a STEM-based water quality unit specifically designed for Madrasah Tsanawiyah students in Palembang.

This study investigates how STEM-Based Problem-Based Learning with explicit CER instruction improves Islamic junior high school students' scientific argumentation skills in the context of Palembang's water quality issues. Conducted in two Madrasah Tsanawiyah schools using multiple data sources CER test results, student work samples, classroom observations, and interviews this research addresses three specific questions. First, how effective is the intervention in improving students' scientific argumentation skills as measured by CER learning outcomes? Second, how do students construct scientific claims, select and use empirical evidence, and develop coherent reasoning connecting data to scientific principles? Third, how do contextual factors such as teacher instructional support, classroom discourse, laboratory infrastructure, and implementation quality shape variations in CER skill development across the two school settings? This research contributes empirical evidence regarding STEM-based argumentation instruction effectiveness in Indonesian Islamic schools, informs curriculum development for environmental science education, and offers practical insights for developing students' scientific argumentation skills through local issues, advancing the broader discourse on culturally responsive science education.

2. Methods

2.1 Research Design

This study adopts an explanatory sequential mixed-methods design (Creswell & Plano Clark, 2023), in which quantitative inquiry precedes qualitative exploration to provide a comprehensive understanding of how junior Islamic school students develop Claim Evidence Reasoning (CER) competencies through STEM-based Problem-Based Learning centred on water quality issues. In this design, the quantitative phase serves as the foundation for identifying patterns and levels of CER performance, while the qualitative phase elaborates these findings by examining the processes and contexts that influence students' reasoning development (Ivankova et al., 2006).

The quantitative component employs a quasi-experimental pre-test–post-test control group design. This design was selected due to the practical need to utilise intact classroom groups without random assignment, a common condition in school-based research. Four eighth grade classes from two Madrasah Tsanawiyah in Palembang participated in the study. Two experimental classes that received STEM-Based Problem-Based Learning instruction explicitly integrating CER, and two control classes that received conventional instruction. All students completed identical CER-focused pretests and post-tests related to water quality assessment. The quantitative analysis involved measuring changes in CER competence using rubric based scoring and normalised gain (N-Gain) calculations to determine the effectiveness of the instructional intervention.

Following the quantitative phase, the research continued with a qualitative multiple case study approach, treating each participating school as a distinct case. This approach allowed for an in-depth exploration of the contextual and instructional dynamics that shape the development of students' scientific argumentation. Qualitative data were drawn from student work samples related to CER argumentation assignments, observational field notes documenting classroom learning processes, student responses during See-Think-Wonder activities, concept mapping artifacts, recordings of group discussions, and reflective writing that revealed students' reasoning pathways. These diverse data sources enabled both intra case analysis and cross case comparisons, following the analytical procedures.

The integration of quantitative and qualitative data occurred at the point where initial statistical results informed the selection of cases and focal participants for further qualitative examination. Contrasting cases could be used to explore how variation in Claim, Evidence, and Reasoning occurred. Through this integrative process, qualitative findings provided interpretive depth to the quantitative results, offering explanations for why certain groups achieved higher levels of CER mastery. Overall, the mixed-methods design enabled this study to meet its primary objectives: assessing students' ability to construct scientific claims, analysing how they identify and use evidence, and examining the sophistication of their reasoning processes. Quantitative measures provided breadth and comparative strength, while qualitative insights shed light on the development of CER in the context of Islamic schools.

2.2 Research Setting and Participants

This study was conducted in two public Islamic junior high schools in Palembang, both of which represent diverse student populations and represent the demographics of junior high school education. In School A, the experimental class consisted of class 8.11, while class 8.10 served as the control group, with the classes randomly selected from available eighth grade classes to ensure representation. In School B, class 8G was designated the experimental group and class 8C as the control group, following the same random selection procedure. The total sample size included 130 students across both schools, with 62 students in School A and 68 in School B. The two schools were selected based on their willingness to participate, similar demographic characteristics, comparable baseline academic performance in science subjects, and administrative support for implementing the research protocol. The eighth-grade level was chosen because students at this stage have sufficient foundational science knowledge to engage meaningfully with water quality concepts while still developing their scientific argumentation skills. (Lizotte et al., 2004; Osborne et al., 2016)

