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Science Teachers' Readiness in Professional Training Programs for Sustainability-Oriented STEM Education

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ABSTRACT Integrating Science, Technology, Engineering, and Mathematics (STEM) with sustainability-oriented education is essential to preparing students to address global environmental and social challenges. Teacher readiness is a key factor in successful implementation, yet there is limited evidence about its current state in Indonesia. This study examined science teachers' readiness to implement sustainability-oriented STEM education, explored the influence of professional development experiences, and identified challenges and opportunities in classroom practice. The study used quantitative and qualitative data from 112 science teachers who completed a structured questionnaire with closed- and open-ended questions. Quantitative analysis included descriptive statistics, correlation analysis, radar plot visualization, and independent sample t-tests, while qualitative data were analyzed thematically. Findings showed that teachers demonstrated a moderate level of readiness, with high internal consistency across constructs. Correlation analysis revealed significant relationships among readiness dimensions, and the radar plot indicated stronger profiles in knowledge and skills but weaker outcomes in professionalism and collaboration. The inferential results highlighted that participation in ESD training significantly enhanced readiness with a moderate-to-large effect size, whereas STEM training alone did not. Thematic analysis generated seven themes: professional development, resources, curriculum, collaboration, knowledge, attitudes, and barriers. Teachers expressed enthusiasm for implementing sustainability-oriented STEM education but noted systemic constraints, including limited training, inadequate resources, heavy workloads, and insufficient institutional support. The study concludes that strengthening professional development programs focused on sustainability, improving facilities, aligning curricula, and fostering collaboration are critical to advancing teachers' readiness to integrate sustainability principles into STEM education meaningfully.

Keywords: Need Analysis; Professional Development; Science Teachers; STEM Education; Sustainability-Oriented Learning

1. INTRODUCTION

Climate change is one of the defining challenges of the twenty-first century, posing serious threats to ecosystems and human societies. Addressing this issue requires not only mitigation efforts but also effective adaptation strategies to reduce the vulnerability of socio-ecological systems and to maintain conditions necessary for human well-being (Lüdtke et al., 2025). Adaptation refers to the capacity of systems to remain functional, minimize adverse impacts, and capitalize on opportunities arising from climate variability (IPCC, 2023). Multiple concurrent global crises, such as land-use change, environmental degradation, and the decline of biodiversity and ecosystem services, underscore this urgency. Furthermore, the international commitment to limit temperature rise to 1.5°C above pre-industrial levels, as set in the Paris Agreement (UNFCCC, 2015), is increasingly challenging to achieve since global temperatures have already reached 1.1°C above pre-industrial levels, while greenhouse gas emissions continue to grow (IPCC, 2023).

In this context, education plays a critical role in strengthening societal capacity to respond to environmental challenges. Education for Sustainable

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Development (ESD) is internationally recognized as a framework that highlights the interconnection between human society and the natural environment at multiple levels, from local to global (Anderson, 2012; Lüdtke et al., 2025). ESD equips learners with the knowledge, skills, attitudes, and values necessary for building a sustainable future (Jasmi et al., 2019; Zguir et al., 2021). Through this framework, students are encouraged to make responsible choices that promote economic viability, ecological integrity, and social justice while respecting cultural diversity (Fathurohman et al., 2023; Ulmeanu et al., 2021). However, in Indonesia, the national school curriculum does not explicitly incorporate ESD as a subject, creating the need for its integration across all disciplines, particularly science education, to support the achievement of the Sustainable Development Goals (Camilleri & Camilleri, 2020; Kioupi & Voulvoulis, 2019)

ESD not only imparts knowledge but also fosters changes in perspective by encouraging students to reconsider their relationship with the world (Sasaki et al., 2024). Sustainability education emphasizes future-oriented actions, environmental stewardship, and the creation of a better society through informed decision-making. Building sustainable lifestyles requires recognizing the interdependence of ecological, social, cultural, and economic systems (Iacovidou et al., 2021; Tomislav, 2018). To achieve this, practical, context-based models of teaching are essential, among which STEM education plays a strategic role.

STEM (Science, Technology, Engineering, and Mathematics) education integrates multiple disciplines and provides meaningful, real-world learning experiences at all levels of education, from primary to higher education (Alali et al., 2023; S.-K. Chen et al., 2022). It encourages students to link academic knowledge to everyday contexts, enhances critical thinking and problem-solving abilities, and strengthens retention of concepts (Abu Khurma et al., 2023; Rennie et al., 2018). Unlike traditional subject-based instruction, STEM creates an integrated learning environment that demonstrates how scientific inquiry is applied in daily life (Gulen, 2018; Sari et al., 2020).

When combined with ESD, STEM becomes a transformative pedagogical approach. Sustainability-oriented STEM learning integration emphasizes inquiry, collaboration, and reflection, enabling students to engage with sustainability issues in exploratory and action-oriented ways (Ulmeanu et al., 2021). It also develops the competencies needed to recognize current challenges, anticipate future risks, and design innovative solutions for sustainability (Khadri, 2022). Despite its potential, implementing sustainability-oriented STEM learning in Indonesia faces significant challenges, including a consumption-driven culture, technological disparities, and limited integration of sustainability competencies in the education system (Del Cerro Velázquez & Lozano Rivas, 2020).

Science teachers play a central role in addressing these challenges by facilitating sustainability-oriented STEM learning. The Indonesian science curriculum at the junior high school level, for example, already requires students to apply sustainable technologies in engineering practices, thereby establishing a natural connection between science education and sustainability. Consequently, the readiness of science teachers to implement sustainability-oriented STEM learning becomes a decisive factor. Teachers are expected to design and deliver learning experiences that respond to global challenges and equip students with twenty-first-century skills. To achieve this, they must develop sustainability-oriented STEM competencies that enable students to become innovative problem-solvers (Fathurohman et al., 2023; Khadri, 2022).

