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EDUCATION FOR SUSTAINABLE DEVELOPMENT BASED ON TECHNOLOGICAL PEDAGOGICAL CONTENT KNOWLEDGE IN BIOLOGY EDUCATION: ASSESSING TEACHERS' READINESS

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ABSTRACT

Teachers' readiness to integrate Education for Sustainable Development (ESD) plays a pivotal role in preparing students to understand and practice sustainable living. This study examined the readiness of 232 in-service biology teachers in South Sumatra, comprising 142 novice teachers (with ≤10 years of experience) and 90 experienced teachers (with>10 years of experience). A descriptive-comparative quantitative design was employed, using two structured questionnaires to measure teachers' perspectives on ESD and their Technological Pedagogical Content Knowledge (TPACK). Findings revealed that teachers generally showed a strong commitment to ESD but only a moderate conceptual understanding. Within TPACK, attitudes were rated the highest, whereas technological and inquiry-based competencies were rated the lowest. Novice teachers scored higher than experienced teachers, while participation in environmental education training or prior teaching experience in related topics improved readiness. This study highlights the importance of continuous professional development in enhancing teachers' technological and inquiry-oriented capacities. Strengthening these dimensions is crucial for effectively embedding ESD into biology teaching and science education more broadly. By addressing these gaps, the integration of ESD can move beyond awareness toward transformative learning that equips students with the skills and dispositions needed for sustainable futures.

Keywords: biology teacher; ESD; environmental education; TPACK; SDG

INTRODUCTION

In recent times, sustainable development has emerged as a crucial issue in preparing the global community to face the challenges arising from global environmental changes. In 2015, all United Nations Member States adopted 17 Sustainable Development Goals (SDGs) aimed at making the world a better place by 2030 (Biermann et al., 2022). Indonesia continues to face environmental, social, and economic issues that impact environmental degradation. High poverty rates and low education levels are significant factors affecting the environment. The education sector has not entirely focused on practical approaches to support sustainable development.

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Students are not contributing to the mitigation of environmental problems (Kolvoord, 2021; Suwarto et al., 2021; Widodo et al., 2023).

Education is a key driver in achieving the Sustainable Development Goals (SDGs), particularly SDG 4, which aims to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all." To realize this, Education for Sustainable Development (ESD) has emerged as a strategic approach that equips learners with the knowledge, skills, values, and attitudes necessary to contribute to a sustainable future (Shulla et al., 2020). ESD is not merely about transferring environmental knowledge; it also emphasizes critical thinking, interdisciplinary learning, and problem-solving, all of which are integral to the overarching vision of the SDGs (UNESCO, 2017; Sund & Gericke, 2020).

ESD has been recognized as a promising educational innovation. It can be integrated into curricula across all levels of education, from primary and secondary schools to higher education (Hariyono et al., 2018; UNESCO, 2020). Recent developments in national policy and school practices, such as the Merdeka Belajar Kampus Merdeka (MBKM) program, Adiwiyata schools, and the use of localized digital applications like BioD, demonstrate how sustainability values are being effectively embedded into the learning environment (Fatimah et al., 2025; Nursafira Sunarya & Rahwa Suwarma, 2024; Suwarto et al., 2021). These innovations reflect ESD's transformative potential to raise students' awareness of sustainability and shape future-ready citizens.

However, despite the growing urgency of sustainability issues and the expansion of ESD initiatives, multiple studies have found that both in-service and pre-service teachers still face challenges in integrating ESD effectively into classroom practice (Durdu & Dag, 2017; Bourn & Soysal, 2021; Vilmala et al., 2022; Albion et al., 2025; Vidal & Kuckuck, 2025). This is especially true in technology integration, a core aspect of the Technological Pedagogical Content Knowledge (TPACK) framework. TPACK offers a comprehensive model for designing instruction that combines content mastery, pedagogical strategy, and digital competence, enabling teachers to deliver meaningful and sustainability-oriented learning experiences.

Most science subjects, particularly biology, align with the SDGs, including topics such as human organ systems (digestive, circulatory, respiratory systems), viruses related to health improvement themes, reproductive systems linked to gender equality themes, biotechnology associated with sustainable lifestyle themes, and materials on biodiversity and ecological interactions connected to biodiversity themes. Furthermore, topics related to environmental change closely align with climate change education themes. However, the implementation percentage of ESD in science learning by teachers remains only 25%, partly due to limited understanding of ESD and the SDGs among teachers and a lack of knowledge on how to implement it in their teaching (Purnamasari & Hanifah, 2021; Ariska et al., 2024; Anwar et al., 2024, 2025). A preliminary study involving 78 physics teachers in South Sumatra revealed that while most teachers were aware of sustainability issues, only 32% had ever attempted to incorporate sustainability topics into their lessons. Furthermore, fewer than 25% were familiar with the concept of ESD or had received any form of training related to the integration of SDGs in education. This underlines a critical need for further investigation into their readiness and capacity.

