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ENHANCING TEACHERS' COMPETENCE IN DESIGNING TPACK-BASED TEACHING MODULES INTEGRATED WITH ESD

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ABSTRACT

This study examines the enhancement of high school teachers' competencies in developing Technological Pedagogical Content Knowledge (TPACK)-based teaching modules integrated with Education for Sustainable Development (ESD) through a structured mentoring program at SMA Negeri 10 Palembang, Indonesia. The program involved 25 science teachers (biology, chemistry, and physics) who participated in workshops, mentoring sessions, and reflective activities aimed at strengthening pedagogical and technological integration for sustainability-oriented learning. The results demonstrate substantial improvement across all TPACK dimensions: Objective (1.8 to 2.6), Concept (1.9 to 2.8), Pedagogy (1.7 to 2.7), Technology (1.5 to 2.4), and Evaluation (1.6 to 2.9), with percentage increases ranging from 44% to 60%. These gains indicate a shift from Pre TPACK and Growing TPACK toward Maturing TPACK, particularly in pedagogical and evaluative competencies. Overall, teachers' TPACK-based ESD competence increased from 2.02 (pre-test) to 2.80 (post-test) on a 4-point scale.
The findings suggest that sustained, context-sensitive mentoring supported by digital practice and collaborative reflection effectively promotes teachers' professional growth in integrating TPACK and ESD, aligning with the Merdeka Curriculum and SDG 4 and SDG 13.

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INTRODUCTION

SMA Negeri 10 Palembang, located in South Sumatra, Indonesia, represents a semi-urban educational environment facing both opportunities and challenges amidst rapid population growth and infrastructure expansion. Education in such regions plays a pivotal role in cultivating intelligent, creative, and competitive generations capable of addressing 21st-century challenges. However, many teachers in these areas, particularly at the high school level, continue to encounter difficulties in designing contextual, innovative, and sustainability-oriented learning materials. Preliminary observations and interviews with school leaders and teachers revealed limited understanding and implementation of Education for Sustainable Development (ESD) and Technological Pedagogical Content Knowledge (TPACK) a finding consistent with previous research emphasizing gaps in teachers' digital-pedagogical integration in emerging contexts (Rieckmann, 2019; Nguyen et al., 2024).

Teachers in SMA Negeri 10 Palembang possess high enthusiasm and educational qualifications (predominantly bachelor's degrees), yet systemic barriers hinder their pedagogical innovation. The primary issues identified include: (1) the absence of teaching modules that systematically integrate technology, pedagogy, and content knowledge; (2) limited professional development opportunities focusing on TPACK–ESD; and (3) insufficient access to digital learning resources and technological infrastructure. These challenges are compounded by low digital literacy and uneven technological readiness in semi-urban schools, particularly in the Alang-Alang Lebar district.

In response, the Indonesian Merdeka Curriculum mandates teachers to create learning modules that not only meet academic standards but also foster the Pancasila Student Profile emphasizing global competence, critical thinking, and environmental responsibility. Furthermore, alignment with the Sustainable Development Goals (SDGs), especially SDG 4 (Quality Education) and SDG 13 (Climate Action), underscores the need for teachers to embed sustainability and technological innovation within classroom practices.

To address these needs, Universitas Sriwijaya (UNSRI) initiated a community-based mentoring program that combines theoretical and practical approaches to professional development. The program emphasizes collaborative learning, inquiry-based pedagogy, and reflective practice while introducing teachers to digital tools that enhance sustainability-focused instruction. Conducted through a combination of workshops, mentoring sessions, microteaching, and follow-up reflection, this initiative aims to transform teachers' conceptual and practical understanding of TPACK and ESD (Dewi & Listiaji, 2024).

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This study provides a critical contribution to the ongoing discourse on teacher professional development in sustainability-oriented education within developing and semi-urban contexts. By integrating the TPACK framework with Education for Sustainable Development (ESD), it addresses a crucial gap in how teachers conceptualize and implement technology-supported, inquiry-based, and value-driven instruction. The research not only strengthens empirical understanding of teachers' pedagogical transformation through structured mentoring but also demonstrates a replicable model for integrating digital and sustainability competencies in education. Its outcomes hold implications for curriculum designers, policymakers, and higher education institutions seeking to localize the Sustainable Development Goals (SDGs) in classroom practice.