Professional development (PD) programs play a key role in strengthening these competencies. Well-designed PD opportunities enable teachers to integrate innovative teaching strategies, learning tools, and appropriate classroom practices (Ahmed et al., 2023; Pitsoe & Letseka, 2014; Widodo & Riandi, 2013). Such programs also emphasize deep subject matter knowledge and pedagogical expertise, allowing teachers to adapt instruction to student needs and build effective learning environments. However, many science teachers in Indonesia report limited opportunities to participate in such training, a lack of resources, and insufficient prior exposure to sustainability-oriented STEM learning (Shernoff et al., 2017; Stouthart et al., 2023). These constraints reduce their readiness to implement sustainability-oriented STEM education.

Most existing studies focus on curriculum development or instructional strategies, while empirical research specifically examining science teachers' readiness for sustainability-oriented STEM learning remains limited, particularly in Indonesia. Moreover, little is known about the extent to which professional development experiences enhance teacher readiness, or about the challenges and opportunities that teachers themselves identify in implementing sustainability-oriented STEM learning at the school level. The present study addresses these gaps by offering novelty in three dimensions. First, it assesses the overall level of readiness among science teachers for sustainability-oriented STEM learning. Second, it examines the influence of professional development, particularly STEM and ESD training, on teacher readiness. Third, it explores the challenges and opportunities identified by teachers in implementing sustainability-oriented STEM learning in schools. By doing so, the study contributes to the limited empirical literature on teacher readiness in sustainability-oriented STEM education. It provides practical insights for designing professional development programs that are more relevant, contextual, and sustainable, supporting the transformation of science education in the twenty-first century. Therefore, this study aims to analyze the need for PD implementation for science teachers in STEM learning for sustainability in Indonesia. Then, the research questions are below:

1. What is the overall level of science teachers' readiness for sustainability-oriented STEM learning?
2. How do professional development experiences, particularly STEM and ESD training, influence science teachers' readiness for sustainability-oriented STEM learning?
3. What challenges and opportunities do science teachers identify regarding the implementation of sustainability-oriented STEM learning in schools?

2. METHOD

The research design is a descriptive mixed-methods approach with a needs analysis, integrating quantitative survey data and qualitative responses to identify and explain the professional development needs of science teachers in sustainability-oriented STEM learning (Birden, 2022). This method is based on research objectives that require an overview of the extent of PD needed for science teachers in sustainability-oriented STEM learning. Data collection was done through distributing questionnaires. The study's steps are divided into four stages, as illustrated in Figure 1.

Figure 1 shows the research steps, which begin with the preparation of a multiple-choice questionnaire. The use of questionnaires aims to collect information that is organized and can be analyzed systematically. The second stage is data collection using the Google Forms application from October to December 2024. Furthermore, data were tabulated from the questionnaire results completed by participants. The last stage is presentation, which analyzes the questionnaire data.

The needs analysis questionnaire on PD for teachers consisted of 51 questions in the form of multiple choice (allowing only one answer) (Eliyawati et al., 2023; Martín-Sánchez et al., 2022; Zuhaida et al., 2024). The questions of the needs analysis questionnaire are summarized in Table 1.

Participant

The respondents in this study were science teachers, sampled using a convenience sampling technique. A total of 112 teachers participated in the survey, with 85 females (75.89%) and 27 males (24.11%).

Regarding educational background, most teachers held a bachelor's degree (85.71%), while a smaller proportion had attained a master's degree (23.21%). Only 1.79% of

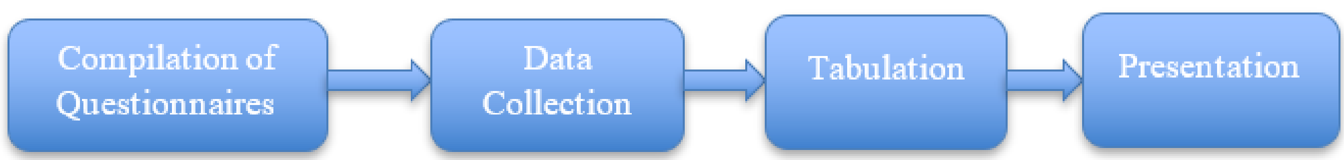

Figure 1 Research Steps

Table 1 Blueprint of the Instrument for Science Teachers' Readiness in Sustainability-Oriented STEM Learning

Dimension	Indicator	Number of Items
Knowledge	Understanding of science content integrated with STEM (basic concepts of science, integration with technology)	12
	Understanding of the integration of STEM with ESD (environmental issues, sustainability, energy, etc.)	11
	Understanding of TPACK principles in sustainability-oriented STEM learning (content, pedagogy, and technology integration)	10
Skills	Designing sustainability-oriented STEM learning (lesson plans, learning tools, instructional media)	4
	Implementing sustainability-oriented STEM learning (classroom activities, use of technology, teaching resources)	3
	Evaluating the process and outcomes of sustainability-oriented STEM learning (reflection, assessment, feedback)	3
Professionalism	Participation in professional development (training, workshops, professional communities related to sustainability-oriented STEM learning)	2
	Initiative for self-development (independent learning, small-scale research, sharing best practices)	2
Collaboration	Collaboration with other teachers/experts/communities in developing sustainability-oriented STEM learning	2
	Collaboration with school stakeholders and sharing innovative ideas	2

Table 2 The distribution of teachers

Variables	N	Percentage
Gender		
Female	85	75.89
Male	27	24.11
Education Background		
Bachelor	96	85.71
Master	26	23.21
Doctoral	2	1.79
Teaching Experience		
< 5 years	37	33.04
5-10 years	15	13.39
11-15 years	25	22.32
16-20 years	15	13.39
> 21 years	20	17.86
Teacher Age		
< 25 years	22	19.64
25-35 years	29	25.89
36-45 years	35	31.25
> 45 years	26	23.21

teachers reported holding a doctoral qualification. These findings suggest that while undergraduate qualifications dominate the professional profile of science teachers, opportunities for advanced degrees are gradually emerging, although doctoral-level attainment remains limited.

