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How place-based professional learning communities shape teachers' self-efficacy for interdisciplinary STEM instruction

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Abstract

STEM education plays a critical role in addressing contemporary ecological, technological, and social challenges; however, STEM teaching in many classrooms remains disconnected from students' real-world experiences and local community contexts. The place-based STEM teacher professional program (PbSTEM-TPP) was developed to support teachers in integrating ecological and community perspectives into STEM instruction through sustained professional learning communities. This mixed-methods study involved 25 in-service science teachers from 10 public schools and 514 students in grades 4-6 over a 32-week implementation period. Data collection included pre- and post-surveys using the teachers' self-efficacy toward STEM practices scale (T-SESTEM) and the TPACK-Place instrument, along with classroom observations, reflection logs, coaching records, interviews, and student artifacts. Quantitative data were analyzed using descriptive statistics, paired-samples t-tests, and effect sizes, while qualitative data were analyzed thematically. The findings revealed statistically significant improvements in teachers' self-efficacy across all five T-SESTEM subscales, including interdisciplinary STEM lesson design, inquiry and engineering design facilitation, technology and data use, place-based ecological integration, and community engagement and collaboration (dz = 1.66-5.00). Significant gains were also found across all dimensions of TPACK-Place competencies, indicating enhanced teacher capacity to integrate technological, pedagogical, and content knowledge within contextualized STEM learning environments. Qualitative findings further demonstrated shifts toward more inquiry-based, interdisciplinary, and community-connected teaching practices. In addition, students showed increased ecological awareness, responsibility, collaboration, and civic participation through engagement with authentic local issues and place-based STEM activities. In conclusion, the PbSTEM-TPP provides an effective and context-responsive model for strengthening teacher self-efficacy, enhancing TPACK-Place competencies, and supporting interdisciplinary STEM learning grounded in ecological and community contexts.

Keywords: in-service teacher education, place-based learning, professional learning community, teacher professional development, self-efficacy in STEM education

INTRODUCTION

Natural phenomena and human activities are increasingly interacting, creating urgent ecological and social challenges. Coastal erosion, mangrove degradation, plastic waste, and discarded fishing gear threaten both ecosystems and local livelihoods, showing how human actions often amplify natural vulnerabilities. Solving these issues requires citizens who are scientifically literate, ecologically aware, and able to apply STEM knowledge to develop sustainable solutions. Globally, STEM (science, technology, engineering, and mathematics) education has gained attention to prepare learners for the demands of a rapidly changing, technology-driven society. However, traditional classrooms often stay disconnected from students' real-life contexts, limiting chances for inquiry, ecological literacy, and civic responsibility (Rickinson et

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Contribution to the literature

- This study offers empirical evidence on how professional learning communities (PLCs) can improve science teachers' inquiry-based teaching and reflection practice.
- It adapts and validates a self-efficacy instrument (teachers' self-efficacy toward STEM practices scale [T-SESTEM]) for elementary science teachers.
- It shows how collaborative, context-aware professional development (PD) can connect national STEM policy efforts with everyday science classroom practices.

al., 2004). To address this, scholars advocate for place-based STEM approaches that integrate disciplinary knowledge with real-world problem-solving, grounded in ecological and cultural contexts (Gruenewald, 2003; Sobel, 2004). These approaches enhance academic performance while fostering social responsibility and sustainability awareness (Bascopé et al., 2021; Smith, 2002; Vander Ark et al., 2020). For instance, Mercier et al. (2025) found that rural students involved in place-based STEM projects developed stronger identities as advocates and problem solvers.

Research also emphasizes the importance of PD in helping teachers implement such approaches. Ongoing, collaborative PD has been shown to increase teacher self-efficacy and confidence in delivering integrated STEM (Kelley et al., 2020; Zhou et al., 2023), while Li et al. (2020) emphasize the need to balance global frameworks with local adaptations. Incorporating STEM into natural and community contexts encourages inquiry, application of the engineering design process (EDP), and 21st century skills (Dugger, 2010; Moore et al., 2014). Early engagement with local environments builds a sense of belonging, identity, and stewardship (Cutter-Mackenzie & Smith, 2003). These outcomes align with calls for sustainability education that promotes critical thinking, ecological literacy, and civic action (Stevenson et al., 2013; Tilbury, 2011). Still, little is known about how PD can systematically prepare teachers to integrate ecological and community perspectives in practice, especially in settings where cultural heritage and environmental diversity intersect (Borko et al., 2009; Li, 2023; Loucks-Horsley et al., 2010).

This study addresses this gap by examining the place-based STEM teacher professional program (PbSTEM-TPP), a year-long project in Phuket, Thailand. The program supports teachers integrating ecological and community perspectives into their STEM teaching through long-term collaboration with schools, communities, and universities. Specifically, this study investigates the following research questions (RQs):

RQ1: How does PbSTEM-TPP enhance teachers' readiness and confidence in STEM instruction?

RQ2: How do teachers incorporate ecological and community perspectives into their teaching practices?

RQ3: What changes happen for students regarding ecological awareness, responsibility, and community involvement?

By exploring these questions, this study adds to broader discussions on sustainable education by proposing a context-aware, pedagogically strong, and globally relevant model of place-based STEM education.

THEORETICAL FRAMEWORK

STEM Education as a Global Imperative

STEM education has become a global priority as nations seek to prepare learners for the complex social, technological, and ecological challenges of the 21st century. Rather than representing four separate disciplines, STEM is increasingly conceptualized as an integrated educational approach that connects knowledge across science, technology, engineering, and mathematics, emphasizes inquiry and problem-solving, and situates learning within authentic real-world contexts (Moore et al., 2014; Resnick, 1987). This perspective highlights interdisciplinarity, experiential learning, and social relevance, fostering both cognitive and affective development (Ballantyne & Packer, 2009; Dewey, 1938).

Research has shown that integrated STEM education promotes higher-order thinking, creativity, adaptability, and scientific literacy while strengthening connections between academic learning and community or environmental issues (Bevan et al., 2020; Brown et al., 2016; Margot & Kettler, 2019). Recent reviews further indicate that STEM learning extends beyond traditional classroom settings. Afterschool STEM programs and technology-enhanced collaborative learning environments provide valuable opportunities for learners to engage in authentic inquiry, develop epistemic understanding, and strengthen interdisciplinary STEM competencies (Kasimatis et al., 2019; Sogut & Taşar, 2024). Place-based STEM initiatives similarly help students develop stronger identities as problem solvers and community advocates (Mercier et al., 2025), while nature-based and interdisciplinary approaches contribute to increased environmental awareness among both teachers and students (Buldur et al., 2018). Early engagement in meaningful STEM experiences also influences motivation, career aspirations, and participation among underrepresented groups (Wang et al., 2021). Consequently, STEM education not only prepares students for future workforce demands but also promotes ecological literacy, civic responsibility, and social justice (Ramulumo & Shabalala, 2024).

At a systemic level, Li et al. (2020) observed that research on STEM education continues to expand globally despite ongoing debates about its conceptual boundaries and implementation. Li (2023) further emphasized the importance of connecting global STEM frameworks with local contexts to ensure that STEM education remains both internationally relevant and locally meaningful. Scholars have argued that STEM education must increasingly address complex issues such as climate change, sustainability, and technological inequity (Li & Schoenfeld, 2019; Swyngedouw, 2010). UNESCO (2017) and Thailand's Office of the Education Council (2020) similarly highlight the importance of STEM education in achieving the sustainable development goals and cultivating 21st century competencies consistent with the Partnership for 21st Century Learning (2009) framework. Overall, effective STEM education requires a balance between disciplinary rigor, technological innovation, and cultural and ecological relevance, enabling learners to contribute meaningfully to sustainable futures (Greenwood, 2013; Gruenewald & Smith, 2008; Wals et al., 2014).