2.3 Sampling Procedure

Purposive sampling techniques were used to select the two schools based on specific criteria. School selection was based on their status as public Islamic schools, accessibility, administrative support for the study, and comparable student demographics and academic achievement (Etikan et al., 2016). In each school, intact classes were randomly assigned to the experimental or control condition using randomisation to minimise selection bias while maintaining existing class structure. Prior to implementation, initial equivalence between the experimental and control groups was assessed through pre-test scores and demographic characteristics. Informed consent was obtained from school administrators, teachers, parents, and students following ethical guidelines for educational research, with assurances of confidentiality and voluntary participation

2.4 Instructional Intervention

The experimental groups in both schools received STEM-based instruction focused on water quality issues, implemented over six sessions consisting of one pre-test, four 40-minute instructional lessons, and one post-test conducted over four weeks. This STEM-based intervention integrated science concepts related to the physical properties of water including indicators such as pH, conductivity, temperature, and turbidity with hands-on water quality testing equipment (Laksono et al., 2025). The engineering practice component involved designing a poster that presented the identified water problem, investigation methods, and proposed solutions to local water quality issues (Dare et al., 2021). The learning sequence followed a modified Problem-Based Learning model incorporating explicit CER instruction, beginning with problem orientation where students explored local water quality issues in Palembang, followed by guided inquiry investigation of water samples from various sources including tap water, gutter water, lake water, mineral water, orange juice, tea, and river water (Shin et al., 2022). Students worked collaboratively in small groups of 4-5 members to collect water samples from their local environment, conduct systematic water quality tests using testing kits, analyse collected data, and construct scientific arguments using the CER framework to substantiate their reasoning about water quality based on empirical testing results (Sampson & Clark, 2008; McNeill, 2021). Throughout the intervention, teachers provided scaffolding through explicit modelling of CER components, guided practice sessions, and individualised feedback on students' argument construction, emphasising how claims about water quality must be supported by evidence from testing and connected through scientific reasoning (Osborne et al., 2016). The control group received conventional instruction on the same water quality topic using traditional teacher-centred demonstration methods, textbook-based activities, and routine exercises without explicit CER instruction or a STEM-integrated approach.

2.5 Goals Data Collection Instruments

Several instruments were used to collect comprehensive data on the development of CER skills and student learning outcomes. The primary quantitative instrument was a CER assessment test developed specifically for this study, consisting of five structured response items addressing water quality concepts and requiring students to formulate claims, identify evidence, and articulate reasoning (reliability coefficient $\alpha = 0.82$). The test was validated by three expert reviewers, including science education faculty and experienced science teachers, and pilot tested with age matched students not involved in the primary study to ensure clarity and appropriate difficulty. A CER rubric adapted from McNeill and Krajcik (2008) was used to evaluate the quality of students' written arguments in the structured response items, rating claims (precise and accurate statements), evidence (sufficient and relevant data), and reasoning (logical relationships between evidence and claims) on a scale of 0–2 for each component.

Additional qualitative data were collected through structured classroom observations using an observation protocol focused on students' argumentation practices, semi structured interviews with selected students ($n = 12$, purposively selected to represent a range of achievement levels) to explore their understanding of CER components, and samples of student work including argument writing.

Table 1

Rubrics CER

Component	Score 0	Score 1	Score 2
Claim	No claim or inaccurate statement	Claim present but vague or partially accurate	Precise, accurate, and complete claim that directly answers the question
Evidence	No evidence or irrelevant data	Some relevant evidence but insufficient or incomplete	Sufficient, relevant, and appropriate scientific data that fully supports the claim
Reasoning	No reasoning or illogical connection	Reasoning attempts to connect evidence to claim but lacks clear scientific principles or contains logical gaps	Clear, logical reasoning that explicitly connects evidence to claim using appropriate scientific principles