The data on teaching experience illustrate a diverse range of professional tenure. Approximately one-third of teachers (33.04%) reported having less than 5 years of teaching experience, indicating a relatively young, early-career cohort. Meanwhile, 22.32% had 11-15 years of experience, 13.39% had 5-10 years, and another 13.39% had 16-20 years. Notably, 17.86% of teachers had more than 21 years of experience, indicating a seasoned group with extensive professional expertise. This variation demonstrates a balanced representation between novice, mid-career, and veteran teachers.

In terms of age distribution, the most significant proportion of participants was in the 36–45-year age group (31.25%), followed by those aged 25–35 years (25.89%) and those aged 45+ (23.21%). Teachers younger than 25 years accounted for 19.64% of the sample. These figures indicate that the teaching workforce is primarily composed of individuals in mid-career. However, there is also a substantial representation of both early-career and senior teachers.

Data Analysis

The data were analyzed using both quantitative and qualitative approaches to capture a comprehensive picture of teachers' readiness for sustainability-oriented STEM learning. Descriptive statistics, including mean, standard deviation, and Cronbach's α, were calculated for the four constructs of readiness: Knowledge (33 items), Skills (10 items), Professionalism (4 items), and Collaboration (4 items). The reliability coefficients ranged from 0.916 to 0.991, indicating excellent internal consistency of the instrument. To explore relationships among constructs, a correlation analysis was used to examine the associations among Knowledge, Skills, Professionalism, and Collaboration. This analysis provided insight into how these dimensions are interrelated and collectively contribute to overall readiness. A radar plot was then generated to visualize the profile of readiness, enabling an intuitive comparison of teachers' strengths and weaknesses across the four constructs.

Inferential analysis was conducted using independent-samples *t*-tests to compare the readiness index between teachers who had participated in STEM training and those who had not, and between teachers with and without ESD training. Effect sizes were reported using Cohen's *d* to allow practical interpretation of the differences. The findings indicated that ESD training significantly influenced readiness with a moderate-to-large effect size, while STEM training showed no statistically significant effect. In addition, qualitative responses from open-ended questions were examined using thematic analysis. Representative quotes were included to illustrate each theme and to enrich the quantitative findings.

3. RESULT AND DISCUSSION

This section integrates descriptive statistics, inferential analyses, and qualitative insights to provide a comprehensive understanding of science teachers' readiness for implementing sustainability-oriented STEM learning. Findings are presented systematically from descriptive profiles to inferential tests and thematic qualitative analysis, with immediate interpretation of results.

Descriptive Statistics of Constructs

Table 3 presents the mean scores, standard deviations, and Cronbach's α values for each construct of sustainability-oriented STEM learning readiness.

Table 3 Descriptive statistics (Mean, SD, Cronbach's α) of sustainability-oriented STEM learning readiness constructs.

Construct	k_items	Mean	SD	Cronbach_alpha
Knowledge	33	2.43	0.76	0.991
Skills	10	2.43	0.8	0.986
Professionalism	4	2.53	0.73	0.916
Collaboration	4	2.58	0.82	0.966

The findings revealed that science teachers demonstrated a moderate level of readiness across all constructs, with mean scores ranging from 2.43 to 2.58 on a four-point scale. Such a moderate readiness level indicates that, although teachers have developed a foundational understanding of sustainability-oriented STEM learning, their capacity for full implementation remains limited. Notably, the results highlight distinct patterns among the constructs. These findings are consistent with the international literature, which indicates that teachers often develop a conceptual understanding of STEM and Education for Sustainable Development (ESD) more readily than they enact it as a sustained professional practice (Bybee, 2013; Quigley et al., 2017). UNESCO's guidance on ESD emphasizes that moving from awareness to action requires building key sustainability competencies—systems thinking, anticipatory competence, normative competence, collaboration, and critical problem solving—through curriculum, pedagogy, and assessment (Taimur & Sattar, 2018; UNESCO, 2015). The results suggest that teachers have the baseline to engage those competencies but lack the structural supports to turn them into routine practice. This finding supports the radar plot in Figure 2.

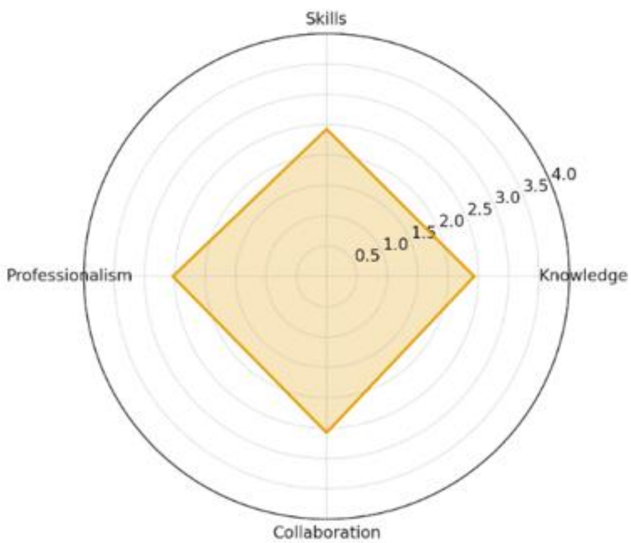

Figure 2 Radar plot of sustainability-oriented STEM learning readiness constructs.

The radar chart (Figure 2) indicates that teachers' professional development (PD) needs are at a moderate level across all measured dimensions. The highest scores are observed in Skills and Collaboration (approximately 2.5), suggesting that teachers perceive a stronger need for support in practical instructional skills and collaborative practices within sustainability-oriented STEM learning. In contrast, Knowledge and Professionalism show slightly lower scores (around 2.0), indicating that while conceptual understanding and professional attitudes remain important, they are perceived as relatively less urgent. Overall, these findings suggest that PD programs should prioritize the enhancement of practical skills and collaborative capacities, while still addressing knowledge and professionalism development. The finding that ESD training (not generic STEM training) is significantly associated with a higher Readiness Index aligns with work showing that content-specific, practice-embedded PD is the most potent predictor of classroom change (Darling-Hammond et al., 2020; Desimone, 2009; Sihombing et al., 2024). ESD-focused PD tends to be curriculum-proximal (lesson designs, place-based projects, authentic assessment tied to sustainability issues) and therefore transfers more directly to instruction than decontextualized workshops (Leal Filho et al., 2018). In short, teachers don't need "more PD"; they need PD targeted to sustainability competencies and co-designed with artifacts they can use immediately.