This study aims to analyze the impact of the TPACK ESD mentoring program on teachers' competencies in designing and implementing sustainability-integrated learning modules. Specifically, it investigates how the intervention influences different dimensions of TPACK objectives, conceptual understanding, pedagogy, technology, and evaluation and identifies the developmental progression from Pre TPACK to Maturing TPACK. By doing so, the research contributes to the growing body of knowledge on contextualized teacher capacity building in sustainability education and offers an evidence-based model for integrating digital and sustainability competencies into teacher professional development in Indonesia.

LITERATURE REVIEW

Community Development through Teacher Mentoring Programs

Community development in education refers to systematic efforts aimed at improving the capacity, autonomy, and sustainability of a target community through participatory and context-based interventions (Phillips & Pittman, 2009). In the school context, teachers represent a strategic professional community whose competence development directly influences educational quality and social transformation. Effective community development programs emphasize empowerment, continuous capacity building, collaboration, and reflection rather than one-time training activities (Ife & Tesoriero, 2006).

Mentoring-based programs are widely recognized as an effective approach in educational community development, as they provide sustained support, peer interaction, and contextual problem-solving opportunities (Desimone & Garet, 2015). Through mentoring, teachers are not positioned as passive recipients but as active participants who collaboratively

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construct knowledge and instructional practices aligned with local needs.

TPACK as a Framework for Professional Capacity Building

Technological Pedagogical Content Knowledge (TPACK) serves as a theoretical framework for strengthening teachers' professional competence in integrating content, pedagogy, and technology (Mishra & Koehler, 2006). Within community development initiatives, TPACK functions as a capacity-building model that supports teachers in designing relevant, adaptive, and technology-enhanced learning resources. Research indicates that structured professional development grounded in the TPACK framework can significantly improve teachers' instructional planning, teaching strategies, and assessment practices (Koehler et al., 2013).

However, studies also reveal that teachers' TPACK development is often uneven, particularly in pedagogical and evaluative dimensions, when professional development lacks sustained guidance and contextual relevance (Chai et al., 2019). Therefore, mentoring-based community programs are essential to support gradual and reflective TPACK growth within school communities.

Education for Sustainable Development (ESD) in Community Empowerment

Education for Sustainable Development (ESD) emphasizes empowering educators and learners to contribute to sustainable social, environmental, and economic development (UNESCO, 2017). Teachers play a key role as agents of change by embedding sustainability values, critical thinking, and real-world problem-solving into subject-based learning. In science education, ESD integration is particularly relevant due to its close relationship with environmental issues and climate action (Wiek et al., 2011).

Despite its importance, many teachers face difficulties in operationalizing ESD concepts into concrete learning activities and teaching modules (Borg et al., 2014). Community development programs that integrate ESD with pedagogical and technological training can bridge this gap by providing teachers with practical frameworks and collaborative learning experiences.

Integrating TPACK and ESD in School-Based Community Development

Integrating TPACK and ESD within a mentoring-based community development program supports teachers in designing sustainability-oriented learning modules that are pedagogically sound and technologically relevant (Angeli et al., 2020). Collaborative workshops, reflective discussions, and guided practice enable teachers to contextualize global

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sustainability goals into local classroom realities. Such approaches promote professional learning communities that sustain innovation beyond the program duration (Fullan, 2016).

In the Indonesian educational context, this integration aligns with the Merdeka Curriculum, which emphasizes learner-centered pedagogy, digital literacy, and character education linked to sustainable development. Community-based mentoring programs that respond to curriculum reform and local school needs have been shown to foster meaningful and sustainable improvements in teachers' professional competence (Kemendikbudristek, 2022; UNESCO, 2020).

Overall, theoretical studies highlight that community development through sustained mentoring, grounded in TPACK and ESD frameworks, is an effective strategy to enhance teachers' professional capacity. Such programs not only improve instructional competence but also strengthen teachers' roles as contributors to sustainable educational development.