Integrating SDG principles into subject matter requires teachers to have a deep understanding of the subject content and the SDGs, relevant aspects of sustainability related to the material, and effective teaching strategies (Pegalajar-Palomino et al., 2021). Integrating the Sustainable Development Goals into school curricula is a core mandate of Education for Sustainable Development. However, effective integration requires more than just awareness of global goals; it demands that teachers possess a deep understanding of subject-specific content, contextual sustainability issues, and appropriate pedagogical approaches. Teachers must be able to connect disciplinary knowledge with relevant sustainability concepts while designing learning environments that foster critical thinking and global citizenship (Fiel'ardh et al., 2023; Guo et al., 2024). Without sufficient training and support, many educators face challenges in linking abstract SDG targets with concrete classroom practices (Schina et al., 2020). In this regard, the Technological Pedagogical Content Knowledge (TPACK) framework provides a comprehensive model for supporting teachers in designing and delivering instruction that integrates technology with content and pedagogy (Mishra & Koehler, 2006a). Within the context of ESD, teachers with strong TPACK abilities are better positioned to create learning experiences that incorporate sustainability values such as environmental responsibility, social justice, and sustainable economic practices using innovative digital tools (Huang et al., 2024; Huang et al., 2025; Veyis & Ciğerci, 2025). The Technological Pedagogical Content Knowledge (TPACK) framework is crucial for teachers in teaching ESD. TPACK defines the knowledge teachers need to effectively integrate technology in teaching, not merely using tools but also a deep understanding of how technology can enhance the delivery of content and pedagogy that aligns with learning objectives (Mishra & Koehler, 2006a; Koehler & Mishra, 2009). In the context of ESD, teachers with strong TPACK abilities can design learning experiences that explicitly incorporate sustainability values, such as environmental awareness, social justice, and sustainable economic practices, using appropriate and innovative technologies.

A preliminary study involving biology teachers and physics teachers found that less than one-third had ever taught EE or received sustainability-related training. However, those who had such experiences demonstrated greater confidence and competence in planning instruction aligned with ESD values. These findings highlight the need for a more in-depth investigation into the factors that influence teachers' TPACK-based ESD competence (Eliyawati et al., 2023; Anwar et al., 2024; Ariska et al., 2024).

TPACK-based learning has been widely studied and applied in biology education. However, there has been limited focus on supporting ESD implementation specifically. Enhancing teachers' readiness to implement ESD must also be integrated into teacher education programs to ensure that future educators are adequately prepared to apply SDGs principles in their teaching. Therefore, evaluating the preparedness of biology teachers and current teachers in implementing TPACK-based ESD is necessary, with the evaluation results expected to inform the development of programs that equip and enhance teachers' capabilities in implementing TPACK-based ESD effectively to achieve the SDGs. Therefore, this study aims to assess the readiness of biology teachers to implement ESD using the TPACK framework. By aligning the research with the objectives of the SDGs, this study contributes to the global effort of enhancing education's role in sustainable development, while also offering empirical insights that can guide teacher training and curriculum design in biology education.

METHODS

This study employed a descriptive-comparative quantitative approach using a sequential explanatory mixed-methods design, adapted from (Creswell & Plano Clark, 2018) The purpose of this design was to compare patterns of teachers' readiness in integrating Education for Sustainable Development (ESD) based on their experience, participation in training, and exposure to environmental teaching, while also explaining the quantitative trends through qualitative follow-up.

The participants of this study consisted of 232 in-service biology teachers from various secondary schools in South Sumatra, Indonesia. The teachers were categorized based on their years of teaching experience: 1) Novice teachers: Those with ten years of teaching experience or less (n = 142). 2) Experienced teachers: Those with more than ten years of teaching experience (n = 90)

This grouping was intended to analyze differences in TPACK-based ESD competence as influenced by the duration of teaching experience. The participants also varied in their prior exposure to Environmental Education (EE), such as attending EE-related training programs and teaching EE content in class. All participants completed the same TPACK–ESD questionnaire, and follow-up interviews were conducted for a subset of teachers to deepen the interpretation of the quantitative findings.