The comparatively fragile scores on Professionalism and Collaboration, paired with higher SDs, echo the literature on opportunity gaps: uneven access to communities of practice, coaching, and cross-institutional networks (Darling-Hammond & Wei, 2009; Guskey, 2002). High-functioning STEM/ESD implementations typically rely on professional learning communities (PLCs) and school–university partnerships that normalize co-planning, peer observation, and iterative refinement of tasks (Fulton & Britton, 2011; Herro & Quigley, 2016, 2017). Collaboration is not a soft add-on; it is the mechanism through which teachers *appropriate* new pedagogies and sustain them. (e.g., *"We rarely receive specific training on sustainability-oriented STEM learning.","We need collaboration with universities and other schools."*) These are classic signals of missing social infrastructure.

From a change-theory perspective, the results align with a well-documented progression: knowledge, practice, and culture. Teachers possess adequate knowledge to initiate sustainability-oriented STEM learning; however, in the absence of coherent professional development, accessible curriculum materials, and networked collaboration, their practices tend to remain sporadic and fragile (Darling-Hammond et al., 2020; Fullan, 2007). This finding explains why the collaboration construct is strongly associated with the overall readiness index in the correlation matrix—it functions as a catalyst that transforms individual capacity into collective efficacy (Demir, 2008).

Correlation Analysis

As shown in Figure 3, the correlation matrix indicates that all constructs are positively interrelated. Notably, Collaboration and Professionalism showed strong associations with the overall Readiness Index, suggesting that sustained professional development and teacher networking are critical predictors of readiness.

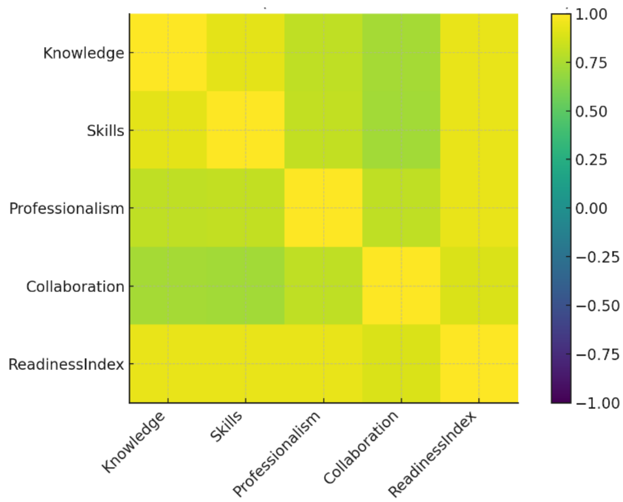

Figure 3 Correlation matrix of constructs and the overall Readiness Index.

The heatmap in Figure 3 illustrates the correlation matrix among Knowledge, Skills, Professionalism, Collaboration, and the Readiness Index. Overall, the results show strong and positive relationships among all dimensions, as indicated by the consistently high correlation values (close to 1.00). In particular, Skills, Professionalism, and Collaboration exhibit strong intercorrelations, suggesting that improvements in one area are closely associated with improvements in the others. The Readiness Index demonstrates a high positive correlation with all four dimensions, indicating that teachers' readiness for sustainability-oriented STEM learning is collectively shaped by their knowledge, skills, professionalism, and collaborative capacity. These findings imply that professional development initiatives should adopt an integrated approach, as enhancing any single dimension is likely to contribute positively to overall teacher readiness. The correlation matrix shows consistently positive associations among Knowledge, Skills, Professionalism, Collaboration, and the Readiness Index. Knowledge and Skills exhibit a strong relationship, suggesting that conceptual mastery in sustainability-oriented STEM learning is directly connected to the ability to apply knowledge in practical contexts. Knowledge also demonstrates substantial correlations with Professionalism and Collaboration, indicating that informed individuals are more likely to display ethical responsibility and engage effectively in teamwork.

Skills show strong correlations with both Professionalism and Collaboration, indicating that technical competence in sustainability-oriented STEM learning is closely aligned with professional conduct and cooperative engagement. Professionalism and collaboration also display a strong association, underscoring that responsible behavior often manifests through teamwork and collective problem-solving (L. Chen & Xiao, 2021; Paniagua & Istance, 2012). Most importantly, all four constructs — Knowledge, Skills, Professionalism, and Collaboration — show robust correlations with the Readiness Index. This result confirms that readiness is shaped not by a single factor but by the integration of cognitive, technical, attitudinal, and interpersonal dimensions (Benson & Morgan, 2016; Papagiannopoulou et al., 2023).

The findings provide empirical evidence that sustainability-oriented STEM learning readiness should be conceptualized as a multidimensional construct. The strong correlations between each build and the overall readiness index highlight that preparedness requires the simultaneous alignment of disciplinary knowledge, applied skills, professional dispositions, and collaborative capacities. These results support previous arguments that effective sustainability-oriented STEM learning must integrate cognitive, behavioral, and social dimensions to comprehensively address sustainability challenges (Bybee, 2013; IBE-UNESCO, 2020)

The strong linkage between Knowledge and Skills highlights the inseparability of conceptual understanding and practical application, supporting the argument that sustainability-oriented STEM learning is most effective when learners can transfer disciplinary knowledge into authentic contexts (Fathurohman et al., 2023). The positive associations between Skills, Professionalism, and Collaboration demonstrate that technical competencies are embedded within broader values-driven practices, which aligns with research emphasizing the centrality of ethical responsibility and teamwork in sustainability education (Rieckmann, 2018). The correlation between Professionalism and Collaboration further validates the view that sustainability-oriented STEM learning fosters not only problem-solving but also responsible engagement in collective action (Johnson, 2012).