Teacher Professional Development and Self-Efficacy

The success of STEM depends on teachers' ability to implement integrated, inquiry-based practices. PD is therefore a key focus, especially regarding teacher self-efficacy—the belief in one's capacity to teach STEM effectively—which influences instructional quality, openness to innovation, and resilience (Hammack et al., 2024; Khut, 2024). Validated tools, such as the T-STEM science self-efficacy scale, provide ways to measure growth and to connect PD to practice (Unfried et al., 2022).

Evidence consistently shows that PD strengthens self-efficacy. Kelley et al. (2020) found that community-of-practice PD boosted teachers' confidence, while Zhou et al. (2023), in a meta-analysis of 21 studies involving 1,412 teachers, reported large effects, especially in longer, more active programs. Sustained PD is more effective than short-term workshops (Darling-Hammond et al., 2017). PD also helps teachers adopt innovative techniques, but barriers such as curriculum demands and limited resources persist (Margot & Kettler, 2019). Aligning PD with standards and local contexts ensures lasting impact (Guzey et al., 2019), and long-term, collaborative formats are more effective than single workshops (Murad et al., 2022; Shernoff et al., 2017).

Teacher beliefs and professional identity also influence PD effectiveness. Context-specific models improve sustainability (Guzey et al., 2019), while innovative formats, such as video-based PD (Tekkumru-Kisa et al., 2017), online learning communities (Johnson et al., 2020), and digital PLCs (Liu et al., 2024), expand accessibility. Teachers with stronger professional identities are more likely to adopt reform practices (Zhai et al., 2024), and collaborative environments strengthen both identity and efficacy (Polizzi et al., 2021). Culture also plays a role, as socio-scientific discussions influence both teachers' and students' identities (Ideland & Malmberg, 2015). PD should therefore build knowledge, confidence, and agency alongside pedagogy (Greenwood, 2009).

Despite progress, gaps remain. Most studies are discipline-specific, short-term, or disconnected from ecological and community contexts, and few connect teacher outcomes with student outcomes, such as environmental literacy or civic engagement (Brand, 2020; Lin et al., 2025). PbSTEM-TPP addresses these gaps through lesson study, coaching, and school-community partnerships. Its design draws on Wenger's (1998) communities of practice, Kolb's (1984) experiential learning cycle, and education for sustainable development principles (Tilbury, 2011; Wals, 2015), positioning it as both a PD model and a contributor to global discussions on sustainability-focused solutions STEM.

METHODOLOGY

Research Design

This study aimed to develop a PD model for science teachers using a school-based approach to promote place-based STEM education in southern Thailand. It also sought to create an integrated learning model tailored to local contexts, encouraging educational innovation in the Phuket Education Sandbox area. A mixed-methods approach with a multistage evaluation design was used, combining a convergent and an explanatory sequential design (Creswell, 2015; Creswell & Plano Clark, 2018). The design emphasized iterative program development and evaluation for continuous improvement.

Sample and Data Collection

The study involved 25 in-service science teachers from 10 public schools in Phuket, Thailand. All taught science at the upper primary level (grades 4-6), ensuring consistency across classrooms. The participating schools, located in both coastal and rural areas, provided authentic ecological and community contexts, such as mangroves, beaches, and fishing villages, thereby grounding science learning in real-world issues affecting local livelihoods and ecosystems. In total, the teachers worked with 514 students, who contributed projects, activities, and learning artifacts.

District officials selected teachers based on two criteria:

(a) active participation in the Phuket Education Sandbox initiative

(b) willingness to join the PbSTEM-TPP.

Of the 25 participants (T1-T25), 16 were female and 9 male, aged 25-42. Most (17) held bachelor's degrees in general science, with two specializing in biology (T7, T13) and one in chemistry (T10). Five teachers (T5, T11, T15, T19, T25) held master's degrees in science education, indicating advanced pedagogical training. Teaching experience ranged from early-career teachers, such as T16 (1 year) and T1 (2 years), to highly experienced veterans, including T9, T14, and T18 (each with 18 years of experience). This blend of novice and veteran teachers enabled the program to benefit from new perspectives and established classroom expertise. An additional aspect of the program was the inclusion of pre-service teachers as co-teachers, which fostered intergenerational learning.

Place-based STEM Teacher Professional Program

The PbSTEM-TPP was created as a comprehensive PD initiative to enhance teachers' ability to integrate ecological and community aspects into STEM education. Based on the principles of experiential and context-responsive teaching, the program focused not only on developing interdisciplinary teaching skills but also on fostering ecological literacy, building community partnerships, and encouraging reflective practice. By leveraging Phuket's unique environmental and cultural context, the program aimed to shift classroom practices from textbook-based instruction to authentic, inquiry-led, and community-connected learning. The program lasted one academic year and was structured into four sequential phases, as shown in **Table 1**. Each phase included specific PD activities, planned outcomes, and clear evidence of teacher learning and program impact.

The PbSTEM-TPP was carried out over 32 weeks in four phases, each aimed at enhancing teachers' skills while strengthening bonds among schools, communities, and the local environment. Before full implementation, the program was pilot tested with a group of teachers from schools with similar contextual backgrounds to assess its feasibility, clarity, and effectiveness. The pilot test with a comparable group resulted in an effectiveness score of 84.50%, surpassing the acceptable threshold of 80%.

1. **Phase 1: Onboarding (week 1-week 2).** Schools formed formal partnerships with community stakeholders and local agencies. PLCs were established, and community co-mentors (e.g., municipal staff and local business leaders) were appointed to connect classroom practice with local knowledge. Baseline surveys assessed teachers' ecological literacy, providing initial benchmarks.
2. **Phase 2: Needs assessment (week 3-week 8).** Teachers participated in surveys, interviews, and ecological audits and community walkabouts to identify assets, challenges, and opportunities. Each school then created a design brief that outlined key questions, learning objectives, and ecological goals.
3. **Phase 3: Capacity-building bootcamp (week 9-week 14).** Six intensive workshops and micro-teaching sessions introduced strategies for integrating the EDP, modeling local phenomena, collecting field data, and co-creating problems with stakeholders—additional modules covered claim-evidence-reasoning (CER) and assessment for place-based tasks. By the end of this phase, teachers developed prototype lesson plans and created task banks.
4. **Phase 4: Lesson study, coaching, and reflection (week 15-week 32).** Teachers collaboratively designed and implemented lessons through lesson study, using observation tools like the Fidelity and Integration Checklist. Weekly classroom and online coaching offered targeted feedback. Mid-cycle community showcases allowed students to present their findings to local audiences. The program ended with an evidence conference where teachers, researchers, and community partners reviewed results and planned for expansion within the Phuket Education Sandbox.

TPACK-Place Instrument

Teachers' technological pedagogical content knowledge (TPACK) in relation to place-based STEM instruction was assessed using the TPACK-Place instrument, which was adapted from the TPACK framework originally developed by Mishra and Koehler (2006). The instrument was contextualized for place-based STEM education by integrating dimensions related to ecological, community, and contextual learning practices. The adapted instrument was designed to evaluate teachers' competencies in integrating technology, pedagogy, STEM content, and local contextual knowledge within authentic learning environments.