Quantitative data were collected through a structured Likert-scale questionnaire (4-point scale), developed based on the TPACK framework (Mishra & Koehler, 2006b) and ESD indicators from UNESCO (2017). The questionnaire included seven dimensions: TPACK-based ESD, General TPACK, Inquiry, Professional Practice, Evaluation and Assessment, Professional Development, and Attitude toward ESD.

The instrument was validated through expert review and pilot testing, as developed by Eliyawati et al. (2023). Reliability analysis indicated that all dimensions had acceptable internal consistency, with Cronbach's Alpha values ranging from 0.97 to 0.99. For the qualitative phase, a semi-structured interview guide was constructed using items adapted from the CoRe and TPaPeRs frameworks (Loughran et al., 2012) to explore teacher readiness in integrating ESD in biology instruction. Two primary instruments were developed and validated to capture participants' competencies and perspectives regarding ESD. Instrument 1 measured biology teachers' perspectives on ESD learning, including three main dimensions: Knowledge and Understanding, Beliefs and Attitudes, and Commitment to Learning. The complete indicators are presented in Table 1.

Table 1. Indicators of Biology Teachers' Perspectives on ESD Learning

Indicator	Observed Action
Knowledge and Understanding	Understand and recognize the fundamental concepts of ESD and their relationship to sustainability issues in the context of education. Demonstrate familiarity with ESD principles and how they can be integrated into the learning curriculum, particularly in science subjects. Demonstrate the ability to apply ESD in the learning process, including designing activities that are relevant to sustainability issues and providing meaningful learning experiences for students.
Beliefs and Attitudes	Believe that the application of ESD principles can improve the relevance and quality of learning by helping students understand their role in facing global sustainability challenges. Demonstrate an understanding that teachers have a crucial role in driving positive change through sustainability-based education, both at the individual and community levels.
Commitment to Learning	Demonstrate a high commitment to understanding the concepts and principles of ESD-based learning as part of efforts to improve the quality of education. Need more support and opportunities in teacher education programs to gain an in-depth understanding and practical skills in implementing ESD.

Instrument 2 assessed teachers' TPACK-based competencies in implementing ESD. This instrument included the following dimensions: TPACK, Inquiry, Professional Practice, Evaluation and Assessment, Professional Development, and Attitude. The complete set of observed actions is displayed in Table 2.

Table 2. Indicators of Biology Teachers' TPACK abilities in Implementing ESD

Indicator	Observed Action
TPACK	Understand and develop ESD content for application in the science curriculum. From planning to application, considering the level of students' abilities and competencies in sustainability, as well as the type of assessment to evaluate an ESD-enriched science lesson. Identify, modify, and integrate appropriate technology to teach ESD-enriched science lessons.
Inquiry	Ask questions, stimulate them to make hypotheses about sustainability issues, and engage students to solve them by conducting scientific investigations. Plan and conduct scientific investigations, and use engineering practices to support scientific investigations in solving ESD. Develop students' scientific thinking and problem-solving competence for lifelong learning. Synthesize a scientific explanation by using evidence and data on science experiments for sustainability, and report scientific investigations in solving ESD problems after conducting science experiments.
Professional Practice	Encourage and practice students to take responsibility for developing and maintaining effective solutions to ESD problems in science learning. Cultivate students' critical awareness about the social changes that arise from the integration of ESD.
Evaluation and Assessment	Develop assessments appropriate for science lessons by embedding ESD Monitor students' understanding of ESD-enriched science lessons through different types of assessments, use formative and summative assessments to evaluate students' prior knowledge and progress in science learning, and its implications on sustainability Analyze and evaluate the results of the ESD-enriched science learning assessment to inform planning for the next lesson.

Professional development	Participate in professional development opportunities to deepen and expand knowledge of science content and ESD practices, collaborate, and communicate effectively with peers and stakeholders to improve the quality of ESD-based science learning. Collect student feedback on ESD-enriched science teaching and learning to improve and follow up on future lessons for continuous improvement in the integration of ESD in science learning.
Attitude	Respond to social, economic, and environmental changes by being involved in communities and society in realizing ESD-based science learning. Have tolerance for students and science learning, and consistently demonstrate a positive attitude and lifestyle. Foster good cooperation with students and the community across cultures, and maintain high expectations by promoting work discipline to achieve personal and family well-being.