2.6 Data Analysis

Quantitative data from the pre-test and post-test assessments were analysed using inferential statistics, including independent sample t-tests to compare differences between the experimental and control groups, as well as paired sample t-tests to examine within group improvement from pre-test to post-test. Normalised gain (N-Gain) scores were calculated using the Hake formula. (Hake, 1999). Statistical analysis was performed using Python with a significance level set at $\alpha = 0.05$ for all hypothesis tests. Qualitative data from classroom observations, interviews, and student work samples were analysed using thematic analysis based on the six-phase framework proposed by Braun and Clarke (2006). The analysis involved familiarisation with the data, initial coding, searching for themes, theme review, theme definition, and report creation. Student responses on constructed response CER items were independently scored by two trained raters using a CER rubric. Qualitative findings and quantitative results were combined to provide a comprehensive understanding of students' CER skill development and to enhance the validity and credibility of the study's conclusions (Creswell & Plano Clark, 2023).

2.7 Research Ethics

To maintain research ethics and protect institutional identities, the participating schools are referred to as School A and School B throughout this report. Data was securely stored in digital files and physical documents accessible only to the research and STEM professional development team. This research poses minimal risk to participants because it involves routine educational activities, and potential benefits include improved science learning and opportunities for teachers to develop their pedagogical practices.

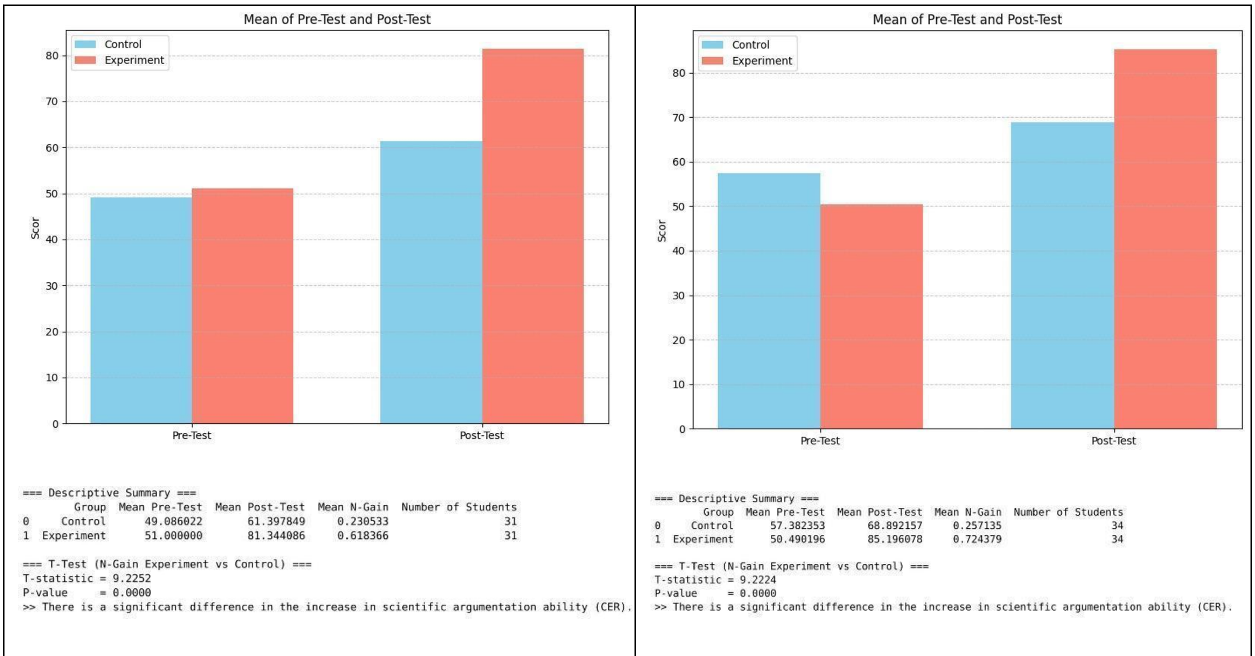
3. Results and Discussion

3.1 Learning Outcomes from CER Test Scores

The implementation of STEM-based Problem Based Learning with explicit CER framework instruction demonstrated significant improvements in students' scientific argumentation skills. Analysis of pre-test and post-test scores revealed substantial improvements in students' ability to construct complete Claim-Evidence-Reasoning arguments on water quality issues. This is shown in Figure 1.