The TPACK-Place instrument consisted of 35 items organized into seven dimensions: technological knowledge (TK), pedagogical knowledge (PK), content knowledge (CK), technological pedagogical knowledge (TPK), technological content knowledge (TCK), pedagogical content knowledge (PCK), and integrated TPACK-Place competency. Each dimension contained five items that assessed teachers' perceived competencies in designing and implementing place-

Table 1. Summary of the program design, showing how activities gradually built teacher capacity, from forming initial partnerships to lesson implementation, coaching, and scaling

Phase	Purpose	PD activity	Outputs & evidence
Pre-partnership and context onboarding *(week 1-week 2)*	Establish school, community partnerships and the ecology and community framing	1. MoU between schools, communities, and local agencies 2. Create PLC and appoint community co-teacher (e.g., municipality and local enterprises) 3. Orientation on place-based and ecological literacy	1. Stakeholder map 2. PLC charter 3. Baseline survey of teachers' ecological literacy
1. Needs assessment and design brief *(week 3-week 8)*	Identify *what to prepare*: teachers' needs for STEM teaching that integrates ecological-community contexts	1. Needs survey and interviews T-SESTEM subscales: interdisciplinary/EDP, place-based self-efficacy) 2. Root-cause analysis workshop (fishbone/5-whys) 3.Place audit & community walk by conducting eco-audit (water, waste, and biodiversity) and asset mapping 4.Design brief: define driving questions and ecology and community outcomes for learning units	1. Needs & causes report 2. Community resource map (assets/issues) 3. School-based design briefs
2. Capacity building bootcamp *(week 9-week 14)*	Build *how to teach*: strategies for integrating ecology-community dimensions into STEM	Six workshop and micro-teaching modules: 1. PB-STEM framing& EDP 2. Local phenomena modeling (e.g., coastal water quality, and marine debris) 3. Field data skills (sensors, sampling, and data collection) 4. Community-linked problem framing (co-design with stakeholders) 5. Scientific argumentation (CER) & data storytelling 6. Assessment for learning (rubrics: EDP, place & ecology integration, community engagement)	1. Micro-teaching records 2. Prototype lesson plan (1 per school) 3. Rubrics & task bank
3. Lesson study and coaching (SPLC cycles) *(week 15-week 29)*	Support in implementation: practice in real classrooms with coaching	1. Lesson study cycles (2-3 iterations) with (a) Co-design lesson plans integrating *eco/community tasks* (b) Co-teaching/peer observation (using *Fidelity & Integration Checklist*) (c) Weekly coaching (in-class/online) 2. Community showcases mid-cycle (students present data to community)	1. Lesson videos and observation notes 2. Ecology-community integration checklist 3. Student artifacts (data logs and CER reports) 4. Coaching logs
4. Reflection, scaling, and refinement *(week 30-week 32)*	Consolidate evidence and refine the model	1. Evidence conference (teachers-community-researchers) 2. Analyze pre-post (T-SESTEM/ the TPACK-Place instrument, student outcomes) and thematic analysis of reflections 3. Design playbook & scaling plan (linked to district/municipal education offices)	1. Program evaluation report 2. PbSTEM-TPP playbook 3. Scaling plan

based STEM instruction supported by technology and community resources. Responses were collected using a 5-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. Higher scores indicated greater perceived competency in integrating technology, pedagogy, CK, and place-based instructional approaches. Sample items included teachers' confidence in using digital tools to support inquiry-based STEM learning, integrating local environmental issues into STEM lessons, and designing interdisciplinary learning experiences connected to community contexts. Prior to implementation, the instrument was reviewed by three experts in STEM education, educational technology, and place-based learning to establish content validity. Item-objective congruence values ranged from 0.67 to 1.00, indicating acceptable content validity. Reliability analysis demonstrated satisfactory internal consistency across all dimensions, with Cronbach's alpha coefficients ranging from .70 to .91, and an overall reliability coefficient above .90, indicating high reliability of the instrument for assessing teachers' TPACK-Place competencies in the context of the PbSTEM-TPP program.

Data for this study were collected over one academic year and involved 25 in-service elementary science teachers from 10 public schools in Phuket, Thailand. The schools were in coastal and rural areas, providing authentic community contexts, such as mangroves, beaches, and fishing villages, for place-based STEM instruction. A multistage evaluation design guided the study, with data gathered across three phases: baseline, implementation, and reflection. Multiple data sources were used to ensure comprehensive coverage of teacher development and student outcomes.

A variety of data sources were used to capture the multifaceted impacts of the PbSTEM- TPP on teachers' practices, beliefs, and student outcomes. The combination of surveys, classroom observations, reflective accounts, coaching records, and interviews provided both breadth and depth, ensuring that findings were triangulated across multiple types of evidence. To examine changes in teacher self-efficacy and knowledge integration, two survey instruments were administered before and after the program. The first instrument, the T-SESTEM, was adapted to include dimensions of ecological and community integration (Khut, 2024; Tschannen-Moran & Hoy, 2001). The scale comprised five subscales:

(1) interdisciplinary STEM lesson design,

(2) inquiry and engineering design facilitation,

(3) technology and data use,

(4) place-based & ecological integration, and

(5) community engagement & collaboration.

The second instrument, the TPACK-Place scale, was designed to assess teachers' technological, pedagogical, and CK within place-based and ecological contexts. Prior to full implementation, both instruments were pilot tested with teachers from non-participating schools to examine reliability and clarity of items. Internal consistency reliability was assessed using Cronbach's alpha coefficients. For the T-SESTEM scale, alpha values ranged from 0.70 to 0.90 across subscales (interdisciplinary STEM lesson design = 0.80, inquiry and engineering design facilitation = 0.85, technology and data use = 0.90, place-based & ecological integration = 0.80, community engagement & collaboration = 0.75), with an overall scale reliability of 0.90. For the TPACK-Place instrument, alpha coefficients ranged from 0.70 to 0.90 across its dimensions, with an overall reliability of 0.88.

All reliability coefficients met acceptable standards, with Cronbach's alpha values ranging between 0.70 and 0.90, indicating acceptable to excellent internal consistency. Values above .70 are considered acceptable, values above .80 indicate good reliability, and values above .90 indicate excellent reliability. Content validity was established through expert review by three specialists in STEM education, place-based learning, and teacher PD, who evaluated the items' relevance, clarity, and alignment with the study's constructs. Minor revisions were made based on their feedback prior to pilot testing.

Classroom observations provided a second layer of evidence. The lesson study cycles teachers undertook were systematically documented through structured protocols, with the Fidelity and Integration Checklist used to monitor the implementation of inquiry, engineering design, and ecological/community integration. To ensure consistency among observers, the observation tools were trialed and calibrated in advance, and inter-rater reliability was established before data collection. In addition to surveys and observations, teachers maintained weekly reflection logs that recorded instructional goals, challenges, and insights from their classroom experiences. These reflections were complemented by the collection of artifacts, including lesson plans, student work samples, rubrics, and products from community showcases, which together provided tangible evidence of shifts in pedagogy and in student engagement with local ecological issues. Instructional coaching added another valuable data source. Coaches kept detailed notes from mentoring sessions, documenting teacher goal setting, feedback exchanges, and iterative lesson refinements. These records shed light on how teachers responded to feedback, the extent of their experimentation with new strategies, and the evolution of their practices throughout the program. Lastly, qualitative data were collected through semi-structured interviews and focus groups. Individual interviews were conducted with 12-13 teachers, and two additional focus groups, each involving 8-10 teachers. The interview prompts explored participants' experiences in the program, their perceptions of changes in practice, the challenges they faced, and their reflections on student outcomes.

Neutral and non-directive language was used to minimize bias, following strategies recommended by Gao et al. (2025). All sessions were audio-recorded, transcribed, and returned to participants for member checking, ensuring accuracy and trustworthiness of the accounts. To enhance reliability and validity, a multifaceted strategy was employed to increase the study's rigor. Survey instruments were pilot tested and verified for internal consistency. Observation checklists were double-coded to establish inter-rater agreement. Triangulation was achieved by combining evidence from surveys, observations, reflections, coaching records, artifacts, and interviews. Additionally, an evidence conference was held with teachers and community stakeholders at the end of the program, serving as a peer validation mechanism for data interpretation.

Data Analysis

This study employed a mixed-methods approach within a multistage design, integrating convergent and explanatory sequential elements to examine the impact of the PbSTEM-TPP on teachers' self-efficacy and pedagogical competencies (Creswell, 2015; Creswell & Plano Clark, 2018).

