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Education for Sustainable Development Based of Technological Pedagogical and Content Knowledge using Mixed-Methods Approach in Physics Teaching

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Abstract

Sustainable development aims to raise the standard of living for present and future generations. The Sustainable Development Goals (SDGs) are a set of 17 objectives related to sustainable development. Education for Sustainable Development, or ESD, is one initiative to achieve the SDGs. Presenting the findings of literature research on the features and use of ESD in science education is the goal of this paper. The primary source material for this literature study came from seven publications published in different journals. This study utilized a mixed-methods approach with a concurrent triangulation design involving questionnaires, interviews, and FGDs with 78 physics teachers. The TPACK scores showed a mean of 3.10, with the highest score in Attitude (3.27) and the lowest in Inquiry (3.04). The analysis's findings indicate that 1) Eight critical competencies are thought to be crucial for promoting sustainable development. 2) Learning tools, learning media, and learning models are ways ESD can be included in science education. These findings demonstrate that integrating ESD capabilities into science instruction can promote sustainable development and help attain the SDGs. The results highlight the need for targeted training in inquiry-based approaches and technology integration to enhance ESD implementation in physics education.

Keywords: sustainable development, technological pedagogical and content knowledge, physics teachers

INTRODUCTION

Sustainable development is wise growth. Sustainable development aims to raise the standard of living for present and future generations worldwide while avoiding the overuse of natural resources that exceed the earth's carrying capacity. According to (Siahaan et al., 2020), sustainable development is defined as development that can satisfy present demands without impairing the ability of future generations to satisfy their own. Accordingly, "sustainable" refers to the idea of a better human life within the constraints of nature by preserving the equilibrium of life in three areas: social, economic, and environmental (Hartono et al., 2022). The 17 objectives of sustainable development, sometimes known as the Sustainable Development Goals (SDGs), have 169 quantifiable accomplishments.

Education is one way that the SDGs are being implemented. Sustainability in education has undergone many changes in recent years (Zamora & Sánchez, 2019). One way to characterize education is as an endeavor to overcome the environmental catastrophe and a big hope for creating a more sustainable future (Ariska, Suhadi, et al., 2024). This approach through education is known as Education for Sustainable Development (ESD) or education for sustainable development. ESD is one of the essential elements in recent decades (Cebrián et al., 2020). Utilizing and managing the environment to preserve the environment well has become a responsibility and challenge for current and future generations. Good environmental management and utilization can guarantee the availability of natural resources. So, education is needed for the community so that they have awareness regarding environmental problems and can make critical decisions for the environment and society (Ariska, Suhadi, et al., 2024). ESD equips students with the knowledge, skills, values, and attitudes to process information, make decisions, and take actions responsible for the environment, economic sustainability, and a just society for current and future generations. Education for sustainable development (ESD) is necessary for quality education (Lai & Peng, 2019). ESD is the key to achieving the SDGs through providing broad and futuristic insight into the global environment and forming understanding, attitudes, and values relevant to social, economic, and environmental (van den Besselaar et al., 2017). Integrating learning with an emphasis on SDGS aims to form critical discussions by discussing specific issues (Kopnina, 2017). Through ESD, it is hoped that future generations will be able to face complex problems because as life develops, especially in the technology field, the problems they will face will become increasingly complex (Nagnedrarao & Selangor, 2017).

In physics education, TPACK allows teachers to use technology (Olofson et al., 2016) such as simulations, interactive physics applications, or virtual laboratory devices to explain abstract concepts such as motion, energy, or waves. The application of TPACK is one way to explain teacher cognition for effective technology integration to achieve meaningful learning (Brantley & Ertmer, 2013). TPACK is an effective teaching model teachers use technology (Schmid et al., 2021). Teachers must apply technological, pedagogical, and content knowledge (TPACK) to the curriculum to be effective in classroom learning (Graziano et al., 2017). TPACK is implemented uniquely to maximize learning (Maor, 2016). TPACK development needs further support when designing ICT-based learning (Koh & Chai, 2014). This relationship can also integrate active pedagogies, such as project-based learning or experiments, that are relevant to physics content. ESD aims to increase students' awareness and competence in sustainability issues, such as climate change, renewable energy, and resource efficiency. Physics education is vital in providing a scientific foundation in the form of physics concepts such as thermodynamics, fluid mechanics, or optics relevant to understanding sustainability issues. Students learn how physics principles can be applied to develop sustainable solutions, such as solar or wind energy technologies. Through experiments and discussions, students can understand the impact of technology use on the environment and society. Integrating TPACK and ESD in physics education can increase the effectiveness of learning while instilling sustainability values. Some ways of integration that can be done include teachers using technology-based simulations to demonstrate the impact of climate change or energy efficiency. Problem-based learning (PBL) can be used to explore sustainability issues in physics, such as energy-efficient building design. Teachers relate material such as kinetic and potential energy to real-world applications, for example, hydroelectric power generation or electric vehicles.