MATERIAL AND METHOD

Research Design

This study employed a pre experimental research design, specifically the one group pretest–posttest design. In this design, a single group of teachers was measured before and after the mentoring intervention. The pre-test was administered to assess the initial level of teachers' competencies, followed by the implementation of the mentoring intervention. After the intervention, a post-test was conducted to determine any changes in competencies. The difference between pre-test and post-test scores was used to evaluate the effectiveness of the mentoring program.

Participants

Participants included 25 teachers (cocial, biology, chemistry, and physics) from SMA Negeri 10 Palembang. Most had over five years of experience but limited exposure to sustainability-based teaching models.

Instrument

The instrument used was a 72-item Science Teacher ESD Competency Questionnaire adapted from (Anwar et al., 2024). Items were grouped into seven competency indicators: TPCK (1–21), Inquiry (22–34), Professional Practice (35–45), Evaluation & Assessment (46–56), Professional Development (57–64), Attitude (65–72), and Overall ESD-based TPACK

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(average of all items). Responses used a four-point Likert scale (1 = Very Low, 4 = Very High).

Implementation Procedure

The mentoring program was conducted between October and December 2025 and consisted of six sessions combining online and offline activities: 1. Needs Assessment (October 6) – Initial observation and identification of teachers' challenges. 2. Program Launch & Theoretical Session (October 8) – Opened by Principal Mr. Rozali, S.Pd., M.Si., and Director of Academic Affairs, Prof. Dr. Ida Sriyanti, M.Si.; theoretical input delivered by Dr. Yenny Anwar, M.Pd. 3. Hands-On Module Design Workshop – Teachers collaboratively developed sustainability-integrated science modules. 4. Mentoring & Feedback Sessions – Continuous coaching from university mentors. 5. Module Presentation & Reflection – Peer evaluation and revision based on expert feedback. 6. Post-Test & Program Evaluation – Assessment of growth using the same instrument.

Data Analysis

Descriptive statistics were used to compare the mean pre-test and post-test scores of teachers' competence in designing TPACK-based teaching modules integrated with Education for Sustainable Development (ESD). The analysis included the calculation of mean to describe teachers' competencies before and after the mentoring intervention. The mean differences (Δ) between pretest and posttest scores were calculated for each competency indicator, such as technological knowledge, pedagogical knowledge, content integration, and ESD integration.

RESULT AND DISCUSSION

Opening Session

The activity began with an opening ceremony held in the main hall of SMA Negeri 10 Palembang. The event was attended by the school principal, teachers, and the implementation team. During the opening session, welcoming remarks were delivered by school representatives and the organizing committee as a form of support for the teacher competence enhancement program.

Following the opening session, the activity continued with a pretest to assess participants' initial understanding related to the training topics. This stage served as a baseline

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measurement to identify teachers' prior knowledge and readiness before the mentoring and workshop sessions.

Figure 1. Opening Session

Subsequently, participants attended a material presentation session delivered by the facilitators. The session introduced the fundamental concepts of the TPACK framework (Technological, Pedagogical, and Content Knowledge) and its integration with Education for Sustainable Development (ESD) principles. The materials emphasized the importance of designing lessons that combine content mastery, appropriate pedagogy, and effective use of technology to promote sustainable thinking and problem-solving skills.

Figure 2. Workshop and plenary session

After gaining the theoretical foundation, participants proceeded to develop TPACK–ESD-based teaching modules. Working individually or in small groups, teachers designed

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lesson plans that demonstrated their ability to integrate technology into pedagogical strategies while embedding sustainability values in the subject matter. The developed modules were then presented and discussed in a plenary session. Each presentation was followed by constructive feedback from peers and facilitators, aiming to refine and strengthen the implementation of TPACK–ESD principles in their lesson design.

After the module presentation stage, participants completed a post-test to measure the improvement of their understanding and competencies after the intervention. The program concluded with a reflection session, where participants shared their learning experiences, discussed challenges faced during the module development process, and expressed insights on how to apply TPACK–ESD in their classroom practice.