These results extend theoretical perspectives on readiness by confirming that preparedness for sustainability-oriented STEM learning should not be treated as a fragmented set of competencies. Instead, readiness is an integrative framework in which each dimension reinforces the others, thereby ensuring a comprehensive approach to education for sustainability (Voogt et al., 2016). Practically, this underscores the need for teacher education and curriculum design that cultivate disciplinary knowledge, applied skills, professional responsibility, and collaborative practices in tandem (Imogen & Wardle, 2018). Such an approach ensures that sustainability-oriented STEM learning implementation equips learners with the holistic competencies required to navigate and respond to the complex sustainability challenges of the twenty-first century (Sajjad & Eweje, 2021).

Inferential Analysis: Effect of Training

Inferential tests (Table 4) compared readiness between teachers who participated in STEM or ESD training and those who did not. The results revealed no significant differences for STEM training, while ESD training was significantly associated with higher readiness, with a moderate-to-large effect size. Figures 4a and 4b further illustrate these patterns.

Table 4 Inferential tests of the Readiness Index by professional development participation.

Comparison	Yes		No		t	pvalue	d
	N	Mean	N	Mean			
STEM training	73	2.557	39	2.371	1.261	0.211	0.26
ESD training	43	2.758	69	2.327	3.455	0.001**	0.626

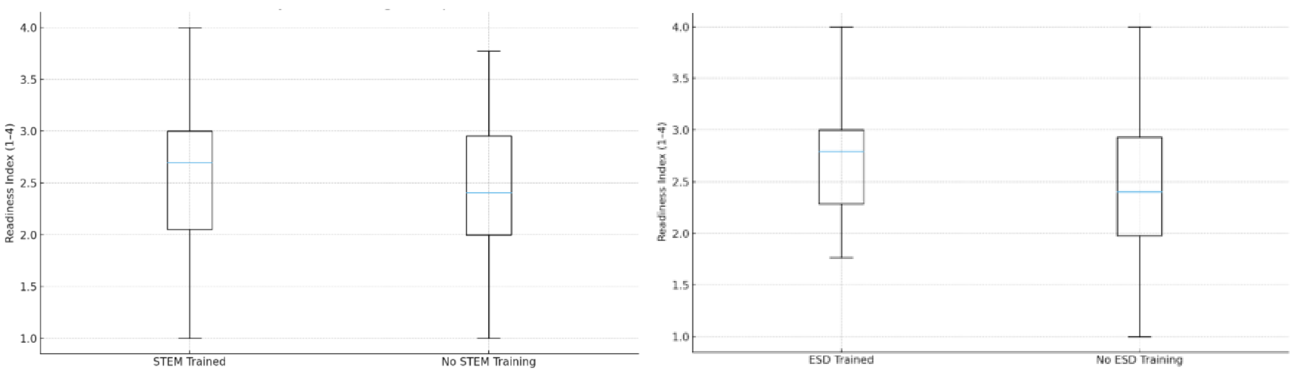

Figure 4 (a) Readiness Index by STEM training participation, (b) Readiness Index by ESD training participation.

The inferential results provide nuanced insights into the role of professional development in shaping teachers' readiness for sustainability-oriented STEM learning. As shown in Table 4 and Figure 4a, participation in STEM training did not significantly increase readiness scores (M = 2.557 vs. 2.371, t = 1.261, p = 0.211, d = 0.26), with both groups showing overlapping distributions. This finding suggests that generic STEM training alone is insufficient to improve teachers' preparedness. Prior research confirms that many STEM workshops focus primarily on content knowledge or technological tools without addressing the integrative pedagogies required for interdisciplinary and sustainability-oriented teaching (Leonard et al., 2016; Quigley et al., 2017). Thus, while such training may raise awareness, it does not necessarily translate into measurable improvements in readiness for sustainability-oriented STEM learning.

By contrast, Figure 4b illustrates that teachers who participated in ESD training achieved significantly higher readiness scores than their counterparts (M = 2.758 vs. 2.327, t = 3.455, p = 0.001, d = 0.626). This medium-to-large effect size underscores the added value of professional development explicitly focused on sustainability. Such training directly supports the development of key competencies identified by IBE-UNESCO (2020) and Rieckmann (2018), including systems thinking, anticipatory competence, and collaboration—competencies that align closely with the constructs measured in this study. Previous studies have also emphasized that ESD-specific professional development encourages teachers to integrate real-world sustainability issues into STEM instruction, fostering both conceptual understanding and practical strategies (Leal Filho et al., 2018; Eliyawati et al., 2023).

These results align with broader scholarship on the effectiveness of professional development, which underscores that PD has its most significant impact when it is sustained, practice-based, and embedded in curriculum materials (Borko, 2004; Darling-Hammond & Wei, 2009). The contrast between STEM and ESD training in this study demonstrates that the quality and focus of PD are more critical than its quantity. In the Indonesian context, where sustainability-oriented STEM learning integration remains emergent, ESD-oriented training equips teachers not only with theoretical knowledge but also with pedagogical tools and collaborative networks necessary for implementation. Without such targeted support, professional growth remains fragmented, leaving teachers moderately ready but unable to advance toward high readiness (Papagiannopoulou et al., 2023; Rivera & Li, 2020).

Participation in Professional Development

Figures 5a and 5b display teachers' participation in professional development programs. While 65,2% of teachers reported attending STEM training, only 34% had participated in ESD training. This imbalance explains the more decisive influence of ESD training on readiness, as exposure remains limited.