Quantitative data were analyzed using descriptive statistics, including means, percentages, and comparative descriptions. This approach was chosen to profile teachers' readiness and highlight meaningful patterns across groups. Inferential statistics such as t-tests or ANOVA were not applied, as the study's primary aim was to map readiness levels rather than to test hypotheses of statistical difference. Descriptive comparisons were therefore considered more suitable for capturing trends in TPACK-based ESD competence.

The qualitative interview data were analyzed using thematic analysis (Braun & Clarke, 2006) to gain a deeper insight into the teaching strategies, beliefs, and challenges that teachers faced in implementing ESD. This mixed-methods approach enriched the interpretation of the results and provided contextual explanations for the observed quantitative patterns.

Teacher readiness to implement Education for Sustainable Development (ESD) was assessed from two perspectives: (1) teachers' views and attitudes toward ESD, and (2) their TPACK (Technological Pedagogical Content Knowledge) for teaching ESD. Data on teachers' perspectives were collected through a questionnaire instrument with indicators outlined in Table 1, while their TPACK in teaching ESD was assessed using a second questionnaire detailed in Table 2. The data were analyzed quantitatively and classified into four categories: very good, moderate, poor, or very poor, based on pre-established score ranges. This classification enabled researchers to describe teacher readiness more holistically. In the qualitative descriptive section, the researcher evaluates the interview results with several teachers in relation to the findings of the previous quantitative analysis.

RESULTS AND DISCUSSION

The study examined teachers' participation in Environmental Education (EE) training and teaching experiences to understand their exposure to and engagement with Environmental Education. The following figure illustrates the percentage of teachers who have attended EE training and who have experience teaching EE content. Figure 1 presents the distribution of respondents based on their attendance in EE-related training, while Figure 2 illustrates the percentage of respondents who have experience teaching EE content. The data in Figures 1 and 2 were obtained from a total of 232 respondents. In Figure 1, 55% of those who had attended EE training were novice teachers (with ≤10 years of experience), while 45% were experienced teachers (with>10 years of experience). Figure 2 shows that 52.9% of the participants with experience teaching EE were novice teachers, while 47.1% were experienced teachers.

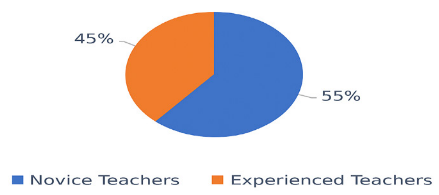

Figure 1. Teachers Who Have Attended Environmental Education Training

Figure 1 presents a pie chart illustrating the proportion of science teachers who have participated in Environmental Education (EE) training. It shows that 55% of the teachers are categorized as novice teachers, while 45% are experienced teachers. Figure 2 reveals that novice teachers also slightly dominate in terms of practical experience teaching EE. This reinforces the idea that novice teachers may be more aligned with contemporary educational priorities, such as integrating sustainability into the science curriculum.

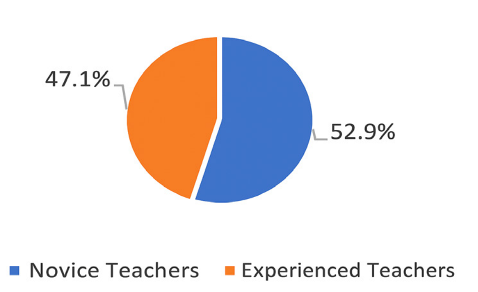

Figure 2. Teachers Who Have Taught Environmental Education

Figure 2 shows that teachers who have attended environmental education training are mostly novice teachers, comprising 55% of the total. Likewise, the percentage of teachers who have taught environmental education shows that most of these teachers are novice teachers, at 52.9%.

These findings suggest that participation in training and teaching practice related to EE is more common among teachers with fewer years of experience. This suggests that novice teachers and experienced teachers are more likely to be exposed to current sustainability-oriented training and are more willing to integrate EE into their teaching practices. It also reinforces the conclusion that teaching experience alone does not determine a teacher's readiness to implement Education for Sustainable Development (ESD). Rather, exposure to training and opportunities to teach EE play a more significant role, especially in supporting the integration of ESD through the TPACK framework.

The first set of data describes teachers' perspectives on Education for Sustainable Development (ESD), collected using a questionnaire covering three indicators: knowledge and understanding, beliefs and attitudes, and commitment to learning. The results are shown in Table 3.