The results of the activity show a significant improvement in teachers' TPACK competencies after the mentoring and workshop sessions. The comparison between the pretest and post-test scores, as well as the analysis of the TPACK–ESD-based modules developed by participants, indicates a noticeable enhancement in their ability to design lessons that integrate technological tools, pedagogical strategies, and subject content within the framework of sustainable education. The following are the test results before and after providing material and assistance in creating teaching modules based on TPACK-ESD.

The following section presents the results of the activity, including the participants' performance and development in each component of the TPACK framework Technological Knowledge, Pedagogical Knowledge, Content Knowledge, and their intersections before and after the mentoring intervention.

Detailed Analysis of TPACK Competence Development

1. Overview

This section provides a detailed separation and analysis of the assessed aspects of teachers' TPACK abilities Objective, Concept, Pedagogy, Technology, and Evaluation based on their observed or self-reported performance before and after the mentoring intervention. The analysis uses a three-level developmental framework, categorizing results into Pre TPACK, Growing TPACK, and Maturing TPACK.

Table 1. The Catogories of TPACK

Assessed Aspect	Score Range	Criteria Description	Percent (0–100%)	TPACK Development Stage

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Objective, Concept, Pedagogy, Technology, Evaluation	0–2	Existing but not yet appropriate	0–40%	Pre TPACK
Objective, Concept, Pedagogy, Technology, Evaluation	2≤x≤3	Existing and almost entirely appropriate	41–80%	Growing TPACK
Objective, Concept, Pedagogy, Technology, Evaluation	< 3	Existing and fully compliant	81–100%	Maturing TPACK

2. Pre Intervention (Pre Test) Findings

Before the intervention, most participating teachers demonstrated competencies falling within the Pre TPACK and Growing TPACK categories. Specifically:

- Objective: Learning objectives were stated but not explicitly linked to sustainability goals or digital learning integration. Average score: 1.8 (approx. 45–50%).
- Concept: Teachers had a moderate grasp of sustainability related content but lacked contextual application. Average score: 1.9 (approx. 47%).
- Pedagogy: Most instructional designs followed conventional approaches; student centered inquiry and project based learning were rarely incorporated. Average score: 1.7 (approx. 43%).
- Technology: Limited technological integration; use of digital tools was minimal and mostly presentation based. Average score: 1.5 (approx. 38%).
- Evaluation: Assessment focused mainly on cognitive recall rather than higher order competencies related to ESD. Average score: 1.6 (approx. 40%).

Overall, teachers' initial TPACK level was categorized as Growing TPACK (early stage)—concepts existed but were inconsistently applied. This is consistent with findings in similar contexts where teachers' TPACK readiness in low resource settings remains underdeveloped due to limited exposure to digital pedagogy and sustainability frameworks (Hai et al., 2024; Rieckmann, 2022;Nguyen et al., 2024).

3. Post Intervention (Post Test) Findings

After the TPACK–ESD mentoring program, substantial improvement was recorded across all five assessed aspects:

Table 2. Post Intervention (Post Test) Findings

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Aspect	Mean Score (Pre)	Mean Score (Post)	Percent Increase	Development Level (Post)
Objective	1.8	2.6	+44%	Growing → Maturing TPACK
Concept	1.9	2.8	+47%	Growing → Maturing TPACK
Pedagogy	1.7	2.7	+59%	Pre → Maturing TPACK
Technology	1.5	2.4	+60%	Pre → Growing TPACK
Evaluation	1.6	2.9	+56%	Growing → Maturing TPACK

The most significant growth occurred in Pedagogy and Evaluation, reflecting the program's focus on lesson design and assessment for sustainability. Technology showed notable improvement but remained the least mature aspect, aligning with infrastructural limitations identified during the mentoring phase. The Objective and Concept dimensions reached near maturity, as teachers began articulating ESD aligned learning goals and linking them to curriculum standards.