In implementing learning, ESD can be included in the curriculum at all levels (Cebrián et al., 2020). All levels of education, including primary and secondary, can contribute to an educational process that enables the young generation to become responsible citizens and promote sustainable development in their environment locally and globally (Ariska, Irfan, et al., 2024). Apart from that, ESD can also be integrated into various fields of study, such as science or science, social sciences, and even languages. (Ariska et al., 2018). One of the goals of learning science is to understand the natural environment and natural resources that need to be protected and preserved. So it is hoped that students can contribute actively to environmental conservation efforts after studying science. The critical role of science and technology in sustainable development in modern society shows the close relationship of science learning in ESD (Misykah & Adiansha, 2018). Igarashi & Suryadarma (2023) also stated that through science learning, it is hoped that students will experience positive changes in attitudes and will later be able to have a positive impact on the environment. Although TPACK has been widely studied in science education, its specific application in promoting ESD among physics teachers has not been widely explored. Most teachers are still reluctant to integrate sustainable development into learning because their skills, knowledge, and interests are still lacking (Kwee, 2021). Teachers do not yet understand This aspect of TPACK (Koh & Chai, 2016). Teachers experience difficulties in integrating technology into student-centered learning (Koh, 2018). The knowledge and skills of prospective teacher educators are still weak and limited to developing TPACK (Voogt & McKenney, 2016). Therefore, teacher educators need to develop an understanding of TPACK in learning activities (Baran & Uygun, 2016). In addition, teachers also need to consider the availability of technology when implementing TPACK (Ling, 2014). Therefore, this study analyzes it comprehensively and in-depth. To find out the characteristics and how to implement ESD in science learning, a literature review was carried out on articles regarding the implementation of ESD in science learning. It is hoped that the literature review resulting from this research will become a reference for implementing ESD in science learning.

METHODS

Educators and aspiring physics instructors in the Palembang region samples from other subdistricts and aspiring teachers enrolled in PPG and Physics Education courses served as the research subjects. These teachers, who were aspiring educators enrolled in PLP (undergraduate programs) and PPG, were randomly selected from several Palembang subdistricts. Method of Collection Concurrent triangulation design, which involves administering tests, interviews, and questionnaires all at once, is the method of data collecting employed in this study. FGD will come next. Several steps are taken to analyze the collected data, including curriculum documents that apply in K13 schools and the Independent Curriculum, sustainable science values in the South Sumatra region, by identifying literature and direct interviews with the local community.

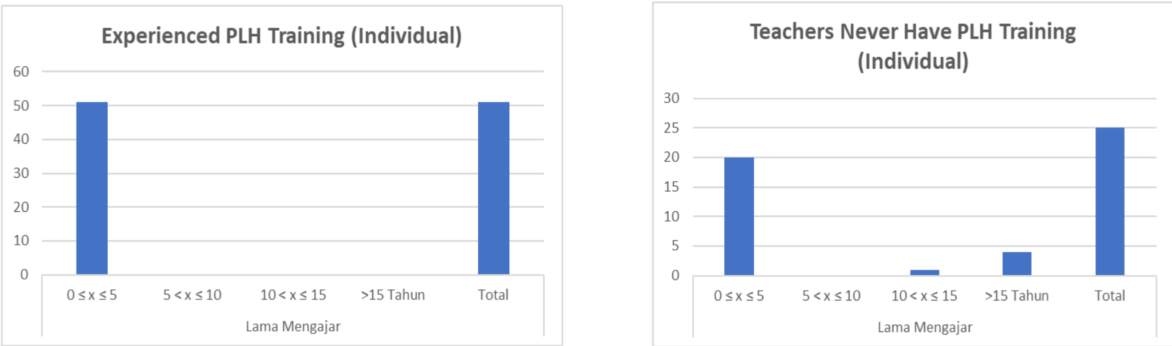
Meanwhile, data from questionnaires, interviews, and FGDs related to respondents' understanding of SDGs, ESD, and TPACK was carried out by analyzing the results of tests, interviews, and FGDs and transcribed in the form of field notes. The next step is coding the transcribed data. This coding involves themes and patterns related to SDGs, ESD, and TPACK 3. Analysis involves examining the data to identify findings by comparing and identifying relationships between different labels and exploring the implications of the findings. Data interpretation involves describing what is found and identifying these implications more broadly. The results of the initial capability analysis of teachers and prospective teachers will provide feedback for developing the program website to equip and improve teachers' abilities in implementing TPACK-based ESD to achieve the SDGs. The website developed will be validated by experts and tested on a limited basis by teachers and prospective teachers.