Figure 1

Learning Outcome CER



Result School A | Result School B

At School A, the experimental class improved from a pretest average of 51.00 to a post-test average of 81.34, achieving an N-Gain of 0.618 (moderate to high category). The control class showed limited improvement from 49.09 to 61.40, with an N-Gain of only 0.231 (low category). At School B, the experimental class showed remarkable improvement with pretest scores averaging 50.49 increasing to post-test scores of 85.20, yielding an N-Gain of 0.724, categorised as high effectiveness according to Hake's (1999) classification. The control class demonstrated moderate improvement from 60.59 to 83.53 with an N-Gain of 0.454 (moderate category).

Table 2

Learning Outcome CER Pre and Post Test

Parameter	School A	School B
Experimental Class		
Pre-test (mean)	51.00	50.49
Post-test (mean)	81.34	85.20
N-Gain	0.618 (Moderate-High)	0.724 (High)
Control Class		
Pre-test (mean)	49.09	60.59
Post-test (mean)	61.40	83.53
N-Gain	0.231 (Low)	0.454 (Moderate)

Independent t-test analysis confirmed statistically significant differences between experimental and control groups at both schools (School A: t = 9.2252, p = 0.000; School B: t = 9.2252, p = 0.000). Both schools demonstrated p-values below the 0.05 significance threshold, confirming that STEM-Based Problem-Based Learning with CER framework integration significantly enhances students' scientific argumentation abilities compared to conventional instruction. Effect size calculations revealed Cohen's d values of 1.4 for School A and 1.8 for school B, both indicating large practical significance (Cohen, 1988). These effect sizes demonstrate that the intervention produced substantial, educationally meaningful improvements in CER skills beyond mere statistical significance.

The significant learning gains observed in this study N-Gain = 0.618-0.724 for experimental groups demonstrate that STEM-based Problem-Based Learning effectively develops scientific argumentation skills when combined with explicit CER instruction. These findings align with broader research on argumentation frameworks (McNeill & Krajcik, 2008; Osborne et al., 2016) while extending understanding of their application in Southeast Asian Islamic educational contexts. The differential performance between schools, despite identical interventional design, underscores the critical role of implementation quality rather than curricular materials alone.
Analysis of individual CER components reveals distinct development patterns across both schools. Table 3 presents the percentage of students who achieved mastery level (score 2 on the 0-2 rubric) for each component in their post-test responses. *The "Integration of all three components"* row indicates the percentage of students who successfully demonstrated mastery across all three CER elements simultaneously within a single scientific argument, representing the highest level of argumentation competence as shown in Table 3.

Table 3

Percentage of Students Achieving Mastery Level (Score 2) in Each CER Component

CER Component	School A (%)	School B (%)	Difference
Clear and specific claims	89	76	13
Evidence based on empirical data	93	81	12
Reasoning connecting theory to data	85	72	13
Integration of all three components	82	69	13

Note: Integration refers to students who achieved a score 2 (mastery level) on all three components (Claim, Evidence, and Reasoning) within the same response, demonstrating complete and coherent scientific argumentation.

These findings indicate that while students at both schools improved across all CER dimensions, School A students demonstrated superior performance in each component. The smallest gap appeared in evidence collection (12% difference), suggesting that data gathering skills develop relatively consistently across contexts. The largest disparities emerged in reasoning quality (13% difference) and complete CER integration (13% difference), suggesting these higher-order skills are more sensitive to implementation quality and contextual factors. The quantitative findings align with research demonstrating that explicit instruction in scientific argumentation frameworks significantly enhances students' reasoning abilities (Laksono et al., 2024; Mcneil, 2021; McNeill & Krajcik, 2008).

The structured nature of the CER framework appears particularly beneficial for students in Indonesian Islamic schools, where traditional pedagogy has emphasised knowledge transmission over argumentation (Kusaeri & Ridho, 2019). By providing explicit scaffolding for claim construction, evidence selection, and reasoning development, the framework addresses documented difficulties Indonesian students face in distinguishing between opinions and evidence-based arguments (Handayani et al., 2018). This finding resonates with research from other Southeast Asian contexts, where explicit instructional frameworks have proven essential for developing higher-order thinking skills in science education.