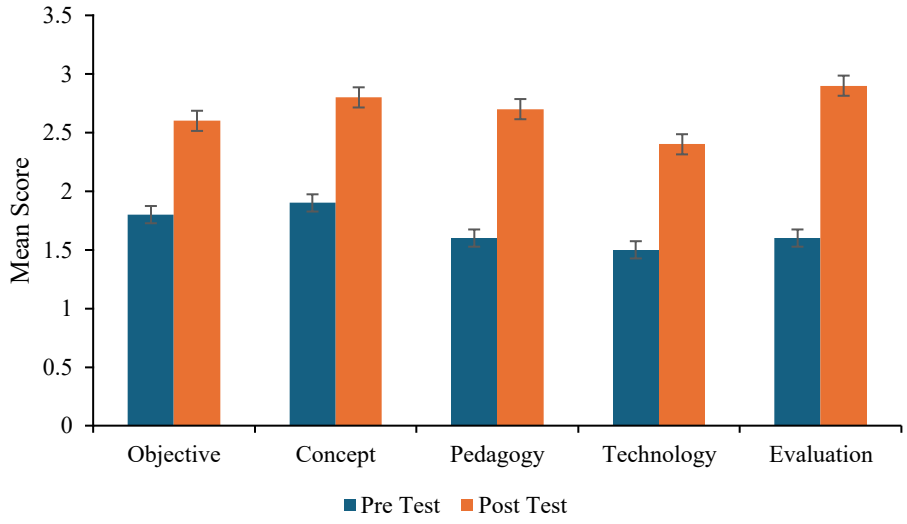

Figure 3. Comparison of Pre-Test and Post-Test Scores Across TPACK Components

Overall, participants transitioned from predominantly Pre TPACK and Growing TPACK levels toward Maturing TPACK. The average composite post test percentage across the five aspects was approximately 82%, indicating functional alignment with TPACK criteria.

Distribution of Developmental Levels (Post Intervention):

• Pre TPACK: 4% of participants

• Growing TPACK: 28% of participants

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• Maturing TPACK: 68% of participants

This distribution suggests a successful capacity building intervention, particularly in pedagogical and evaluative competencies. However, sustained mentoring is required to deepen teachers' technological adaptation and integration of digital innovation tools (Harris et al., 2017).

Integration of TPACK and ESD Results

When combining the results of TPACK ability assessment with the overall TPACK related to Education for Sustainable Development (ESD), the data reveal a coherent pattern of growth and conceptual alignment. The total composite mean of ESD related TPACK increased from 2.02 (pre intervention) to 2.80 (post intervention), corresponding to an overall shift from Growing TPACK toward Maturing TPACK.

Table 3. Comparison of pre- and post-test mean scores across competency indicators.

Indicator	Mean Pre-Test	Mean Post-Test	Δ (Change)
TPCK	1.986	2.00	+0.014
Inquiry	2.015	2.80	+0.785
Professional Practice	1.970	2.07	+0.100
Evaluation & Assessment	2.117	3.06	+0.943
Professional Development	2.024	2.87	+0.846
Attitude	2.060	3.00	+0.940
Overall ESD-based TPACK	**2.021**	**2.80**	**+0.779**

This integration shows that teachers not only improved in the technical and pedagogical components of TPACK but also increasingly contextualized these competencies within sustainability principles. Teachers began explicitly connecting digital tools to sustainability driven lesson goals, selecting technologies that foster critical thinking, environmental awareness, and social responsibility. The post mentoring results indicate that 70% of participants reached the Maturing ESD TPACK stage, while 30% remained in the Growing stage.

Interpreting indicator-level changes

1. Evaluation & Assessment (+0.94)

The most pronounced gain in Evaluation & Assessment suggests participants acquired both conceptual and practical tools for designing authentic, formative and summative assessments that capture sustainability learning outcomes. The increase likely reflects the program emphasis on aligning learning objectives, performance tasks, rubrics, and reflective activities to ESD competencies—practices that teachers can adopt with relatively modest resource needs (e.g., rubric templates, peer assessment routines). Scholarship on authentic

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assessment in higher and school education emphasizes how targeted capacity-building can rapidly improve teachers' assessment practices, especially when coupled with concrete artifacts and exemplars (Vlachopoulos & Makri, 2024).

Practical implication: assessment mastery provides a leverage point—if teachers can assess sustainability competences effectively, they can then iterate curriculum and pedagogy around those assessment tasks, thereby establishing a durable focus on ESD in everyday teaching.