The main objective of this research is to achieve the SDGs by maximizing the central role of education and teachers. Therefore, developing a program to improve teachers' abilities in teaching Education Sustainable Development (ESD) to achieve the SDGs is necessary. Identifying the curriculum and exploring the abilities of teachers and prospective teachers in teaching ESD by integrating it with technology is carried out in identifying TPACK test results. The method used is mixed by combining qualitative and quantitative data using a concurrent triangulation design. This program was developed through the analysis, design, development, implementation, and evaluation stages.

TABLE 1. Indicators For Learning ESD Based On TPACK

Indicators	Observed actions
Technological Pedagogical Content Knowledge	- Understand and develop the ESD content, application in the science curriculum. From making planning to application by considering the level of students' abilities and competencies in sustainability and how assessment type to evaluate ESD enriched science lesson. - Identify, modify and integrate appropriate technology to teach ESD-enriched science lesson.
Inquiry	- Ask questions, stimulate ti make hypotheses about sustainability issues and engage students to solve them by doing scientific investigations. - Plan and conduct scientific investigations, Use engineering practices to support scientific investigations in solving ESD - Ability to develop students' scientific thinking competence and students' scientific problem-solving competence for lifelong learning. Synthesize a scientific explanation by using evidence and data on science experiment for sustainability and report scientific investigations in solving ESD problems after conducting science experiments.menyelesaikan tugas sederhana.
Professional Practice	- Encourage, practice students to take responsibility for maintaining ways to solve 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 assessment 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 plan a follow-up to the next lesson.
Professional development	- Participate in professional development opportunities to deepen and expand science content knowledge and ESD practices, collaborate, communicate effectively with peers and stakeholder 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	- Responding 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,

	demonstrate consistently the positive attitude and lifestyle - Having good cooperation with students and community across culture, have high expectations by building work discipline in achieving personal and family well-being



(a) (b)

FIGURE 1 (a). Percentage of Teachers Who Have Participated in PLH Training, (b). Percentage of Teachers Who Have Taught PLH

Seventy-eight teachers, the majority of whom were junior teachers, served as the research subjects. Based on their involvement in training and teaching PLH and their prior teaching experience, the evaluated teachers are differentiated. Sixty-three teachers have taught PLH, 15 teachers have not, 51 individuals have completed PLH training, and 27 have not. Teachers who have just been teaching for about five years make up most of those who participate in PLH training. Participants were selected based on their involvement in PLH training and years of teaching experience to ensure a diverse representation.

TABLE 2. Percentage of Teachers Who Have Participated in PLH Training

	Total	Ever Taught	Never Taught
TOTAL/TPACK	3.28	3.39	3.06
PCK	3.27	3.37	3.06
Inquiry	3.25	3.38	2.97
Professional Practice	3.30	3.42	3.07
Evaluation And Assessment	3.26	3.37	3.03
Professional Development	3.31	3.43	3.05
Attitude	3.37	3.42	3.25

Percentage of educators who have participated in PLH-related training. As can be seen from the above image, 89.34% of teachers who have participated in PLH training have less than five years of teaching experience. Similarly, 68.36% of instructors who have taught PLH had less than five years of teaching experience, which is the majority of teachers who have taught PLH. This study compares average scores in several quantitatively analyzed categories, including TPACK, Inquiry, Professional Development, Evaluation, and Attitude. The findings of the preliminary capability analysis of educators and aspiring educators will inform the creation of programs that will better prepare and enhance teachers' capacity to use TPACK-based ESD to accomplish the SDGs. The analysis emphasizes how categories were created from the data and stresses how crucial it is to comprehend the context.