Table 3. Questionnaire Analysis of Teachers' Perspectives on ESD Learning

Perspectives on ESD Learning	Average
Knowledge and Understanding	2.99
Beliefs and Attitudes	3.01
Commitment to Learning	3.33
Total	3.11

The data indicate that teachers generally have a positive perspective on ESD, with the highest score in commitment to learning (3.33), followed by beliefs and attitudes (3.01). This shows that most teachers are willing and motivated to support sustainability-focused learning, although their conceptual understanding remains at a moderate level. This indicates that biology teachers have a strong commitment to enhancing their knowledge and skills related to ESD as preparation for implementing ESD in their future teaching. They also feel a need for more opportunities to gain a deeper understanding and practical skills related to ESD-based learning within teacher education programs. This commitment serves as a vital foundation for creating educators who can effectively integrate sustainability principles into the learning process, thereby supporting the achievement of more sustainable educational goals in the future. To facilitate the development of ESD competencies in teacher education, changes in the content and structure of teacher education programs are necessary (UNESCO, 2017). Leicht (2018) suggests that university curricula should include content related to poverty, climate change, the environment, and other issues, aiming to prepare future teachers to understand the world in which they will work and address the challenges it presents.

The indicator of Knowledge and Understanding received the lowest score of 2.99, indicating that teacher still have limitations in their deep understanding of the concepts and principles of Education for Sustainable Development (ESD). This aligns with Erlina (2021), who shows that the percentage of ESD understanding among science teachers is 78.9%. This suggests that although these future teachers have a high commitment to learning, there is still a need for stronger material and insights on sustainability issues and how to integrate them into the learning process. This deficiency may pose a barrier for students in designing and implementing ESD-based learning effectively. Therefore, further efforts are needed in teacher education programs to enhance this aspect of knowledge and understanding. This is in line with the report "Progress in ESD and Education for Global Citizenship" (UNESCO, 2020), which highlights the need to improve teacher education to build sustainable communities.

The second analysis focused on assessing the TPACK abilities of biology teachers in implementing ESD, using a six-dimensional instrument. The average scores are presented in Table 4.

Table 4. Questionnaire Analysis of Biology Teachers' TPACK abilities in Implementing ESD

TPACK-Based ESD	Average
Technological Pedagogical Content Knowledge	2.77
Inquiry	2.77
Professional Practice	2.85
Evaluation And Assessment	2.83
Professional Development	2.87
Attitude	3.16
Total	2.84

Among the six dimensions, the Attitude dimension scored the highest (3.16), indicating that teachers are generally open to implementing ESD. However, the lowest scores were found in TPACK knowledge and inquiry-based instruction (both 2.77), suggesting that teachers may lack the instructional and technological strategies to deliver ESD effectively. It indicates that biology teachers have a very positive attitude toward ESD. Teachers with a positive attitude toward ESD tend to be more sensitive to sustainability issues and more enthusiastic about integrating them into their teaching. On the other hand, TPACK and Inquiry received the lowest score of 2.77 (Tables 5 and 6). This indicates that, despite having a very positive attitude, teachers still face challenges in developing the skills necessary to integrate technology, pedagogy, and ESD content effectively. Additionally, teachers struggle to apply inquiry-based learning approaches in the context of ESD, which requires the ability to design learning activities that encourage exploration and problem-solving.

Table 5. Technological Pedagogical Content Knowledge of Teachers

Technological Pedagogical Content Knowledge	Average
Understand the ESD content in the science curriculum.	2.84
Understand science concepts and their application to sustainability.	2.81
Apply science concepts to solve problems in the sustainability domain.	2.78
Develop ESD-enriched science materials by considering the science curriculum.	2.76
Explain science knowledge systematically and its implications on ESD by considering the level of students' abilities and competencies.	2.76
Demonstrate a critical understanding of ESD developments in the science curriculum.	2.68
Demonstrate science knowledge to creatively and innovatively process ESD content.	2.67
Set learning objectives for science education that focus on sustainability.	2.84
Plan a relevant teaching strategy for science learning and its implications on sustainability.	2.76
Plan an ESD-enriched science lesson by considering the level of students' abilities and competencies.	2.76
Plan well-structured activities that explore science concepts and their applications in sustainability.	2.84
Align the learning objectives and assessment type to evaluate the ESD-enriched science lesson.	2.80
Identify appropriate technology to teach an ESD-enriched science lesson.	2.75
Integrate specific technologies into ESD-enriched science learning to support students' conceptual understanding.	2.75
Modify technology to improve ESD-enriched science lessons.	2.63
Understand students' backgrounds and characteristics to teach meaningful science lessons in the context of ESD.	2.76
Modify science lessons for sustainability when faced with unexpected conditions.	2.80