2. Attitude (+0.94) and Professional Development (+0.85)

High gains in Attitude and Professional Development reflect shifts in teachers' motivation, identity, and willingness to engage in continuous learning. Mentoring approaches that combine collaborative problem-solving, peer feedback, and reflective practice commonly foster this kind of affective and professional change ((Aykan & Yıldırım, 2022; Ghamrawi, 2025; Kholid et al., 2023)). The literature on professional learning communities (PLCs) and sustainable teacher professional development corroborates that ongoing collegial support is a strong predictor for sustained practice change and longer-term adoption of new curricula (Meesuk et al., 2021).

Practical implication: strong attitude and PD gains provide the social capital necessary for scaling classroom innovations. Investment in PLCs and follow-up coaching can convert motivation into sustained pedagogical shifts.

3. Inquiry (+0.78)

Improvement in Inquiry indicates that teachers more confidently planned and facilitated student-centered investigations relevant to local sustainability issues. This is important because inquiry-based approaches are central to ESD: they foster critical thinking, evidence use, and action-oriented learning—capacities that students need to address sustainability problems. Teaching inquiry in an ESD context often transfers relatively well in short interventions when teachers are guided to design concrete investigation sequences linked to local contexts (Baptista et al., 2025).

Practical implication: inquiry-based modules can serve as the scaffold for deeper TPACK integration; once teachers have inquiry tasks and assessment aligned, they may more readily adopt supporting technologies and pedagogical strategies (Brianza et al., 2022).

4. TPCK (+0.014 — minimal change)

The minimal change in the TPCK indicator is arguably the most diagnostic result. TPACK is not merely knowledge of technology tools; it is the situated capacity to choose,

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adapt, and orchestrate technological affordances in service of content and pedagogy (Acevedo-Duque et al., 2022; Ning, Y. et al., 2024). Developing TPCK therefore typically requires repeated cycles of design, enactment, reflection, and access to appropriate technologies and infrastructures (Álvarez-Otero et al., 2018; Koehler et al., 2022; Nguyen, 2024). The small increase here likely reflects three interrelated constraints: (a) limited time in the intervention to practice and master technology-rich designs, (b) uneven access to devices and connectivity in the semi-urban partner schools, and (c) the cognitive complexity of integrating TK, PK and CK in novel ESD tasks (Papanikolaou, 2017).

Practical implication: to raise TPCK meaningfully, future literations should allocate more time for iterative design–teach–reflect cycles, provide hands-on technology labs or simulations, and secure minimal hardware or software resources at partner schools (Kim et al., 2024, Krabonja et al., 2024).

Cross-cutting themes and theoretical integration

Situatedness and context

The results underscore the importance of context. TPACK evolves within specific classroom ecologies—teacher beliefs, student profiles, school resources, and local curriculum mandates shape what is feasible (contextual TPACK literature). In this project, regional constraints (limited digital access in Alang-Alang Lebar, varying school resources) moderated technology uptake even when teachers were motivated. This supports the contextual critiques of TPACK that emphasize situated implementation rather than decontextualized tool training (Bibi & Khan, 2017; Otom et al., 2025).

Professional learning design: bridging short term gains and long-term capacity

Short, intensive mentoring often produces immediate gains in aspects that are procedural and conceptual (assessment design, inquiry tasks, attitudes). However, deep integration—especially with technology—needs longitudinal professional learning models such as PLCs, coaching, microteaching cycles, and embedded inquiry projects (Ernst, 2010; Vičič Krabonja et al., 2024). In line with sustainable PD literature, the blend of workshops + mentoring + peer reflection deployed here likely catalyzed observed changes, but sustainability of these changes will depend on continued institutional support (Papanikolaou et al., 2022; Paulauskaite-Taraseviciene et al., 2022; Ali et al., 2023).

Assessment for sustainability as a change agent

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The large gain in assessment competence suggests assessment practices can act as an important lever for ESD integration. When teachers learn to articulate ESD learning outcomes and align assessments with those outcomes, classroom instruction tends to reorient toward student-centered, project-based, and action-oriented tasks. Recent work advocates rethinking assessment for sustainability to emphasize evidence-based, formative, and community-engaged assessments—approaches that were central to the program's activities (Filho et al., 2015; Berglund et al., 2025; Veyis et al., 2025).