RESULTS AND DISCUSSION

Multiple ability indicators, including TPACK, inquiry, professional practice, evaluation and assessment, professional development, and attitude, can assess a teacher's capacity to teach TPACK-based ESD. The questionnaire was completed by 78 physics teachers and aspiring teachers, including seasoned and novice educators.

TABLE 3. Results of Teacher TPACK Ability Questionnaire Analysis in Implementing ESD

TPACK Aspects	Mean
Technological Pedagogical Content Knowledge	3.09
Inquiry	3.04
Professional Practice	3.15
Evaluation And Assessment	3.06
Professional Development	3.06
Attitude	3.27
Total	**3.10**

The teacher's proficiency with TPACK-based ESD falls into the "quite good" level. Junior instructors who participated in the course filled out the results, which are used to calculate this score. With a score of 3.19, the Attitude component has the most incredible score, while the Inquiry component has the lowest, at 2.66. With a score of 3.19, attitude obtains the highest rating. This indicates that the teachers have a very favorable attitude toward applying ESD. This mindset is crucial because it is the cornerstone for behavioral modification and a more long-lasting teaching strategy. Instructors with a favorable attitude toward ESD are more likely to be excited about incorporating sustainability concerns into the curriculum and instructional activities. The low inquiry score demonstrates that teachers still struggle to apply the inquiry-based learning approach in ESD despite their positive attitudes. To create and facilitate a learning process that emphasizes investigation, exploration, and the growth of critical thinking, inquiry-based learning calls for specialized abilities. This low score would suggest that teachers' capacity to create and oversee successful inquiry-based learning in the context of ESD still needs to be improved.

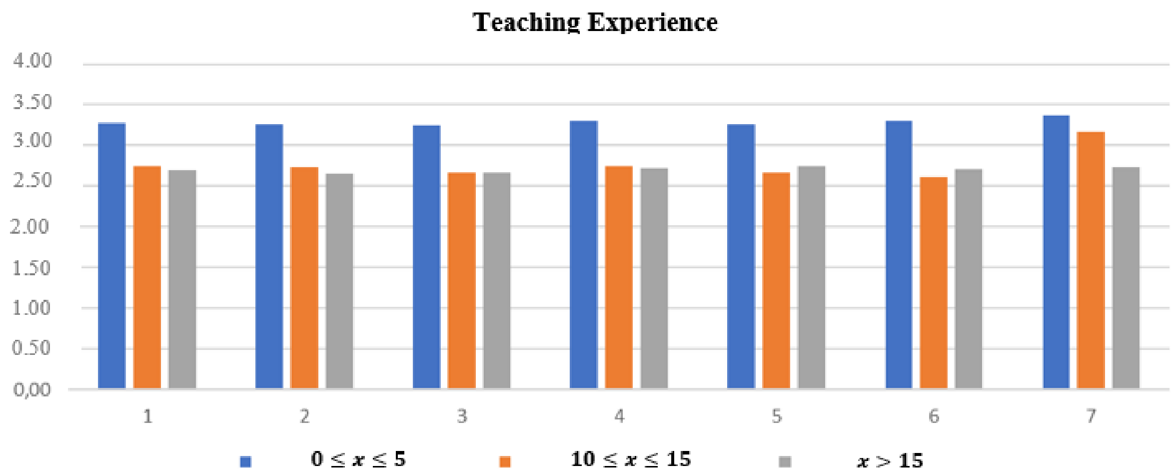


FIGURE 2. Comparison of TPACK-based ESD Learning Scores based on Teachers' Teaching Experience

FIGURE 2 compares teachers' TPACK-based ESD teaching scores based on length of teaching experience. The picture above shows that the longer the teacher's teaching experience, the lower the teacher's TPACK in implementing ESD. This is in line with the results of previous research and that conducted by Lestari (2015) which shows that the length of teaching experience is not directly proportional to the increase in TPACK abilities. This is influenced by many factors, including rapid technological advances that cannot be followed optimally by senior teachers who find it challenging to keep up with existing technological developments. Being busy is one of the reasons why senior teachers cannot find time to learn new things, especially the latest technological advances in supporting the teaching process in the classroom. The results of interviews with several senior teachers also showed that there was resistance to change; this was also a contributing factor. More experienced teachers may feel that traditional methods are compelling enough, and they may not see the need to integrate new technology or approaches into their teaching. As a result, they may not develop TPACK competencies optimally, which ultimately impacts their ability to teach ESD.