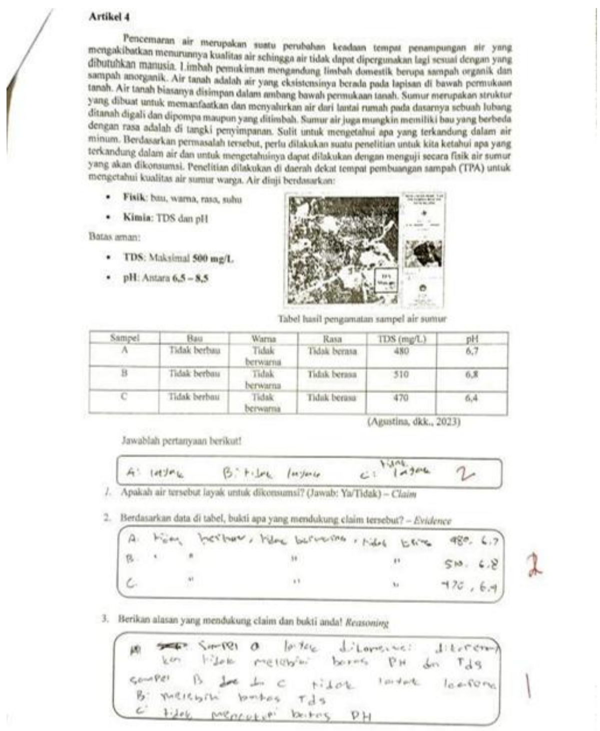
3.2 Scientific Explanation Process of CER

Student work samples revealed clear patterns in how students gradually learned to formulate scientific claims about water quality throughout the intervention. At School A, students showed a steady movement from descriptive observations toward more analytically grounded claims. Early in the intervention, students' statements were mostly observational, such *as "The water looks dirty."* As instruction proceeded with explicit scaffolding using the Claim-Evidence-Reasoning (CER) framework, their claims became increasingly focused and aligned with scientific questions. By the end of the intervention, many students produced claims that were concise, purposeful, and anchored in measurable criteria. One representative example was: *"River water is not suitable for drinking."* This statement illustrates a clear evaluative stance, specificity regarding the intended use, and scientific relevance, showing that students had begun to frame their claims in ways that address testable water quality problems. Classroom observations indicated that the implementation of the See-Think-Wonder strategy contributed substantially to this development. By encouraging students to observe water samples, interpret what those observations might imply, and formulate wonderings that evolved into investigable questions, the strategy functioned as an effective bridge toward more sophisticated claim construction a pattern consistent with the role of scaffolding emphasised work on scientific explanation (McNeill & Krajcik, 2008; Novak et al., 2016)

A similar progression was observed at School B, though the level of specificity in claim formulation was somewhat less developed. Students produced clear and testable claims, such as *"Bottled water is safe for consumption,"* yet these claims tended to remain at a relatively straightforward interpretive level. Field notes showed that students engaged enthusiastically with water quality investigations, but they occasionally struggled to move beyond surface level observations toward more nuanced scientific judgments. Compared with School A, the opportunities for extended modelling and feedback appeared less systematic, which aligns with findings in the literature that sustained teacher modelling is essential for helping students advance from descriptive statements to explanatory scientific claims (McNeill & Krajcik, 2011). The result is shown in figure 3.