Quantitative analysis

Quantitative data were collected using the T-SESTEM and the TPACK-Place instrument. Data were analyzed using IBM SPSS Statistics. Descriptive statistics, including means (Ms) and standard deviations (SDs), were calculated for pre- and post-test scores across all dimensions. To determine changes in teachers' self-efficacy and TPACK-Place competencies following participation in the PbSTEM-TPP, paired-samples t-tests were conducted for dimensions that met parametric assumptions. Prior to inferential analysis, assumptions for paired-samples t-tests were examined. Normality of the difference scores for each T-SESTEM and TPACK-Place dimension was assessed using the Shapiro-Wilk test, together with inspection of skewness, kurtosis, and Q-Q plots. Results indicated no significant deviations from normality across all dimensions (Shapiro-Wilk W = .94-.98, p > .05), supporting the use of paired-samples t-tests for all analyses. The statistical test used for each dimension is identified in the corresponding result tables. Effect sizes for paired-samples t-tests were calculated using Cohen's dz, and 95% confidence intervals (CIs) were reported to support interpretation of the magnitude of change. Accordingly, the quantitative results tables present pre- and post-test Ms and SDs, mean differences (M_diff), standard deviations of difference scores (SD_diff), inferential statistics (t or Z values), p-values, effect sizes (dz), and 95% CIs for each dimension.

Qualitative analysis

Qualitative data consisted of teacher reflection logs, coaching notes, lesson plans, classroom observations, student artifacts, and semi-structured interview transcripts. These data were analyzed using thematic analysis following the procedures proposed by Braun and Clarke (2006). Initial coding was conducted deductively using categories aligned with the program objectives, including ecological integration, community engagement, pedagogical innovation, barriers, and supports. Subsequently, inductive coding was employed to identify emergent themes grounded in participants' experiences. To enhance coding consistency and analytical rigor, approximately 30% of the qualitative data were independently coded by two researchers. Inter-rater reliability was assessed using Cohen's kappa, yielding a coefficient of κ = 0.82, indicating strong agreement. Any discrepancies were resolved through discussion and consensus. Member checking was additionally conducted during evidence-conference sessions to verify the credibility and accuracy of thematic interpretations.

Integration of findings

Quantitative and qualitative findings were integrated during both convergent and explanatory sequential phases of analysis. In the convergent phase, joint displays were used to compare and synthesize findings in order to identify areas of convergence, divergence, and complementarity between datasets. For example, quantitative improvements in engineering design self-efficacy were interpreted alongside classroom observations, lesson artifacts, and teacher reflections describing changes in instructional practice. In the explanatory sequential phase, qualitative findings were used to explain variations observed in the quantitative results, particularly differences in the degree of teacher growth across dimensions. This integration provided deeper insight into how contextual factors, collaborative learning processes, and coaching experiences influenced teacher development throughout the PbSTEM-TPP.

To ensure methodological rigor and trustworthiness, the study adhered to the criteria proposed Lincoln and Guba (1985), namely credibility, transferability, dependability, and confirmability. Credibility was established through triangulation of multiple data sources, peer debriefing among the research team, and member checking with participants. Transferability was supported through detailed descriptions of the research context, participant characteristics, and implementation processes. Dependability was ensured by maintaining a comprehensive audit trail documenting methodological decisions and analytical procedures. Confirmability was strengthened through reflexive memoing, systematic documentation of the analytic process, and collaborative coding among researchers to minimize potential bias.

RESULTS

Teacher Preparedness and Growth

To examine the impact of the PbSTEM-TPP on teachers' preparedness and professional growth, both quantitative and qualitative data were analyzed using a mixed-methods approach. The quantitative component focused on changes in teachers' self-efficacy toward STEM teaching practices before and after participation in the program. Teachers completed the T-SESTEM, which consisted of five dimensions: interdisciplinary STEM lesson design, inquiry and engineering design facilitation, technology and data use, place-based and ecological integration, and community engagement and collaboration. Pre- and post-test scores were analyzed using paired-samples t-tests to determine whether statistically significant changes occurred following participation in the PbSTEM-TPP intervention. In addition to significance testing, descriptive statistics, including Ms and SDs (M [SD]), M_diff, SD_diff, effect sizes (Cohen's dz), and 95% CIs, were calculated to evaluate the magnitude of teacher growth across each dimension of STEM practice.

As presented in **Table 2**, statistically significant improvements were observed across the overall self-

Table 2. Pre- and post-test results by subscale of teachers' self-efficacy toward STEM practices: Descriptive statistics, significance tests, and effect sizes (N = 25)

Subscale	M_pre (SD_pre)	M_post (SD_post)	M_diff	SD_diff	t (24)	p	dz	95% CI for dz
Overall self-efficacy	1.90 (0.13)	3.53 (0.11)	1.63	0.46	17.37	< .001	3.48	[2.39, 4.56]
Interdisciplinary STEM lesson design	1.70 (0.13)	3.49 (0.14)	1.79	0.35	24.98	< .001	5.00	[3.43, 6.56]
Inquiry and engineering design facilitation	1.79 (0.12)	3.71 (0.16)	1.92	0.39	24.06	< .001	4.81	[3.31, 6.32]
Technology and data use	1.84 (0.10)	3.47 (0.13)	1.63	0.51	15.81	< .001	3.16	[2.17, 4.16]
Place-based & ecological integration	2.16 (0.13)	3.48 (0.17)	1.32	0.64	10.32	< .001	2.06	[1.34, 2.79]
Community engagement & collaboration	2.24 (0.14)	3.52 (0.15)	1.28	0.80	8.30	< .001	1.66	[1.04, 2.28]

Note. Results are based on paired-samples t-tests comparing pre- and post-test scores following participation in the PbSTEM-TPP intervention; Cohen's dz values indicate large effect sizes across all subscales, suggesting substantial improvements in teachers' self-efficacy toward STEM practices; Confidence intervals for dz were calculated at the 95% level; & Descriptive and inferential statistics were derived from reconstructed individual participant data (N = 25)

efficacy scale and all subscales following the intervention ($p < .001$). The results indicate substantial increases in teachers' confidence in interdisciplinary STEM lesson design, facilitation of inquiry and engineering design, technology integration, ecological and place-based instructional practices, and collaboration with community stakeholders. Particularly large effect sizes were found in the dimensions of interdisciplinary STEM lesson design and inquiry and engineering design facilitation, suggesting that the program strongly supported teachers in designing and facilitating authentic STEM learning experiences connected to local contexts.

Table 2 presents the complete quantitative results, including pre- and post-test Ms and SDs, M_diff, paired-samples t-test statistics, p-values, effect sizes, and CIs for the overall scale and each subscale. These quantitative findings are further supported by qualitative evidence from teacher reflections, lesson plans, coaching records, and classroom observations, which provide deeper insight into how increased self-efficacy translated into changes in classroom practice and instructional implementation.

Table 2 demonstrates that participation in the PbSTEM-TPP resulted in significant improvements in teachers' self-efficacy across all dimensions of STEM teaching practice. Overall teacher self-efficacy increased substantially from a pre-test M of 1.90 (SD = 0.13) to a post-test M of 3.53 (SD = 0.11), with a large M_diff = 1.63 and a very large effect size (dz = 3.48). This finding suggests that the PD program had a strong positive influence on teachers' overall confidence in implementing STEM instruction. Among the individual dimensions, the greatest improvement was observed in interdisciplinary STEM lesson design, which increased from M = 1.70 (SD = 0.13) before the intervention to M = 3.49 (SD = 0.14) after the intervention. The large M_diff = 1.79 and extremely large effect size (dz = 5.00) indicate that the program was particularly effective at strengthening teachers' ability to design integrated STEM learning experiences that connect multiple disciplines in authentic, place-based contexts.