TABLE 4. TPACK capabilities

TPACK Competences	Mean
Understand the ESD content in the science curriculum.	3.12
Understand science concepts and the application on sustainability.	2.91
Apply science concepts to solve problems in the sustainability domain.	2.92
Develop ESD enriched science materials by considering science curriculum.	2.83
Explain science knowledge systematically and its implication on ESD by considering the level of students' abilities and competencies.	2.86
Demonstrate a critical understanding of ESD developments in the science curriculum.	2.74
Demonstrate science knowledge to creatively and innovatively process ESD content.	2.83
Set the learning objectives for science learning towards sustainability.	3.08
Plan a relevant teaching strategy for science learning and its implication on sustainability.	2.91
Plan ESD enriched science lesson by considering the level of students' abilities and competencies.	2.95
Plan well-structured activities for exploring science concepts and its application on sustainability.	3.06
Align the learning objectives and assessment type to evaluate ESD enriched science lesson.	2.97
Identify appropriate technology to teach ESD enriched science lesson.	2.99
Integrate specific technologies in ESD enriched science learning to support students' conceptual understanding.	3.05
Modify technology to improve ESD-enriched science lesson.	3.02
Understand student's background and characteristics to teach meaningful science lesson in the context of ESD.	3.03
Modify science lesson for sustainability when faced with unexpected conditions.	2.95
Total	3.10

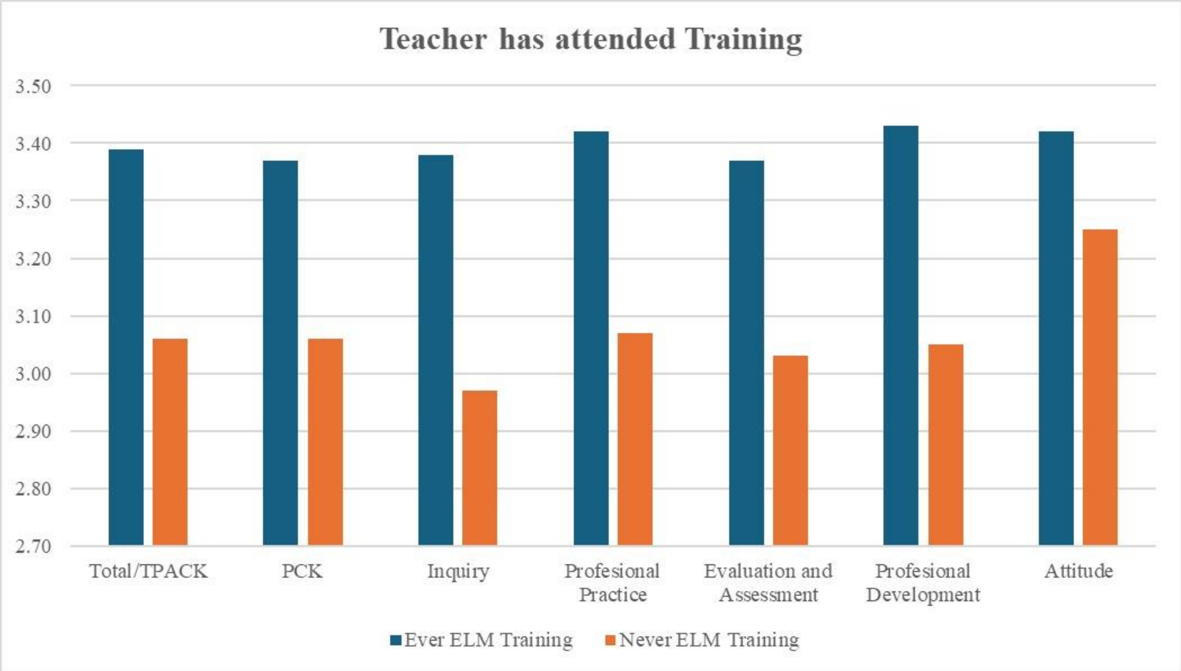


FIGURE 3. Comparison of TPACK-based ESD Learning Scores based on ELM -related Training