Practical recommendations based on results

1. **Extend the mentoring timeline and embed cycles of enactment**: To strengthen TPCK, subsequent programs should include sustained cycles where teachers design modules, teach them in class, receive mentor and peer feedback, revise, and retest. These cycles foster situated TPACK growth.
2. **Invest in minimal technology infrastructure**: A small but reliable pool of devices, connectivity solutions, and teacher training in relevant edtech tools (e.g., data-collection apps, multimedia authoring, low-bandwidth LMS usage) will lower the barrier for TPCK uptake.
3. **Focus on assessment design as an entry point**: Given the large gains in assessment competencies, scale this as an entry pathway: train teachers to craft ESD-aligned rubrics and performance tasks, then build pedagogies and technologies around those tasks.
4. **Institutionalize Professional Learning Communities (PLCs):** Encourage school-based PLCs that meet regularly to discuss module implementation, troubleshoot technology issues, and share student work; PLCs are a durable mechanism for sustaining PD gains.
5. **Leverage local contexts**: Strengthen the link between local sustainability issues and inquiry tasks to increase relevance and student engagement; contextualized ESD tasks also reduce dependence on advanced tech.

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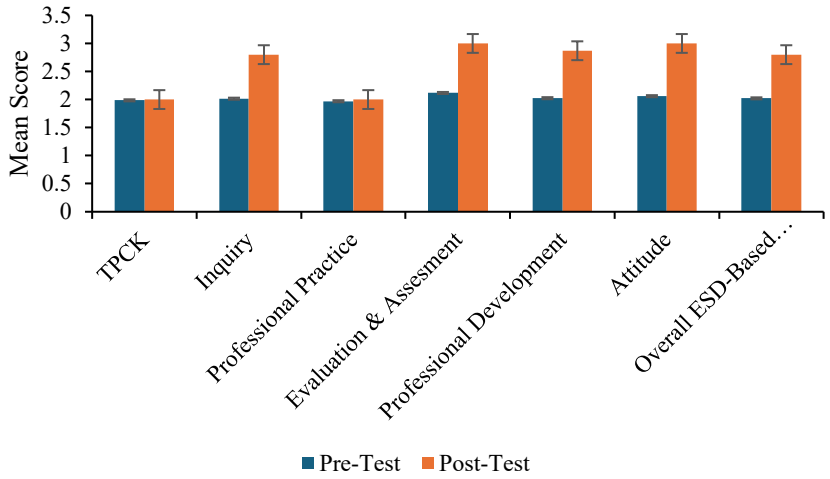

Figure 4. Chart illustrating teachers' competency growth.

The mentoring program demonstrates that targeted, collaborative professional development can produce substantial improvements in teachers' ESD-relevant assessment, inquiry practices, attitudes, and commitment to professional learning. However, integrating technology meaningfully into pedagogical content true TPCK requires more sustained coaching, infrastructural investment, and situated practice. The program's combination of workshops, mentoring, and reflective practice provides an effective model for initiating change; scaling the approach with attention to technological access and longer-term learning cycles will be essential to translate early gains into sustained, systemic transformation. In summary, the synthesis between TPACK and ESD results demonstrates that the mentoring intervention successfully fostered holistic competence bridging technological integration, pedagogical design, and sustainability orientation thereby supporting transformative teaching practices for sustainable development.

Limitations and directions for future research

While the quantitative pre–post comparison demonstrates positive movement, the study has limitations. First, the design lacked a control group, which constrains causal claims. Second, reliance on self-reported measures can introduce social desirability and response biases; future studies should incorporate classroom observation rubrics and student learning outcomes. Third, the post-test was taken immediately after the intervention; longitudinal follow-up (6–12 months) is needed to verify the persistence of gains. Finally, to probe TPCK development more deeply, mixed-methods studies that include detailed design case studies, artifact analysis (teacher modules and student work), and classroom video analysis would be valuable.