Similarly, the inquiry and engineering design facilitation dimension showed substantial improvement, increasing from M = 1.79 (SD = 0.12) to M = 3.71 (SD = 0.16), with a very large effect size (dz = 4.81). This result suggests that teachers became significantly more confident in facilitating inquiry-based learning and EDPs through contextualized STEM activities. The technology and data use dimension also demonstrated significant growth, with scores increasing from M = 1.84 (SD = 0.10) to M = 3.47 (SD = 0.13). The large effect size ($d_z = 3.16$) reflects the program's effectiveness in supporting teachers' integration of digital technologies and data-driven instructional practices in STEM learning environments. In terms of contextualized teaching practices, place-based and ecological integration improved from M = 2.16 (SD = 0.13) to M = 3.48 (SD = 0.17), yielding a large effect size (dz = 2.06). This finding indicates that teachers developed stronger confidence in integrating local ecological issues and community contexts into STEM instruction.

Finally, community engagement and collaboration increased from M = 2.24 (SD = 0.14) to M = 3.52 (SD = 0.15), with a large effect size (dz = 1.66). Although this dimension demonstrated the smallest effect size among the subscales, the findings still suggest meaningful improvement in teachers' confidence in collaborating with community members and external stakeholders as part of STEM learning implementation. Overall, the findings indicate that the PbSTEM-TPP intervention had a strong positive impact on teachers' self-efficacy across multiple dimensions of STEM teaching practice, particularly in interdisciplinary lesson design, inquiry facilitation, and technology integration.

In addition to improvements in teachers' self-efficacy, the results from the TPACK-Place instrument also demonstrated substantial growth in teachers' ability to integrate technological, pedagogical, and CK within place-based and ecological learning contexts. Pre- and post-test comparisons revealed increases across all dimensions of TPACK-Place, suggesting that participation in the PbSTEM-TPP enhanced teachers' capacity to design and implement context-responsive

Table 3. Pre- and post-test results of teachers' TPACK-Place competencies: Descriptive statistics, significance tests, and effect sizes (N = 25)

Dimension	M_pre (SD_pre)	M_post (SD_post)	M_diff	SD_diff	t (24)	p	dz	95% CI for dz
TK	2.01 (0.18)	3.64 (0.16)	1.63	0.52	15.67	< .001	3.13	[2.15, 4.11]
PK	2.35 (0.17)	3.79 (0.14)	1.44	0.49	14.69	< .001	2.94	[2.01, 3.87]
CK	2.48 (0.16)	3.81 (0.15)	1.33	0.45	14.78	< .001	2.96	[2.02, 3.89]
TPK	1.92 (0.19)	3.73 (0.15)	1.81	0.40	22.63	< .001	4.53	[3.12, 5.95]
TCK	1.98 (0.17)	3.68 (0.16)	1.70	0.44	19.32	< .001	3.86	[2.66, 5.06]
PCK	2.14 (0.15)	3.76 (0.14)	1.62	0.47	17.23	< .001	3.45	[2.37, 4.53]
Overall TPACK-Place competency	2.15 (0.14)	3.74 (0.13)	1.59	0.41	19.39	< .001	3.88	[2.67, 5.08]

Note. Results are based on paired-samples t-tests comparing pre- and post-test scores following participation in the PbSTEM-TPP intervention; Cohen's dz values indicate large effect sizes across all TPACK-Place dimensions, suggesting substantial improvements in teachers' technological, pedagogical, and place-based instructional competencies; & CIs for effect sizes were calculated at the 95% level

STEM instruction grounded in authentic community and environmental issues.

As presented in **Table 3**, statistically significant improvements were found across the overall TPACK-Place competency scale and all individual dimensions following the intervention ($p < .001$). These findings indicate that the program effectively strengthened teachers' integrated competencies related to technology use, pedagogy, STEM content, and place-based instructional design. Overall TPACK-Place competency increased substantially from a pre-test M of 2.15 (SD = 0.14) to a post-test M of 3.74 (SD = 0.13), with an M_diffe of 1.59 and a very large effect size (dz = 3.88). This result suggests that the PbSTEM-TPP had a strong positive impact on teachers' ability to integrate technology, pedagogy, and contextualized STEM content in ways that support meaningful and locally relevant learning experiences.

Specifically, teachers demonstrated greater ability to integrate technology meaningfully into place-based learning activities, such as using digital tools for field data collection, visualization, and communication of findings. Pedagogically, teachers improved at designing student-centered, inquiry-driven learning experiences that connect classroom concepts to real-world ecological issues. In terms of CK, teachers exhibited deeper understanding of how scientific concepts can be contextualized within local environments, including mangrove ecosystems, coastal processes, and community livelihoods. Although the quantitative gains were consistent across dimensions, these findings should be interpreted cautiously given the one-group pre-post design. The observed changes are therefore best understood as indicators of development within the program context rather than definitive measures of causal impact.

These quantitative results were supported by qualitative evidence. Teachers reported increased confidence in integrating technology with pedagogy and content in authentic contexts, as reflected in statements such as, "I can now use simple digital tools to help students collect and analyze data from the mangroves," and "I understand how to connect science concepts with local environmental issues in ways that make learning meaningful." This convergence of quantitative and qualitative data suggests that the PbSTEM-TPP contributed to strengthening teachers' TPACK within place-based STEM education.

The qualitative evidence provided rich explanatory depth for these statistical gains. Prior to participation, teachers often described their practice as textbook-driven, siloed, and teacher-centered, with low confidence in interdisciplinary design, minimal use of technology, and weak integration of local or ecological contexts. For example, teachers admitted, '*I usually teach science directly from the textbook and don't connect it with mathematics or technology*' (T1) and '*I thought STEM was only for high-level students, not for primary children*' (T6). Others expressed uncertainty in facilitating inquiry or engineering, noting reliance on manuals and passive student learning: '*STEM feels complicated; I only focus on experiments from the manual*' (T3). Technology was underused or misunderstood: '*I am not familiar with using technology to support science lessons*' (T10), while local contexts such as mangroves or fishing villages were rarely incorporated: '*My lessons rarely use the local environment; I rely mostly on school resources*' (T4).

After engaging in PbSTEM-TPP, however, teachers reported significant shifts in both understanding and practice that mirror the quantitative improvements. The largest gains in interdisciplinary and inquiry domains were reflected in teachers' descriptions of designing integrated units and guiding students through authentic investigations. As one noted, '*I can design lessons that connect science with mathematics and technology in meaningful ways*' (T2). Another emphasized the shift from content delivery to inquiry facilitation: '*Before PbSTEM-TPP, I mainly delivered content from the textbook. Now, I guide my students to ask their own questions when we visit the mangroves, and I feel proud when they discover patterns I never pointed out*' (T7).