Figure 3

Example CER Student



Artikel 4

Pencemaran air merupakan suatu perubahan keadaan tempat penampungan air yang mengakibatkan menurunnya kualitas air sehingga air tidak dapat dipergunakan lagi sesuai dengan yang dibutuhkan manusia. Limbah pemukiman mengandung limbah domestik berupa sampah organik dan sampah anorganik. Air tanah adalah air yang eksistensinya berada pada lapisan di bawah permukaan tanah. Air tanah biasanya disimpan dalam ambang bawah permukaan tanah. Sumur merupakan struktur yang dibuat untuk memanfaatkan dan menyalurkan air dari lantai rumah pada dasarnya sebuah lubang ditanah digali dan dipompa maupun yang ditimbah. Sumur air juga mungkin memiliki bau yang berbeda dengan rasa adalah di tangki penyimpanan. Sulit untuk mengetahui apa yang terkandung dalam air minum. Berdasarkan permasalah tersebut, perlu dilakukan suatu penelitian untuk kita ketahui apa yang terkandung dalam air dan untuk mengetahuinya dapat dilakukan dengan menguji secara fisik air sumur yang akan dikonsumsi. Penelitian dilakukan di daerah dekat tempat pembuangan sampah (TPA) untuk mengetahui kualitas air sumur warga. Air diuji berdasarkan:

- **Fisik**: bau, warna, rasa, suhu
- **Kimia**: TDS dan pH

Batas aman:

- **TDS**: Maksimal **500 mg/L**
- **pH**: Antara **6,5 – 8,5**

Tabel hasil pengamatan sampel air sumur

Sampel	Bau	Warna	Rasa	TDS (mg/L)	pH
A	Tidak berbau	Tidak berwarna	Tidak berasa	480	6,7
B	Tidak berbau	Tidak berwarna	Tidak berasa	510	6,8
C	Tidak berbau	Tidak berwarna	Tidak berasa	470	6,4

(Agustina, dkk., 2023)

Jawablah pertanyaan berikut!

A: layak B: tidak layak C: tidak layak 2

1. Apakah air tersebut layak untuk dikonsumsi? (Jawab: Ya/Tidak) – *Claim*

2. Berdasarkan data di tabel, bukti apa yang mendukung claim tersebut? – *Evidence*

A: tidak berbau, tidak berwarna, tidak berasa 480, 6.7
B: " " " " 510, 6.8
C: " " " " 470, 6.4
2

3. Berikan alasan yang mendukung claim dan bukti anda! *Reasoning*

Sampel a layak dikonsumsi dikarenakan tidak melebihi batas PH dan Tds
sampel B dan C tidak layak karena
B: melebihi batas Tds
C: tidak mencukupi batas PH
1

Students' approaches to collecting and selecting evidence also developed notably across both contexts. At School A, students showed a deliberate and increasingly strategic pattern of evidence use. Their evidence statements frequently combined quantitative data such as "*pH = 8.5*" with relevant qualitative indicators including turbidity, odour, and the presence of visible particles. The use of appropriate scientific terminology (e.g., "*turbid*") signalled growing fluency in communicating scientific observations. Classroom discussions further revealed that students actively negotiated which types of measurements would best support particular claims, demonstrating metacognitive awareness regarding the purpose of evidence. Such practices reflect the kind of epistemic thinking emphasised in the literature on scientific inquiry and argumentation, including perspectives from Osborne (2016).

At School B, students also collected accurate and organised evidence, producing statements that combined numerical measurements with descriptive observations. However, students occasionally included information that did not originate from their own investigation for example, noting that a water sample was "*commercially processed*." This suggested that while data collection procedures were well executed, students were sometimes less clear in distinguishing empirical evidence from assumptions or background knowledge. Collaborative group work nonetheless played a key role in helping students evaluate the relevance of their evidence, as peer discussions frequently prompted questions about accuracy, validity, and appropriateness of measurement.

The reasoning component where students articulate how their evidence supports their claims using scientific principles proved to be the most intellectually demanding aspect of the CER framework. School A demonstrated particularly strong growth in this domain. Students gradually developed multi-layered explanations that integrated empirical data, theoretical principles, and practical implications. A representative reasoning statement was: *"Drinking water should have neutral pH (6.5-8.5) according to WHO standards, be clear, odourless, and free from contaminants to prevent waterborne diseases."* This type of explanation shows an ability to connect data to accepted scientific standards, articulate causal relationships, and integrate multiple water quality indicators into a coherent explanatory structure. Observations during concept mapping activities revealed that students were increasingly able to relate chemical, physical, and biological aspects of water quality, an indicator of the interdisciplinary reasoning emphasised in STEM education literature (Lizotte et al., 2004; Novak & Treagust, 2018). Moreover, when students were confronted with new scenarios during post-tests, many transferred their reasoning patterns to unfamiliar contexts, suggesting deeper conceptual understanding rather than simple pattern recognition.