From Table 5, several TPACK abilities still need to be addressed: 1) Modify technology to improve ESD-enriched science lessons (2.63). The low score suggests that educators may struggle to identify and select suitable technology for teaching ESD. This competency is crucial because the right technology can provide a more meaningful learning experience related to sustainability issues. 2) Demonstrate science knowledge to creatively and innovatively process ESD content (2.67). This suggests that teachers' creativity and innovation in creating learning content related to sustainability still need to be enhanced to make ESD teaching engaging and relevant. 3) Demonstrate a critical understanding of ESD developments in the science curriculum (2.68). This indicates a need to enhance understanding of ESD developments in response to evolving global environmental and social issues. This competency is important for ensuring that ESD learning remains relevant and up-to-date.

Table 6. Inquiry Competencies

Inquiry Competencies	Average
Ask questions about sustainability issues and engage students in solving them through scientific investigations.	2.77
Stimulates making hypotheses based on scientific questions in ESD-enriched science learning	2.79
Plan and conduct scientific investigations to solve ESD problems	2.75
Use engineering practices to support scientific investigations in solving ESD problems	2.73
Develop students' scientific thinking and problem-solving competence for lifelong learning.	2.76
Synthesize a scientific explanation using evidence and data from a science experiment related to sustainability.	2.74
Generate class discussions to conclude the analysis of scientific investigations related to ESD in science learning.	2.83
Report scientific investigations in solving ESD problems after conducting scientific experiments.	2.80

From Table 6, several Inquiry competencies still need attention: 1) Use engineering practices to support scientific investigations in solving ESD problems (2.73). This indicates that teachers may struggle to guide students in conducting scientific investigations and using engineering practices to address sustainability issues. This skill is crucial for ensuring that students can effectively identify, analyze, and address environmental and social challenges in sustainability education. 2) Synthesize a scientific explanation by using evidence and data from science experiments for sustainability (2.74). This suggests a lack of ability among teachers to guide students in describing scientific explanations using data from science experiments related to sustainability contexts. 3) Plan and conduct scientific investigations to solve ESD problems (2.75). This indicates that teachers' ability to facilitate students in planning and conducting scientific investigations to address sustainability issues still requires improvement. These skills are crucial in applying inquiry-based learning approaches in the context of ESD.

To examine the influence of teaching experience on teachers' readiness to implement ESD, this study compared TPACK-based ESD competencies between novice and experienced teachers. Figure 2 illustrates the average scores in seven components of TPACK-based ESD instruction: TPACK, Inquiry, Professional Practice, Evaluation and Assessment, Professional Development, and Attitude. The blue bars represent novice teachers (with ≤10 years of experience), and the red bars represent experienced teachers (with >10 years of experience).

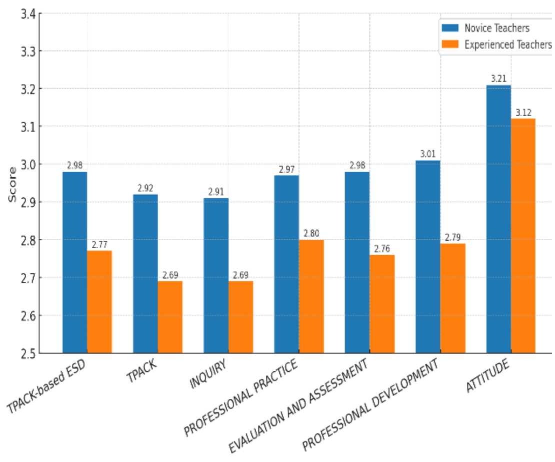

Figure 3. Comparison of TPACK Scores Based on Teachers' Years of Experience

Figure 3 shows that novice teachers consistently outperformed experienced teachers across all categories. The most noticeable differences appear in the areas of Inquiry (2.91 vs. 2.69), Evaluation (2.98 vs. 2.76), and Professional Development (3.01 vs. 2.79). Even in the Attitude component, novice teachers scored slightly higher (3.21) than experienced teachers (3.12).