FIGURE 3 compares the TPACK scores of teachers who have attended training related to ELM and teachers who have never attended training related to teacher teaching Environmental Learning Materials (ELM). The picture above shows that teachers who have attended training have higher scores than teachers who have never participated in training related to ELM. This shows that the training related to ELM that was carried out positively increased teachers' TPACK abilities to implement ESD. To implement ESD effectively in the classroom, teachers need training to increase their competence (Xu & Yue, 2019). Most of the teachers who have attended ELM training are teachers with <5 years of teaching experience; this is one of the factors that causes the length of teaching experience to be inversely proportional to the teacher's TPACK ability. Older teachers are less enthusiastic about participating in various training or development programs for various reasons, such as resistance to change, the perception that the content provided is irrelevant, or the feeling that they already have enough knowledge and experience. In contrast, younger teachers are more open to training and professional development and see training as an opportunity to improve their skills and stay updated with the latest teaching methodologies.

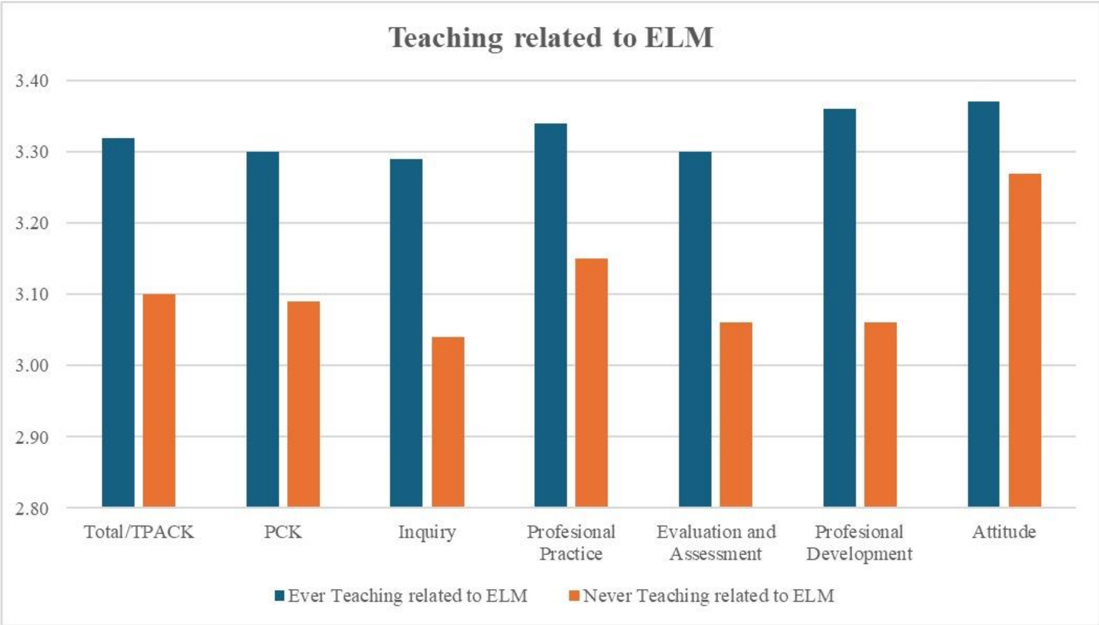


FIGURE 4. Comparison of TPACK-based ESD Learning Scores based on PLH Teaching Experience

FIGURE 4 above shows that teachers who have taught ELM have higher scores than teachers who do not have that experience. These findings indicate that ELM teaching experience significantly increases teachers' TPACK competence for ESD teaching. This experience makes teachers more skilled at integrating technology, pedagogy, and content relevant to sustainability issues. Recent studies also show that practical experience teaching environmentally related content enriches teachers' understanding and improves their ability to design ESD-relevant learning (Indana et al., 2022). Most teachers who have taught PLH have <5 years of teaching experience, namely 65.36%. This is also one of the factors that causes the length of teaching experience to be inversely proportional to the teacher's TPACK ability.