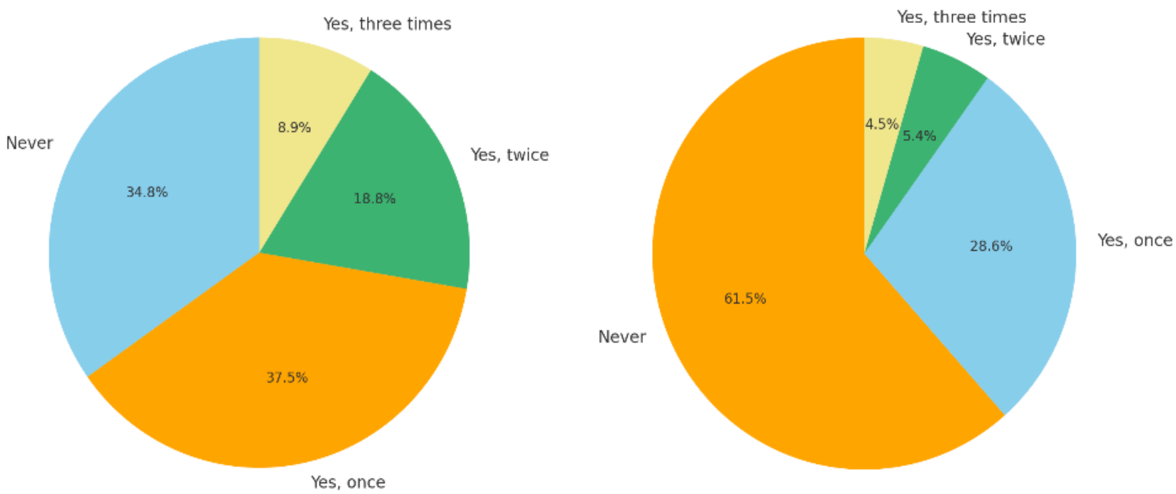

Figure 5 (a) Distribution of teachers' participation in STEM training programs, (b) Distribution of teachers' involvement in ESD training programs

This disparity provides an essential explanation for why ESD training demonstrated a more substantial influence on readiness: because exposure to ESD is limited, those who receive such training experience a significant shift in knowledge, skills, and professional capacity compared to their untrained peers. This pattern reflects findings in prior studies showing that while STEM initiatives are increasingly integrated into teacher development worldwide, sustainability-oriented training remains underrepresented, particularly in developing contexts (Leal Filho et al., 2018; IBE-UNESCO, 2020). Consequently, ESD training serves as a differentiating factor that enhances readiness by equipping teachers with competencies directly aligned with global sustainability challenges, such as systems thinking, collaboration, and anticipatory competence (Rieckmann, 2018). The results emphasize the need to balance investments in STEM and ESD professional development, ensuring that teachers are proficient in disciplinary integration and prepared to address the sustainability dimensions of science education.

The usefulness of sustainability-oriented STEM learning in science learning

The next component that justifies the need for PD for science teachers in sustainability-oriented STEM learning is the usefulness of the learning. Teaching implemented using STEM requires careful consideration of practices that can integrate various fields (Juškevičienė et al., 2021; Shernoff et al., 2017; Zowada et al., 2021). Sustainability-oriented STEM learning is expected to be functional by providing learning programs that instill and raise awareness of sustainable technologies that benefit society. In this study, the usefulness of sustainability-oriented STEM learning in science is evident through three factors: its importance, accuracy, and effectiveness in increasing students' passion for science learning. Figure 6 shows the importance of implementing sustainability-oriented STEM learning in science learning. 53% of teachers stated that sustainability-oriented STEM learning is significant to be implemented in science learning.

STEM education for sustainable development plays an essential role in helping students understand global issues and support societal action to overcome these challenges by leveraging their competencies and the process of science as the primary foundation for all actions they take (Rieckmann, 2018; Shernoff et al., 2017). While science alone cannot provide a comprehensive solution, it is an essential element for action based on students' knowledge. By educating the younger generation about learning that relates to everyday life and involves the surrounding community, we can at least engage students to address and take action on the most complex issues of today and future generations (Herro & Quigley, 2017; Leal Filho et al., 2018).

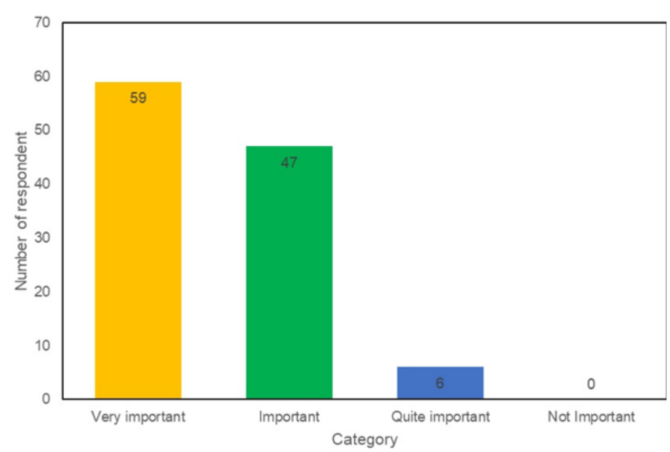

Figure 6 Results of Teachers' Opinions on the Importance of Sustainability-Oriented STEM Learning

Furthermore, Figure 7 shows that 44% of teachers reported that sustainability-oriented STEM learning is essential for advancing alternative approaches in science education. This finding indicates a strong connection between science learning and sustainability-oriented STEM learning. Science education emphasizes students' inquiry skills, which align closely with the ESD competencies they are expected to develop. In addition to inquiry, science learning also requires students to apply technology and engineering principles to solve real-world problems, which is consistent with the objectives of STEM learning (Abdurrahman et al., 2023). Therefore, integrating sustainability-oriented STEM learning into science education can cultivate students who are not only skilled in inquiry but also competent in ESD, technologically adept, and capable of engaging in engineering practices

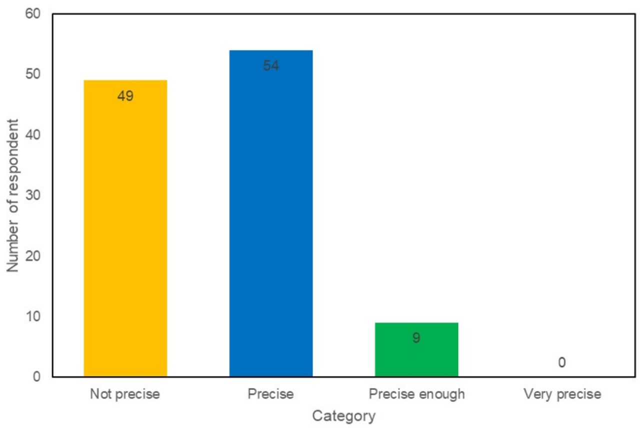

Figure 7. Results of Teachers' Opinions on the Appropriateness of Sustainability-Oriented STEM Learning in Science Subjects

The component that states the usefulness of sustainability-oriented STEM learning is further shown in Figure 8. The figure shows that 69% of teachers said that sustainability-oriented STEM learning can increase students' passion for learning science. Sustainability-oriented STEM learning requires student involvement in hands-on and interactive work in the classroom (Chien et al., 2021). Creating this learning environment can challenge and stimulate students' curiosity, which in turn can increase students' passion for learning.