Growth in the technology and data use subscale was evident in new practices of digital documentation and analysis. Teachers highlighted purposeful integration of tools previously seen as inaccessible: '*I used to think STEM meant robotics or expensive equipment. After this*

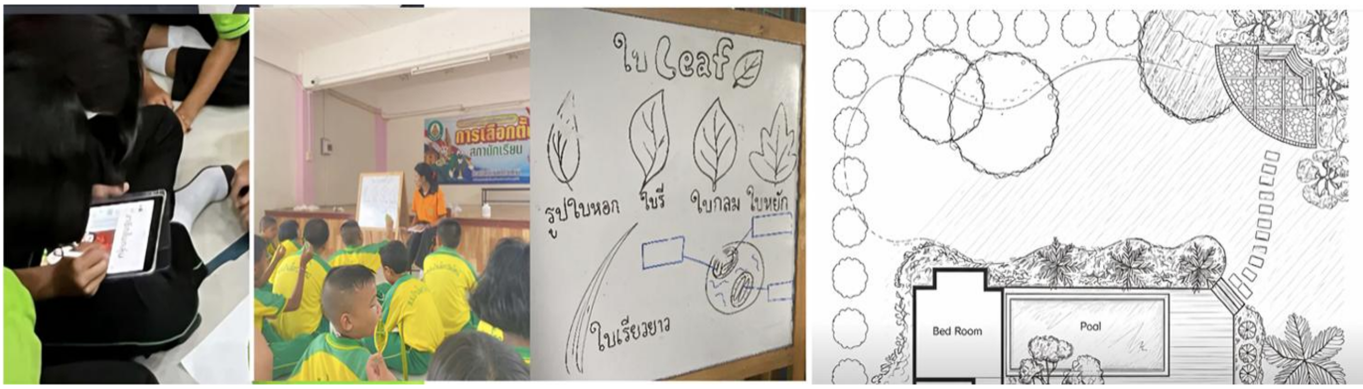

Figure 1. Classroom action in place-based STEM lessons: Students engaged in redesigning school gardens to promote biodiversity and water conservation (photograph taken by the authors during the PbSTEM-TPP implementation)

program, I realized that even simple things like counting plastic bottles on the beach and turning them into graphs are meaningful STEM learning' (T14). Place-based and ecological integration also advanced markedly. Teachers described confidence in connecting STEM to authentic local issues, such as erosion, mangrove health, and fishing livelihoods: *'I feel more confident in linking science lessons to real community issues, such as coastal erosion'* (T23). Finally, improvements in community engagement and collaboration were strongly reflected in post-program narratives. Teachers shifted from preparing lessons in isolation to co-designing with colleagues, parents, and local organizations: *'Now, I design lessons around the fisherman village, where students interview elders about waste from fishing gear and create posters to raise awareness'* (T20). This represents a profound change from the before reflections, where teachers commonly admitted, *'I usually prepare lessons alone and don't collaborate with other subject teachers'* (T12). These pedagogical shifts were not only articulated in teacher reflections but were also vividly demonstrated through classroom actions. As shown in **Figure 1,** students engaged in hands-on inquiry by redesigning school gardens to promote biodiversity and water conservation, illustrating how place-based STEM activities fostered curiosity, critical thinking, and confidence in applying knowledge to authentic ecological challenges.

Synthesizing the quantitative and qualitative evidence, teacher preparedness and growth were enhanced through the PbSTEM-TPP. The quantitative findings demonstrated statistically significant and meaningful improvements across all five subscales, while the qualitative reflections illuminated how these gains were enacted in practice. Teachers moved from fragmented, content-driven, and resource-limited instruction toward confident facilitation of integrated, inquiry-based, technology-supported, ecologically grounded, and community-connected STEM learning. This convergence of evidence substantiates the effectiveness of the PbSTEM-TPP in reshaping teacher preparedness and professional identity, aligning measurable growth in self-efficacy with demonstrable transformation in classroom practice. The program emphasizes teacher PD, the utilization of digital technologies, and the implementation of innovative pedagogical methods, including project-based learning, lesson study, and online coaching. This systematic and context-aware strategy ensures the program effectively improves STEM literacy and teaching skills, establishing Phuket as a prominent example of educational transformation in Thailand.

Pedagogical Strategies Implemented

Classroom observations across the five lesson contexts showed significant improvements in teachers' ability to combine STEM with real ecological and community issues. Teachers consistently based five lessons on local environmental systems (mangroves, beaches, fisherman villages, and schoolyard environments), involved students in field-based data collection, and guided them through engineering design and CER reasoning. Community involvement was apparent in extension activities with parents, fishermen, NGOs, and local leaders, as shown in **Table 4**.

Analysis of teacher reflections and classroom observations revealed that all 25 participating teachers experienced a significant shift in their lesson design and instructional practices as a result of the PbSTEM-TPP. Lessons were consistently anchored in authentic ecological issues directly relevant to the local context. Beach garbage lessons emphasized waste classification and environmental impacts; mangrove lessons highlighted the role of roots in protecting against erosion; fisherman village lessons examined the problem of discarded ghost nets; beach life projects focused on crabs and shells as ecological indicators; and schoolyard explorations linked waste and energy use to everyday student experiences. These changes in lesson design and instructional practice were evident not only in teacher reflections but also in student engagement. As shown in **Figure 2,** students actively participated in field-based data collection and ecological exploration, connecting STEM concepts to real-world contexts, including mangroves, beaches, and fishing villages. This illustrates

Table 4. Observed pedagogical dimensions in place-based STEM lessons: Descriptions, levels of implementation, and exemplary evidence across five contexts

Dimension	Description	Observed across lessons	Exemplary evidence
Ecological phenomena	Lesson anchored in authentic ecological issue relevant to the local context	Strong in all five lessons	Beach garbage investigation focused on waste classification and impacts; mangrove lesson used erosion protection as anchor; fisherman village centered on ghost nets; beach life focused on crabs/shells; schoolyard walk linked to local waste/energy
Field data collection	Students collect, analyze, or interpret authentic/local data	Adequate to strong in four lessons	Mangrove data: seedling counts, salinity measures; beach garbage: weighing plastics, recording types; fishing waste: tallying nets, ropes; beach life: counting shells/crabs
EDP	Students engage in design, testing, and improvement cycle	Adequate in most lessons	Students created prototypes: eco-bins, crab-safe paths, recycling mats; water filters and posters in schoolyard projects
Scientific argumentation (CER)	Students make claims supported by evidence and reasoning	Emerging to adequate across lessons	CER structured in reflections (e.g., microplastics harm crabs because evidence shows fragments in sand) and mangrove pledges, stronger in beach garbage and mangrove cases
Community engagement	Lesson connects to community stakeholders or sharing outcomes	Emerging to strong depending on lesson	Fisherman village included direct links to cooperatives; beach garbage tied to municipality partnerships; mangrove clean-up with parents and local officials; beach life brought in elders' knowledge; schoolyard eco-project linked to NGOs

Figure 2. Students engage in field-based data collection and ecological explorations as part of place-based STEM lessons, linking STEM concepts to their local environments (photograph taken by the authors during the PbSTEM-TPP implementation)

how the PbSTEM-TPP anchors science learning in authentic experiences, fostering more profound understanding and personal relevance.

These five lessons and classroom practices were integrated with the EDP, where teachers encouraged their students to engage in iterative cycles of designing, testing, and refining solutions. Teachers supported the creation of prototypes, including eco-bins, crab-safe walkways, recycling mats, simple water filters, mangrove plantations, and environmental awareness posters. As these lessons fostered students' interaction with their environment and community members, the teachers aimed to develop empathy, responsibility, and a deeper appreciation for shared spaces, incorporating these objectives into their assessment design. These practices highlighted how teachers utilized the EDP to empower students, demonstrating both problem-solving skills and a growing sense of responsibility. As illustrated in **Figure 3**, students combined hands-on field experiences, digital tools, and creative outputs such as posters and journals, demonstrating both problem-solving skills and a growing sense of responsibility for protecting natural ecosystems.

Analysis of classroom practices revealed that scientific argumentation (CER) is emerging as a prominent strategy in place-based STEM instruction. Students increasingly demonstrated the ability to make claims supported by evidence and reasoning. For example, in one reflection, a student noted, 'Microplastics harm crabs because evidence shows fragments in sand.' In the mangrove unit, students made pledges that explicitly linked erosion data to the ecological importance of mangroves. Stronger use of CER was observed in lessons about beach garbage and mangroves, where local data supported students' claims and reasoning. Evidence also showed that community engagement was included to different extents across lessons, extending STEM learning beyond the classroom and encouraging community ownership. Teachers led collaborative projects with local partners, including fishing cooperatives that supported village activities, municipal agencies that participated in beach garbage

Figure 3. Students participated in engineering design projects, including digital prototyping, mangrove fieldwork, and creating reflective environmental awareness posters, as part of place-based STEM lessons (photograph taken by the authors during the PbSTEM-TPP implementation)

efforts, parents and local officials who assisted with mangrove clean-ups, and elders who shared their knowledge about beach life. Additionally, NGOs partnered in schoolyard eco-projects.