These findings suggest that years of experience do not necessarily correlate with higher ESD teaching competence. On the contrary, novice teachers appear to be more prepared, likely due to their exposure to updated curricula and recent professional development programs that emphasize sustainability and technological integration. This highlights the need for continuous professional training, especially for more experienced teachers, to keep pace with evolving educational paradigms such as TPACK and ESD. This aligns with the research by Anwar et al. (2024), which indicates that longer teaching experience does not correlate with an increase in TPACK abilities. This could be attributed to various factors, including the busy schedules of experienced teachers, which prevent them from taking the time to learn new things, particularly advancements in technology that support the teaching process in the classroom.

Additionally, experienced teachers tend to be more resistant to change and feel more comfortable with traditional teaching methods, which can lead to a lack of motivation to adopt technology-based approaches. Anwar et al. (2024) and Bhaskar and Gupta (2021) state that resistance to change is one of the barriers to the utilization of information and communication technology in education. TPACK is closely related to teachers' beliefs about technology and their pedagogical beliefs. Understanding teachers' pedagogical reasoning can help reveal how they make decisions regarding technology integration (Fahadi & Khan, 2022; Khan & Gul, 2022; Nilsson, 2022; Tseng et al., 2022). As a result, the TPACK abilities of experienced teachers are challenging to develop, which impacts their ability to teach ESD effectively.

To evaluate the impact of Environmental Education (EE) training on teacher competence, the study compared the average scores across six key dimensions of TPACK-based ESD instruction between teachers who had attended EE training and those who had not.

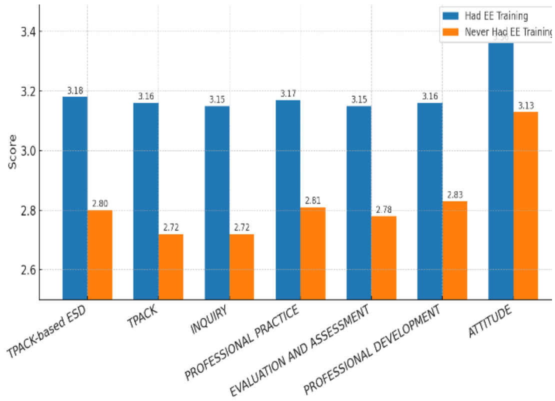

Figure 4. Comparison of TPACK Scores Based on Environmental Education Training

From Figure 4, it is evident that teachers who received EE training consistently outperformed those who did not across all categories. The most significant gap was observed in the domains of Inquiry (3.15 vs. 2.72) and Attitude (3.36 vs. 3.13). These results emphasize the positive impact of EE training on strengthening both pedagogical and attitudinal readiness to integrate ESD, underscoring the need for targeted professional development programs to support sustainable education. Environmental education is crucial in schools at all levels, from preschool to university (Tran, 2024; Kim et al., 2025). This highlights that training related to EE has a positive impact on teachers' TPACK abilities for implementing Education for Sustainable Development (ESD). EE, being fundamental to ESD, has long been taught in relation to environmental sustainability.

It is important to note that ESD has gained more momentum following the decade of ESD proposed by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) (Acosta Castellanos & Queiruga-Dios, 2022; Sandri & Holdsworth, 2022). In its part, EE has a deeper historical root in several regions of the planet. The one key factor influencing teachers' TPACK skills is the provision of training and professional development (Joshi, 2023; Çam & Koç, 2024; Amemasor et al., 2025). Teacher training in Environmental Education (EE) helps teachers enhance their teaching practices, transform their pedagogy, and influence how they organize classroom content, leading to actions that facilitate other teachers' understanding of EE (Rundgren & Yamada, 2023).

Most teachers who have participated in training are novice teachers. Novice teachers tend to have a strong desire to learn and grow. They view training as an opportunity to enhance their competence and teaching quality. In contrast, experienced teachers often feel they already possess sufficient experience and knowledge, which leads them to see less of a need for further training. This discrepancy contributes to the lower TPACK-based ESD teaching capabilities among experienced teachers compared to their novice counterparts.

Teachers who had attended EE-focused training demonstrated significantly stronger competence in all dimensions, especially in integrating sustainability into content delivery and digital tools. These findings confirm what Amemasor et al. (2025) highlighted: continuous and targeted professional development plays a pivotal role in shaping teachers' pedagogical transformation. Similarly, Çam and Koç (2024) assert that structured training fosters reflective teaching practices essential for sustainable instruction.