STEM learning for sustainability is an innovative strategy that integrates technology to support sustainable development. Students must actively participate in all learning activities to instill knowledge, awareness, and action. Using STEM learning for sustainability that combines exploratory learning with complex science subject matter can deepen students' cognitive abilities. It also captures their attention, encouraging and enhancing their passion and creativity. Thus, learning that utilizes technology, integrates interdisciplinary knowledge, and uses state-of-the-art teaching can increase learning effectiveness, improve student participation and attitudes towards STEM learning for sustainability, and foster young minds, passions, and creativity (Juškevičienė et al., 2021).

Based on the explanation of the three components

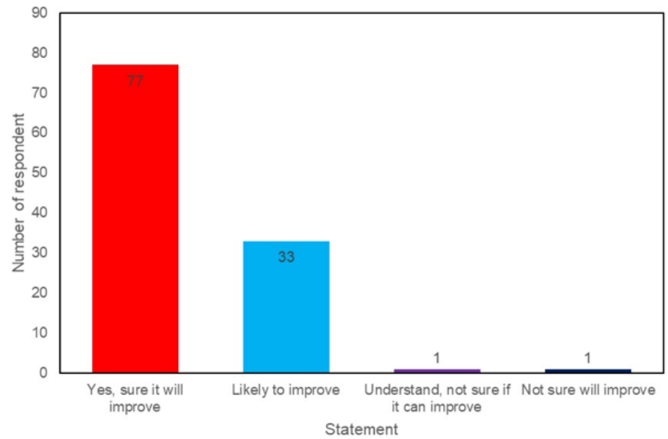

Figure 8 Results of Teachers' Opinion on the Benefits of Sustainability-Oriented STEM Learning to Increase Students' Passion in Learning

above, sustainability-oriented STEM learning plays an essential and appropriate role in being integrated into science subjects. In addition, it is believed to enhance students' motivation and engagement in learning. Sustainability-oriented STEM learning enables students to explore learning activities by developing relevant technologies that foster creativity, problem-solving, and higher-order thinking skills (Solihah et al., 2024; Septiyanto et al., 2024). These skills must be supported by strengthening teachers' competencies to facilitate effective learning. Previous studies have shown that professional development (PD) can improve teachers' competencies, enhance teaching quality, and positively influence student learning outcomes (Uerz et al., 2018). These findings highlight the need for systematic implementation of PD for science teachers in sustainability-oriented STEM learning to ensure effective classroom practices. Implementing PD prepares and strengthens teachers' competencies, enabling them to deliver sustainability-oriented STEM learning effectively. As teachers are the key agents in implementing such learning, the initial step should involve developing their competencies through PD activities such as training, workshops, seminars, and other capacity-building programs (Adebusuyi et al., 2022; Zuhaida et al., 2025).

Teachers' Initial Knowledge of Sustainability-Oriented STEM Learning

Teachers' initial knowledge is one of the most essential components of PD implementation. To improve student learning, teachers need to acquire knowledge of sustainability-oriented STEM content and specific pedagogical techniques for teaching it. PD is required to reinforce the idea that once teachers have gained new knowledge and skills, they desire to apply them to students in classroom practice (Adebusuyi et al., 2022; Chai, 2019).

The results of the open-ended questionnaire with short answers show data on teachers' initial knowledge of sustainability-oriented STEM learning seen from three aspects, namely teachers' initial understanding of STEM and ESD learning, science materials that have relevance to sustainability-oriented STEM learning, and needs in implementing sustainability-oriented STEM learning in the classroom. Based on short-answer responses from 112 teachers, most cannot explain what they know and know only the term by its definition. Teachers mentioned that STEM is a learning discipline encompassing Science, Technology, Engineering, and Mathematics. Another finding is that a small number of teachers mention that STEM is an integrated learning approach that teaches students to solve problems and can improve students' thinking skills.

Regarding ESD, most teachers were unable to describe the concept clearly, and only a small number could state what the acronym ESD stands for—Education for Sustainable Development. In terms of teachers' prior knowledge of STEM and ESD learning, the findings indicate that teachers tend to have a stronger understanding of STEM learning than of ESD. This difference in understanding corresponds to the results presented in Figures 1 and 2, which show that more teachers have never participated in training, workshops, or seminars on ESD than on STEM. Consequently, this limited exposure may have contributed to teachers' lower initial knowledge of ESD relative to their understanding of STEM.

The second aspect concerns teachers' opinions on which science materials are connected to sustainability-oriented STEM learning. The current school science curriculum structure in Indonesia does not include sustainability-oriented STEM learning subjects. So integration can be sought in specific subjects, such as science. Most teachers mentioned that all science materials can be integrated into sustainability-oriented STEM learning, but some do not know which materials to incorporate. Some of the materials cited by teachers that connect with sustainability-oriented STEM learning include substances and their changes, the solar system and celestial bodies, energy and its changes, temperature and heat, electricity, force, magnetism, biotechnology, digestive system, respiratory system, environmental issues, and biodiversity.

The connection between science material and sustainability-oriented STEM learning can be seen by linking it to one or more of the 17 Sustainable Development Goals. Science materials in the independent curriculum consist of four content areas, namely living things, substances and their properties, energy and its changes, and earth and space. One topic in living things is biodiversity and its classification. This material relates to SDGs 2 (zero hunger), as knowledge of biodiversity and its classification helps us find alternative food sources and develop superior ones by utilizing the diversity we have; SDGs 14 (marine ecosystems); and SDGs 15 (terrestrial ecosystems). The sustainability of marine and terrestrial ecosystems depends on their diversity. Therefore, it is essential to maintain biodiversity in both ecosystems.