Students at School B demonstrated solid foundational reasoning skills, though their explanations tended to be more linear and less elaborated. A common form of reasoning connected evidence to established standards for example, noting that WHO guidelines require neutral pH and absence of physical contaminants but often without fully articulating the underlying scientific mechanisms. Classroom discussions showed that students were enthusiastic and willing to explain their thinking, but their reasoning sometimes jumped directly from observation to conclusion without exploring causal pathways or alternative explanations. This pattern aligns with research suggesting that developing sophisticated scientific reasoning requires extended opportunities for explicit instruction, feedback, and sustained practice (Mcneil, 2021; McNeill & Krajcik, 2011; Osborne et al., 2016).

Across both School A and School B, a comparative analysis showed that the development of CER skills was shaped by the consistency of instruction, the level of modelling provided, and the richness of classroom discourse. Schools that engaged students more frequently in structured discussions, explicit scaffolding, and integrative reasoning tasks tended to show stronger growth in claim construction, evidence selection, and explanatory reasoning. These findings strengthen the argument that scientific explanation as conceptualised is not simply a product of laboratory activities, but is fundamentally a practice that requires deliberate instructional design, iterative feedback, and opportunities for students to build and refine their thinking over time (Lizotte et al., 2004; McNeill & Krajcik, 2008).

3.3 STEM-Based Problem-Based Learning Implementation and Theoretical Interpretation

Classroom observations showed that the quality of STEM-Based Problem-Based Learning significantly influenced the development of students' Claims, Evidence, Reasoning (CER) competencies at both research sites. In School A, the integration of Science, Technology, Engineering, and Mathematics occurred with greater enthusiasm and motivation. Students used practical measurement tools such as water tests, analysed data through tables and graphical representations, and applied reasoning when designing water quality testing procedures. This integrated approach created problem-solving that facilitated deeper, evidence-based argumentation (Nussbaum, 2021). In contrast, although activities at School B incorporated STEM elements, they remained conservative because the practical work could only be conducted in the classroom, enhanced by water test technology. This limited the scientific character that is central to STEM education. This observation aligns with McDonald (2016) findings that meaningful STEM integration requires explicit pedagogical design, not simply discipline specific activities.

Teacher instructional support at School A demonstrated a more systematic scaffolding pattern. The See-Think-Wonder strategy was implemented progressively, moving from observation to interpretation and questioning, with explicit modelling of scientific reasoning and structured feedback targeting each component of the CER framework. In School B, while teacher enthusiasm was evident, support was less consistent in guiding students to establish logical connections between claims, evidence, and reasoning. This difference reinforces McNeill and Krajcik, (2011) assertion that developing scientific explanations requires ongoing support, rather than brief conceptual introductions. Their research emphasised that students need repeated opportunities to engage in scaffolding practices that gradually build metacognitive awareness of the foundations of sciene (McNeill & Krajcik, 2008).

The availability of laboratory infrastructure also shaped student achievement. The more comprehensive laboratory facilities at School A tended to better facilitate the collection of diverse and precise evidence, thus enhancing the quality of the reasoning students could construct. Conversely, although School B faced time constraints due to an Islamic competition during the lesson, collaborative work helped maintain learning engagement and maintain the quality of the scientific reasoning process. These findings reflect observations in the literature that while material resources are important, social collaboration factors can compensate for infrastructure constraints

The characteristics of student engagement showed different patterns across locations. Students in School A demonstrated stronger cognitive engagement, evidenced by questions about the mechanisms and relationships among water quality parameters. They engaged in what they call "*cognitive engagement,*" characterised by effort, strategy use, and deep concentration on conceptual problems. Students in School B demonstrated more pronounced social engagement, displaying strong collaboration and enthusiasm for hands-on activities. Both types of engagement supported the development of CER, albeit with different contributions. Cognitive patterns strengthened scientific reasoning, while social engagement supported procedural implementation and systematic observation (Engelmann et al., 2016).