Teachers also emphasized the importance of co-design with community stakeholders, noting a clear shift from working alone to building partnerships. One teacher said, *'I can confidently plan place-based STEM projects that involve parents and local leaders,'* while another shared, *'I can work with local NGOs and invite them to enhance classroom STEM projects.'* These stories demonstrate a significant shift from previous practices, where lesson planning frequently occurred without community involvement. Implementing outdoor fieldwork was described as transformative. Teachers gained new confidence in guiding students through ecological investigations, saying, *'I now feel confident guiding students to collect data in the mangroves,'* and *'I now see how to use the schoolyard and nearby ecosystems as outdoor classrooms.'* These changes contrasted sharply with earlier reliance on classroom-only, worksheet-based lessons.

Finally, student showcases, and community connections were highlighted as key teaching strategies. Projects shared with families and community members not only validated student work but also encouraged ecological responsibility and civic pride. One teacher reflected, 'I feel prepared to involve students in projects that connect directly with their families and community. Such activities strengthened the real-world relevance of STEM learning by linking student inquiry to local challenges and sustainability issues. Finally, teachers described adapting lessons to local contexts as a pivotal change. One noted, *'I can connect STEM lessons to local livelihoods, like fishing and farming, to make them relevant,'* while another reflected, *'I feel more confident in linking science lessons to real community issues, such as coastal erosion.'* Analysis of teacher reflections and classroom observations revealed that *the PbSTEM-TPP* contributed to clear shifts in pedagogy, moving from traditional, content-focused approaches toward practices that fostered students' awareness of their own communities. These changes were evident across five dimensions of teaching practice, as summarized in **Table 5**.

Analysis of teacher reflections and classroom observations revealed that the PbSTEM-TPP led to significant shifts in teaching, moving from traditional, content-focused lessons to methods that enhanced students' awareness of their communities. These changes were observed across five interconnected areas of teaching practice, summarized in **Table 5** and aligned with the step-by-step model of place-based STEM teaching.

The first area, helping students identify community features, transitioned from classroom activities, such as using pictures or storytelling, to real-world, field-based explorations. Teachers led students in exploring mangroves, beaches, and fishing villages through mapping, collecting ecological data, and conducting interviews with community members. In several schools, these investigations culminated in community projects, where students presented their findings to families and local leaders. One teacher highlighted the real-world relevance, saying, 'I feel prepared to involve students in projects that connect directly with their families and community.'

In promoting respect for local traditions and culture, teachers shifted from occasionally mentioning cultural festivals to actively involving parents and elders as co-mentors in the learning process. Lessons increasingly incorporate local livelihoods, such as fishing, farming, and crafts, thereby validating community knowledge and fostering pride in cultural heritage. At higher levels, long-term cultural projects were undertaken, with students showcasing their work at community events, thereby strengthening school-community ties. Some teachers took further steps, helping students design stewardship campaigns and local environmental projects. For example, student-led events on waste reduction and water conservation not only reinforced learning but also fostered civic pride and ecological responsibility.

Table 5. Behavioral indicators of teaching practices to promote students' awareness of their own community

Dimension	Emerging practice	Developing practice	Proficient practice	Exemplary practice
1. Facilitate identification of community features	Uses pictures or stories of local places in class	Plans field trips or nature walks to explore local areas	Guides students in investigating local landmarks or natural features through mapping, interviews, or surveys	Co-creates community exploration projects where students collect and present findings to real audiences
2. Promote respect for local traditions and culture	Introduces festivals or traditions in classroom storytelling	Invites parents or elders to share cultural knowledge or practices	Integrates local traditions in lesson content (e.g., science through local crafts, math through local markets)	Develops long-term cultural learning units with student-led exhibitions or community events
3. Empathy & environmental stewardship	Recognizes the importance of caring for nature or others when reminded	Participates in classroom discussions on caring for the environment	Joins community actions (e.g., clean-up day) with guidance	Organizes or promotes local stewardship initiatives with peers
4. Connect classroom learning to local experience	Uses examples from students' everyday lives to explain concepts	Designs lessons that use local problems or contexts (e.g., flooding, waste)	Integrates interdisciplinary projects grounded in students' local realities	Encourages students to co-design inquiry-based learning that links directly to community improvement
5. Foster place attachment and identity	Encourages students to share feelings about their neighborhood	Promotes reflective activities (drawings, journals) about places they love	Builds emotional connections by linking student stories to local environment and heritage	Empowers students to take ownership of place (e.g., school–community ambassador roles, and place-advocacy campaigns)

DISCUSSION OF RESULTS

Findings from both the quantitative results (T-SESTEM and TPACK-Place) and qualitative reflections indicate that the PbSTEM-TPP substantially strengthened teachers' confidence and competencies in implementing STEM instruction within authentic, real-world contexts. Teachers reported increased confidence in designing interdisciplinary lessons, facilitating inquiry and EDPs, integrating technology meaningfully, and connecting STEM learning to ecological and community issues. These findings support the view that effective PD should be sustained, collaborative, and grounded in authentic practice (Creswell & Plano Clark, 2018; Loucks-Horsley et al., 2010). Previous research has consistently identified teacher self-efficacy as a key factor influencing instructional quality, willingness to adopt innovative practices, and student outcomes (Hammack et al., 2024; Unfried et al., 2022). The substantial gains observed across all T-SESTEM dimensions in this study are also consistent with meta-analytic findings demonstrating that well-designed PD programs can produce strong positive effects on teachers' confidence and instructional practice (Zhou et al., 2023). In addition, the significant improvement in TPACK-Place competencies suggests that teachers became more capable of integrating technological, pedagogical, and CK into contextualized, place-responsive STEM learning environments.

Classroom observations further demonstrated that teachers increasingly anchored instruction in authentic ecological phenomena, including mangrove erosion, beach waste, fishing debris, and schoolyard energy use. Students actively participated in field-based data collection, engineering design activities, and scientific argumentation (CER), while teachers facilitated collaboration with parents, fishermen, NGOs, and municipal agencies. These practices reflect key principles of place-based education, which emphasize grounding learning in local ecological systems and cultural practices to enhance relevance, engagement, and social responsibility (Gruenewald, 2003; Neher-Asylbekov & Wagner, 2023; Sobel, 2004). The findings also extend previous research suggesting that contextualized STEM learning enhances student achievement, motivation, and civic engagement (Bascopé et al., 2021; Rickinson et al., 2004). In particular, the integration of ecological and cultural knowledge responds to growing calls for STEM-in-context approaches that connect disciplinary learning with social and environmental realities (Bevan et al., 2020; Brown et al., 2016).

The findings additionally highlight the importance of teacher beliefs and professional identity in shaping PD outcomes. Teachers in this study demonstrated a clear shift from initial uncertainty regarding inquiry-based instruction and technology integration toward greater confidence in co-designing lessons with colleagues and community stakeholders. These shifts were consistently reflected in teacher reflections, coaching records, lesson artifacts, and classroom observations. Such findings align with previous research indicating that teachers often experience both enthusiasm and concerns regarding STEM integration, particularly related to time, resources, and instructional readiness (Margot & Kettler, 2019). The PbSTEM-TPP addressed these challenges through school-based PLCs, lesson study, and ongoing coaching, approaches widely recognized as effective for supporting sustained instructional improvement (Borko, 2004; Đuranović et al., 2024; Murad et al., 2022; Shernoff et al., 2017; Vescio et al., 2008). These collaborative structures also appear to have strengthened teachers' professional identity and self-efficacy, encouraging continued engagement with innovative and context-responsive practices (Polizzi et al., 2021; Zhai et al., 2024).