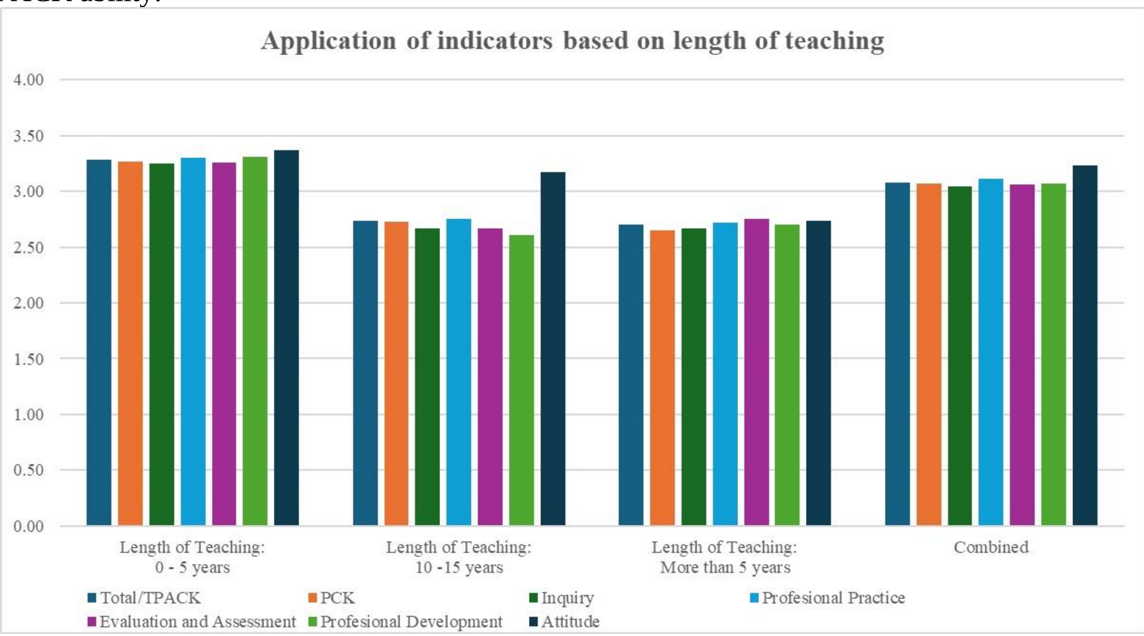


FIGURE 5. Comparison of each indicator

FIGURE 5 shows that physics subject teachers have higher TPACK abilities, so they are better prepared to implement ESD than chemistry and biology subject teachers. One factor that supports this finding is that most physics teachers (67%) have experience teaching PLH and have attended relevant training. The low Inquiry scores (3.04) may reflect limited training in facilitating student-led investigations, highlighting a gap in current teacher education programs. This is consistent with literature that states that teachers with a physics background tend to be more familiar with technological and experimental approaches, which is one of the key components of TPACK (Kanli, 2015). More experienced teachers may have less confidence in teaching using methods they have used for years. Thus, they are less likely to engage in professional development emphasizing innovation and integrating new technologies. This may stagnate their ability to adopt and implement ESD-enabled TPACK-based learning approaches. In contrast, younger teachers or those just entering the profession may be more open to innovation, as they may have more exposure to the latest teacher education curricula, which often include an emphasis on approaches such as TPACK and ESD.

Research by Knezek and Christensen (Kanli, 2014) shows that senior teachers tend to have greater reluctance to adopt new technology in the classroom compared to their younger colleagues. This supports the finding that longer experience does not always correlate positively with the ability to implement TPACK. Additionally, a study by Kanli, (2014) emphasizes that ongoing professional development is critical for teachers, especially in integrating new technologies and pedagogies, including TPACK and ESD. Without ongoing training, more experienced teachers may struggle to keep up with new developments in education. To address these challenges, it is essential to provide ongoing training focused on integrating TPACK and ESD and foster a school environment that supports innovation and pedagogical change. Thus, it is hoped that teachers with various experience levels can continue to improve their competence in teaching TPACK-based ESD. The teaching role of teachers in the learning process has a significant role in education. Teaching requires a variety of competencies because teaching is complex, delicate and challenging work that occurs amidst tensions between the public and the private (Keshta, 2013).

TPACK-based ESD learning requires unique competencies. The evaluation results show that teaching experience and training influence teacher competence in teaching TPACK-based ESD. These results indicate that although there is a strong basis in science teachers' attitudes towards ESD, additional efforts must be needed to strengthen other aspects, especially Inquiry. Further training or more intensive support may be needed to help teachers be more confident and competent in implementing inquiry-based learning methods (Ardiansyah, 2020). This may also include the development of resources or tools that support inquiry-based learning in an ESD context.