From a theoretical perspective, variations in CER outcomes can be explained through the perspective that higher-order thinking develops through structured interactions with cultural tools such as CER frameworks, scientific discourse practices, and measurement instruments. As students internalise these tools through guided participation, their capacity for independent scientific explanations increases. The effectiveness of the CER framework aligns with McNeill and Krajcik (2011) conceptualisation of "*scientific explanation*" in which an explicit claim-evidence-reasoning structure helps students internalise the epistemic practices of science. These practices demonstrate how scientists establish and justify knowledge claims. This framework functions, as described, as a supporting tool that mediates students' understanding of scientific argumentation. Furthermore, the context of the actual water quality problem reflects a constructivist perspective that emphasises that scientific understanding is actively constructed when students encounter situations that demand argumentation based on data, not just knowledge. As students engage with real-world problems involving authentic data collection and analysis, they develop what Fortus et al., (2005) identified as "*deep conceptual understanding*" grounded in authentic scientific practices. The integration of STEM elements within this problem-based context creates what National Research Council (2000) describe as a "*learning environment*" that utilises multiple numerical, graphical, and verbal representation systems to support the construction of robust scientific concepts.

The divergent results in School A and School B underscore the importance of deliberate pedagogical design in STEM-Based Problem-Based Learning contexts. While infrastructure and resources provide the necessary conditions, the quality of instructional scaffolding, the consistency of teacher modelling, and the richness of classroom discourse emerge as important mediating factors in the development of CER. These findings extend the research of Krajcik, McNeill, and colleagues on scientific explanation by demonstrating that the interaction between the quality of STEM integration, instructional support systems, and sociocultural context collectively shape how students develop and refine evidence-based reasoning practices over time.

4. Conclusion

This study explored the development of Claim-Evidence-Reasoning skills among junior Islamic school students in Palembang through STEM-Based Problem-Based Learning focused on water quality investigations. The findings demonstrate that the intervention effectively improved students' scientific argumentation abilities across all three CER components, with experimental classes achieving significant improvements and substantially outperforming control classes at both schools. Students successfully progressed from simple descriptive observations to sophisticated scientific assertions grounded in measurable water quality parameters, demonstrating their ability to construct precise claims, utilise empirical data from multiple water quality indicators, and connect evidence to scientific principles through coherent reasoning.

Students constructed scientific claims by formulating clear, testable statements about water quality based on their investigations of various water sources including tap water, gutter water, lake water, river water, and other samples. They selected and used empirical evidence by systematically collecting data across multiple parameters such as pH, turbidity, temperature, and conductivity, ensuring their evidence was sufficient, relevant, and directly supported their claims. In developing reasoning, students demonstrated the ability to explain logical connections between their evidence and claims by applying scientific principles related to water quality standards and the physical properties of water, moving beyond simple data reporting to meaningful scientific interpretation.

Contextual factors significantly shaped variations in CER skill development across the two school settings. Teacher instructional support, particularly through consistent modelling of CER components and provision of targeted feedback, emerged as the most critical factor influencing student success. Classroom discourse quality, characterised by opportunities for students to articulate and defend their arguments, facilitated deeper understanding of the argumentation process. While laboratory infrastructure and available testing equipment provided necessary resources for hands-on investigation, the quality of instructional implementation ultimately determined the depth of student learning. The differential performance between schools indicates that pedagogical expertise and systematic scaffolding strategies outweigh material resources in developing scientific argumentation skills.

This study was limited to two Islamic junior high schools in Palembang over a four-week instructional period, which may constrain generalisability to other regional contexts and assessment of long-term skill retention. Future research should investigate the sustainability of CER skill development through longitudinal studies tracking students' argumentation abilities over extended periods and across different grade levels. Examining how CER skills transfer to other scientific contexts beyond water quality, such as biodiversity, climate change, or energy issues, would provide valuable insights into the broader applicability of this pedagogical approach. Additionally, comparative studies exploring CER development across diverse cultural and educational contexts, including both Islamic and secular schools in various Indonesian regions, would strengthen understanding of how cultural values and institutional contexts influence scientific argumentation instruction and inform the development of culturally responsive science education practices nationwide.

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