Student outcomes further support the effectiveness of the program. Student learning was assessed using analytic rubrics focused on ecological awareness, problem-solving, and community engagement. Rather than relying solely on holistic evaluations, student performance was examined across four proficiency levels: emerging, developing, proficient, and excellent. Analysis of student artifacts, including CER reports, eco-bin prototypes, reflective journals, and water filtration designs, showed that many students achieved Proficient and Excellent levels, particularly in applying scientific concepts to local ecological issues, supporting claims with evidence, and developing context-responsive solutions.

Although the results indicate positive trends in student learning outcomes, it is important to acknowledge that the study primarily reports aggregated patterns of performance rather than detailed frequency distributions or comprehensive descriptive statistics for each rubric level. Therefore, these findings should be interpreted as indicators of overall improvement in student competencies rather than precise estimates of achievement gains.

These findings are consistent with prior research demonstrating that authentic and context-based STEM learning experiences can enhance problem-solving abilities, ecological literacy, and civic engagement (Moore et al., 2014; Stevenson et al., 2013; Tilbury, 2011). They also support evidence that meaningful engagement with local environments during childhood contributes to long-term environmental responsibility and strengthens students' identities as active problem solvers and community contributors (Mercier et al., 2025; Yildirim et al., 2025). The findings from Phuket further suggest that local ecological issues can serve as powerful anchors for integrating scientific learning with community engagement, thereby promoting both scientific understanding and civic agency. Taken together, the findings suggest that the PbSTEM-TPP functions as a context-responsive PD framework consisting of three interconnected dimensions:

(1) teacher preparation through locally situated PD,

(2) pedagogical enactment through ecological and community integration, and

(3) student and community outcomes related to ecological literacy, problem-solving, and civic participation.

This aligns with broader international discussions positioning STEM education as both a national priority and a global necessity (Li, 2023; Li et al., 2020). It also responds to critiques of education for sustainable development that emphasize the need for pluralistic and place-conscious educational approaches that connect academic rigor with ecological and cultural realities (Greenwood, 2009; Wals, 2015).

In summary, the PbSTEM-TPP demonstrates how sustained, locally grounded PD can simultaneously promote teacher growth, student learning, and community engagement. The findings suggest that STEM education, when rooted in local contexts and supported by strong school-community partnerships, can serve as a meaningful pathway toward education for sustainable development by positioning teachers as facilitators of inquiry and students as active contributors to sustainability and community resilience. Although this study was conducted within the Phuket Education Sandbox, the findings have broader relevance for other ecological and cultural contexts. The PbSTEM-TPP illustrates how contextually grounded PD can be adapted across settings while maintaining alignment with global STEM education priorities. At the same time, although very large effect sizes were observed, these findings should be interpreted cautiously given the relatively low baseline scores and the intensive, year-long nature of the intervention.

CONCLUSION

The findings of this study show that the PbSTEM-TPP has had a transformative impact on both teaching and learning. Over the course of one academic year, the program enhanced teachers' readiness and confidence in teaching STEM in ways that were both interdisciplinary and deeply connected to their communities. Teachers who once relied on textbooks and isolated lessons began approaching instruction with confidence, designing integrated units that combined science, mathematics, and technology, while guiding students through inquiry and engineering design. Their reflections revealed a clear sense of professional growth; many described feelings newly capable of linking classroom learning with real ecological challenges, such as mangrove erosion and marine debris, and of facilitating investigations that allowed students to ask their own questions and pursue their own solutions.

Equally important was how teachers began to incorporate ecological and cultural perspectives into their daily practice. Lessons are no longer centered on abstract concepts but instead draw on the lived realities of coastal erosion, waste management, and local livelihoods such as fishing and farming. Parents, elders, and community organizations were welcomed into classrooms as co-mentors, ensuring that cultural traditions and local expertise were recognized as valuable sources of knowledge. Teachers spoke of the confidence they gained in co-designing projects with their communities and in using the surrounding environment as an outdoor classroom. These practices not only enriched teaching but also validated community heritage, fostering a sense of pride and responsibility among students. The impact on learners was equally significant. More than 500 students participated in projects that required them to collect data, design prototypes, and engage in scientific reasoning. Nearly nine out of ten reached proficient or excellent levels on measures of ecological awareness, environmental responsibility, and civic engagement. Their work, ranging from eco-bins and water filters to reflective journals and CER reports, showed not just mastery of content but also a strong sense of agency. Students participated in clean-up campaigns, mangrove-planting initiatives, and recycling efforts, and, in doing so, began to see themselves as stewards of their communities. Their confidence in applying STEM to real-world challenges was accompanied by growing ecological awareness and civic pride.

In conclusion, these findings position the PbSTEM-TPP as a strong model of PD, deeply rooted in local contexts yet broadly applicable to international STEM education. By integrating ecological and community realities into instruction, the program not only enhanced teachers' professional identities but also empowered students to become problem solvers and responsible citizens. More broadly, the study highlights the role of STEM education in advancing the goals of education for sustainable development and shows how local innovations can address pressing global challenges, such as climate change and sustainability. Although designed within the ecological and cultural setting of Phuket, the model offers transferable insights for diverse educational contexts worldwide. By aligning global STEM education priorities with local sustainability challenges, the PbSTEM-TPP demonstrates how place-based PD can be scaled and adapted to strengthen teacher learning and foster student ecological literacy across regions. Future research should continue exploring how place-based PD can be adapted to different cultural and ecological contexts. Long-term studies would help determine whether the improvements in teacher confidence and student agency observed here are sustained over time. More work is also needed to understand how partnerships among schools, communities, and policymakers can be expanded to provide the resources and structural support necessary to sustain this kind of innovation. In summary, the PbSTEM-TPP shows that when teachers are empowered through context-specific PD, they not only improve their own practices but also cultivate a generation of students capable of critical thinking, responsible action, and meaningful contributions to their communities' sustainability.

While this study offers valuable insights into teacher development and contextualized STEM education, some limitations should be acknowledged. First, the 32-week data collection period captures only short-term changes in teacher self-efficacy and teaching methods, which limits the ability to evaluate the long-term sustainability of these outcomes. Future longitudinal research is recommended to explore how teachers sustain and adapt their STEM integration over time. Additionally, although the mixed-methods approach provided a comprehensive understanding of teacher and student experiences, reliance on self-reported data and researcher-led observations may have been influenced by social desirability bias or researcher bias. Combining these findings with independent classroom assessments, student achievement data, or peer observations could enhance the credibility and depth of future analyses. Lastly, because this study was conducted within the Thai educational context, cultural and policy differences may affect the transferability of the PbSTEM-TPP model to other settings. Comparative and cross-national research—especially between Thailand and Australia—would offer valuable insights into how national policies, professional learning systems, and community partnerships influence the implementation and outcomes of place-based STEM education. Despite these limitations, this study makes several significant contributions to the fields of teacher PD and STEM education. It provides evidence that a sustained, place-based professional learning model can enhance teachers' self-efficacy, promote interdisciplinary collaboration, and connect STEM instruction to authentic ecological and community issues. The combination of quantitative and qualitative data provides a comprehensive understanding of teacher growth and student learning, demonstrating how locally grounded approaches can transform classroom practice. Additionally, the PbSTEM-TPP framework provides a practical model aligned with national and international priorities for education for sustainable development, teacher capacity-building, and community engagement. Its emphasis on linking local wisdom, environmental contexts, and global STEM skills provides useful insights for policymakers, educators, and researchers aiming to create more responsive and equitable professional learning systems.

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writing – review & editing; **WSN:** supervision, validation, writing – review & editing. Both authors agreed with the results and conclusions.

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