TABLE 5. Results of Teacher TPACK Ability for Each Indicators

		ELM Training		Teaching related to ELM		Length of Teaching		
	Total	Ever	Never	Ever	Never	$0 \leq x \leq 5$	$10 < x \leq 15$	>15
TOTAL/TPACK	3.08	3.39	3.06	3.32	3.10	3.28	2.74	2.70
PCK	3.07	3.37	3.06	3.30	3.09	3.27	2.73	2.65
Inquiry	3.04	3.38	2.97	3.29	3.04	3.25	2.67	2.67
Professional Practice	3.11	3.42	3.07	3.34	3.15	3.30	2.75	2.72
Evaluation And Assessment	3.06	3.37	3.03	3.30	3.06	3.26	2.67	2.75
Professional Development	3.07	3.43	3.05	3.36	3.06	3.31	2.61	2.70
Attitude	3.23	3.42	3.25	3.37	3.27	3.37	3.17	2.74

The Inquiry aspect has the lowest score, namely 3.08. This may indicate that although teachers have a good attitude, they still experience difficulties implementing inquiry-based learning approaches in ESD contexts. Inquiry-based learning requires special skills in designing and facilitating a learning process that focuses on exploration, investigation, and developing critical thinking. This low score could indicate that improvement is still needed in the ability of science teachers to develop and manage effective inquiry-based learning in the ESD context. The science teachers involved consisted of chemistry, physics, and biology teachers. Physics teachers who had experience teaching ELM and had attended training showed higher readiness to integrate ESD in their learning. ELM teaching experience provides a strong foundation for teachers to develop the pedagogical and technological skills necessary to teach sustainability concepts more effectively. In addition, the training they attended appeared to have a positive impact on developing their ability to integrate technology with pedagogical approaches that support ESD (Rijani, 2018).

From the results, it also appears that teaching experience or length of teaching does not guarantee that a teacher can teach TPACK-based ESD well. More experienced teachers may have high confidence in teaching using methods they have used for years, so they tend to be less involved in teaching. professional development that emphasizes innovation and integration of new technologies. This may stagnate their ability to adopt and implement ESD-enabled TPACK-based learning approaches. In contrast, younger teachers or those just entering the profession may be more open to innovation, as they may have more exposure to the latest teacher education curricula, which often emphasize approaches such as TPACK and ESD.

Judging from several aspects of TPACK's capabilities, several things are still weak, such as modifying technology and adapting it to unexpected conditions that are adapted to the science curriculum, so efforts are still needed to increase critical understanding of the latest ESD developments and how this is applied in the science curriculum. Educators should be introduced to the latest case studies, best practices, and relevant curriculum updates with additional training to improve skills in modifying technology for flexible ESD lessons; they need to get more support or training on how to adapt and optimize technology to support learning goals. Based on the data in TABLE 6, it can be concluded that the average Technology Pedagogy Knowledge of Physics Education students in the Basic Technology Education (PTD) course is in the sufficient category (55.1%). This shows that students are not teaching content well enough using appropriate pedagogical methods and technology. This is also in line with the results of research conducted by Turmuzi & Kurniawan (2021). In this component, prospective mathematics teacher students fall into the sufficient category. This shows that students still have limited knowledge of physics-related computer applications and processing them into physics learning. In fact, according to Sintawati & Indriani (2019), prospective teachers in the 21st century must have TPACK to integrate technology into learning to train students' abilities by the demands of 21st-century human competence.

CONCLUSION

These results highlight the value of giving teachers from various fields, such as physics, chemistry, and biology, hands-on experience in teaching material content, methodology, and technology, in addition to ongoing training. It is intended that by expanding science teachers' access to ESD-related training and teaching experiences like PLH, they will be able to enhance their overall TPACK-based ESD teaching skills and help all scientific teachers apply ESD to the best of their abilities. These results offer a favorable assessment of teachers' preparedness to use TPACK to implement ESD while acknowledging that some areas still require improvement to attain better outcomes, particularly inquiry, ESD-related teaching experience, and the capacity to adapt and incorporate technology for ESD instruction. There needs to be efforts to continue to improve teachers' abilities in teaching TPACK-based ESD to achieve the SDGs. Future research should explore the long-term impact of TPACK-based ESD training on student outcomes and sustainability practices. Teacher training programs should prioritize inquiry-based approaches and provide continuous professional development to address gaps in TPACK competence.

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