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Discussion

The transition toward *Maturing TPACK* mirrors international research on staged TPACK development, which identifies incremental progression through exposure, practice, and reflection (Anwar et al., 2025). Programs integrating collaborative workshops, contextual inquiry, and reflective mentoring like the present initiative are known to accelerate movement from *Pre* to *Growing* stages (Koehler & Mishra, 2005; Mishra & Koehler, 2006; Harris et al., 2009; Harris et al., 2017). Nonetheless, achieving full maturity necessitates longer engagement cycles (Nguyen et al, 2024).

Teachers' improvements in pedagogical and evaluative aspects echo findings by (Fischer et al., 2022) and (Baptista et al., 2025), emphasizing that sustainability-oriented pedagogy and authentic assessment can drive meaningful shifts in teacher cognition and classroom culture. The relatively slower advancement in technological integration parallels evidence from Krabonja et al. (2024), which shows that institutional constraints connectivity, device access, and technical confidence are critical bottlenecks in achieving comprehensive TPACK. The results revealed a consistent improvement across all indicators, with the overall mean increasing from 2.02 to 2.80. This indicates a transition from a 'moderate' to 'high' competency level, suggesting that the mentoring intervention was effective in enhancing teachers' TPACK-ESD integration skills.

Significant growth in *Evaluation & Assessment* (+0.94) and *Inquiry* (+0.78) reflects teachers' enhanced ability to facilitate student-centered learning and design authentic assessments aligned with sustainability goals. Setyowati & Rahmajanti (2023) and Kranboja et al. (2024) argued that inquiry and assessment are core drivers of transformative ESD pedagogy, as they empower learners to critically engage with real-world sustainability challenges. The increase in *Professional Development* (+0.85) and *Attitude* (+0.94) indicates greater teacher motivation and reflective engagement in sustainability discourse. This aligns with Veyis et al. (2025), who highlighted that professional learning communities (PLCs) and collaborative reflection foster teachers' identity as agents of educational change.

Despite the overall improvement, the minimal change in the TPCK indicator (+0.014) suggests that technological integration remains a major challenge. Research by Fabian et al. (2024) and the meta-analysis by *Computers & Education* emphasized that TPACK development requires contextualized practice, resource access, and systemic support from educational institutions.

Implications for Educational Practice

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1. **Institutional Support:** Schools should provide technology access and continuous professional learning infrastructure.
2. **Sustained Mentorship:** Ongoing TPACK-ESD mentoring is crucial to translate conceptual understanding into classroom practice.
3. **Collaborative Networks:** Establishing teacher communities of practice enhances peer learning and sustainability innovation.

The intervention effectively advanced participating teachers from early conceptual understanding to practical competence in ESD-aligned module design. Future programs should combine digital resource provision, ongoing coaching, and classroom-based inquiry to reinforce teachers' journey toward *Maturing TPACK* in all five domains.

CONCLUSION AND RECOMMENDATION

The implementation of the TPACK–ESD mentoring program at SMA Negeri 10 Palembang has proven effective in enhancing teachers' competence in designing and implementing learning modules that integrate technological, pedagogical, and content knowledge with sustainability principles. The quantitative and qualitative findings consistently indicate significant improvements in assessment literacy, inquiry-based pedagogy, and professional development motivation. Teachers have shown the ability to design contextual learning objectives aligned with ESD, apply inquiry-based strategies, and use authentic assessment tools that reflect sustainability competencies. The developmental analysis further demonstrates that most participants advanced from *Pre* and *Growing TPACK* stages to *Maturing TPACK* levels, particularly in pedagogical and evaluative domains. While progress in technological integration was evident, infrastructural and digital literacy limitations remained barriers to full technological mastery. These results reaffirm that teacher capacity building for ESD must be iterative, context-sensitive, and supported by continuous access to digital tools and peer learning communities. To sustain these achievements, future programs should prioritize long-term mentoring cycles, institutional collaboration, and professional learning communities (PLCs) to embed TPACK–ESD practices into daily teaching culture. Moreover, incorporating follow-up evaluations, classroom observations, and student learning outcomes would strengthen evidence of long-term pedagogical transformation. Overall, this initiative contributes to the national agenda of improving educational quality and sustainability literacy, supporting Universitas Sriwijaya's mission to foster impactful community engagement through research-based teacher

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