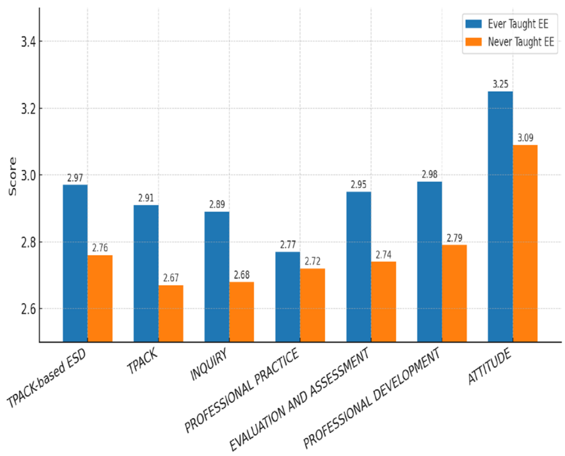

Figure 5. Comparison of TPACK Scores Based on Experience Teaching Environmental Studies

Teaching experience alone may not fully reflect a teacher's readiness to implement ESD. Therefore, to better understand the role of practical teaching experience in Environmental Education (EE), this figure compares the TPACK-based ESD competencies of teachers who have taught EE with those who have not.

The data in Figure 5 show that teachers with EE teaching experience demonstrate stronger competence in all measured aspects of TPACK-based ESD, including Pedagogical Knowledge, Inquiry, and especially Attitude (3.25 vs. 3.09). Teachers who had taught EE scored higher than their counterparts with no such experience. This aligns with Valderrama et al. (024), who found that teaching environmental topics enhances ecological reasoning and critical reflection among science teachers. Morales-Aguilar et al. (2025) also argue that teachers with EE teaching backgrounds are better equipped to connect the environmental, social, and economic pillars of sustainability. Husin et al. (2025) further emphasize that such an experience not only strengthens knowledge but also fosters the internalization of sustainability values. These results suggest that hands-on experience in teaching sustainability-related content enhances teachers' ability to integrate ESD effectively, reinforcing the need to provide authentic teaching opportunities in EE as part of professional development and initial teacher education.

Teaching environmental studies provides teachers with a strong foundation for delivering ESD. Teachers who have taught EE tend to have a better understanding of environmental sustainability, which is one of the main pillars of sustainability (Valderrama et al., 2024; Choudhury, 2025; Husin et al., 2025; Morales-Aguilar et al., 2025). This understanding prepares them to integrate sustainability concepts into their teaching. They are skilled at designing active learning experiences and connecting teaching materials to real-life situations. Most teachers who have taught Environmental Education are relatively novice; this may be due to the teacher education curriculum increasingly emphasizing environmental and sustainability aspects over time, equipping graduates of new teacher education programs with more relevant knowledge and skills in environmental studies. This is also one factor that contributes to the lower ability of experienced teachers to teach ESD based on TPACK compared to novice teachers. Similar patterns have been observed in comparative studies of pre-service teachers in Indonesia and Malaysia, where modest differences in TPACK and ESD understanding were noted, highlighting the influence of teacher education programs on readiness for sustainability integration (Dewi & Listiaji, 2024).

Teacher readiness for ESD cannot rely solely on experience or motivation, but must be supported by access to high-quality, contextualized professional learning opportunities. This includes exposure to EE content, engagement with inquiry-based pedagogy, and the ability to integrate technology effectively in ways that promote sustainability thinking.

These findings contribute to biology education in Indonesia by identifying areas where teachers require stronger technological and inquiry-based competencies, providing input for curriculum development and teacher professional training. However, the study is limited by its geographic scope (South Sumatra), reliance on self-reported data, and the absence of inferential statistical analysis. These limitations suggest that future research should expand to other regions, combine self-reports with classroom observations, and apply inferential methods to strengthen generalizability.

CONCLUSION

This study reveals that biology teachers' readiness to implement Education for Sustainable Development (ESD) is shaped more by training and environmental teaching experience than by teaching tenure. Although teachers expressed strong commitment and positive attitudes, gaps persist in their conceptual understanding and technological and inquiry-based competencies. The stronger performance of novice teachers highlights the value of recent exposure to ESD-oriented pedagogy. These findings contribute to biology education in Indonesia by pinpointing areas that require targeted support to strengthen teacher capacity for transformative ESD integration. Practical recommendations include embedding ESD–TPACK into pre-service teacher education curricula, prioritizing sustainability-focused pedagogy and digital strategies in professional development workshops, and offering tailored in-service training for experienced teachers. By adopting these measures, teacher readiness can be enhanced, enabling biology and science education to prepare students more effectively with the knowledge, skills, and dispositions needed for sustainable futures.

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