The properties and reactions of substances are related to processes in the body's systems, such as the digestive and respiratory systems. The material aligns with several SDGs, including SDGs 2 (zero hunger), 3 (healthy and prosperous life), 6 (clean water and sanitation), and 11 (sustainable cities and settlements). The body's systems are closely linked to health and disease. They are therefore closely related to the intake of the right amount of food, clean water, sanitation, and a healthy environment (Eliyawati et al., 2023).

Energy content and its changes are related to SDG 7 (the availability of clean and affordable energy), for example, biogas. Meanwhile, the earth and space content focus on environmental issues, pollution, and climate change. The material content can be linked to SDGs 6 (access to clean water and sanitation) and 13 (climate action). Based on all the explanations above, it can be seen that almost all science materials can be associated with using sustainability-oriented STEM learning (Eliyawati et al., 2023).

The last aspect that becomes part of teachers' initial knowledge concerns their understanding of the need to implement sustainability-oriented STEM learning in science instruction. Some teachers stated they did not know what their needs were because they lacked an overview of the implementation of sustainability-oriented STEM learning. A small number of teachers mentioned that the components of teaching materials, the internet, learning media, learning methods, and the support and adequacy of infrastructure are among the needs that support sustainability-oriented STEM learning. Teachers want these components provided so they can directly practice learning in the classroom. However, most teachers revealed that technology and teacher competence are the most needed things in implementing sustainability-oriented STEM learning. Before teachers implement learning in the school, they should be equipped with sufficient competence and adequate technology.

Implementing STEM learning for sustainability requires several aspects to support effective learning. Some elements that support the implementation of learning are the availability of technological devices, relevant learning strategies, learning tools, learning facilities, stakeholder support, teacher competence, and collaboration (Bouwma-Gearhart, 2012; Gutwill & Allen, 2012; Mohd Saat et al., 2021). STEM learning for sustainability cannot be separated from the use of technology to support it, so students and teachers must be proficient in its use to ensure learning proceeds smoothly.

Strategies, tools, and learning facilities are the main aspects that cannot be separated from conducting new learning. The teacher must carefully prepare these three aspects to ensure the learning objectives are achieved optimally. Furthermore, stakeholder support, both internal and external to the school, is essential, as STEM learning for sustainability is an integrated endeavour involving many parties. The support is expected to help students and teachers become more comfortable in conducting learning and to be cultivated and recognized in the school and surrounding environments (Abdurrahman et al., 2023).

The main aspect that is needed in the implementation of sustainability-oriented STEM learning is the teacher's ability to understand, design, implement, and conduct assessments. Teachers who have the competence can certainly facilitate learning to the fullest to achieve STEM learning objectives for sustainability (Uerz et al., 2018). Another aspect that is necessary for STEM learning to be sustainable is teacher collaboration with fellow teachers, experts, or specific communities (Suwono et al., 2019). The implementation of cooperation is expected to strengthen and develop STEM learning for sustainability, considering that it is an integrative learning that can involve various disciplines.

The needs analysis, based on the questionnaire results—multiple-choice and short-answer questions to explore the three components above—revealed the need for PD implementation in sustainability-oriented STEM learning. Integrating science learning with sustainability-oriented STEM learning, teachers are not only required to have good mastery of the subjects taught, but also mastery of sustainability-oriented STEM learning, sustainability aspects related to the subject matter, and teaching strategies. So far, sustainability-oriented STEM learning has not been widely practiced and has experienced several obstacles, including 1) teachers not being equipped with STEM and ESD understanding and teaching strategies, 2) teachers' habit of focusing only on the subjects they teach, and 3) curriculum structure and lesson hour arrangements that do not support integrative learning (Eliyawati et al., 2023). Implementing PD for science teachers in sustainability-oriented STEM learning is needed to overcome these obstacles, as this study's results support. The PD is expected to be a solution in the implementation of science learning integrated with sustainability-oriented STEM learning so that teachers are ready to practice learning in the classroom.

Qualitative Thematic Analysis with Quotes

Table 5 presents the thematic synthesis of teachers' qualitative responses, including descriptions and representative quotes that illustrate each theme in their own words.

The qualitative results presented in Table 5 provide essential insights into the contextual factors influencing teachers' readiness for sustainability-oriented STEM learning. A recurrent concern was the lack of professional development opportunities, with teachers emphasizing that "*attending training first*" and "*there must be training or workshops whose results can be applied in schools*" are essential prerequisites for meaningful practice. This finding aligns with prior studies showing that teacher professional development is most impactful when it is sustained, practice-based, and closely connected to curriculum needs (Borko, 2004; Darling-Hammond et al., 2020). Without such structured opportunities, teachers are left to rely on fragmented experiences that do not adequately build capacity for integrating sustainability-oriented STEM learning.

Equally prominent were issues of resources, where teachers noted the absence of adequate facilities, media, and teaching materials, highlighting the need for "*teaching devices and teaching materials, smartphone or laptop, LCD, student worksheets,*" and "*laboratories or practice rooms.*" These findings echo Leal Filho et al. (2018), who identified insufficient infrastructure and teaching materials as significant barriers to embedding sustainability in school curricula. The scarcity of resources not only limits instructional variety but also undermines the development of practical, project-based learning that is essential to sustainability-oriented STEM learning (Leonard et al., 2016).

Challenges in curriculum alignment were also evident, with teachers noting that "*supporting resources and teacher competence are crucial*" to link sustainability-oriented STEM learning content to existing requirements. This difficulty reflects a broader tension observed globally: while sustainability-oriented STEM learning emphasizes interdisciplinary learning and sustainability competencies, national curricula often remain fragmented and content-heavy, leaving little room for innovation (IBE-UNESCO, 2020; Rieckmann, 2018).

The theme of collaboration further underscores the systemic nature of readiness, as teachers stressed the need for "*cooperation with local industries*" and peer networking to enhance 21st-century skills. Previous research highlights that collaborative professional learning communities and cross-sector partnerships are critical to sustaining pedagogical innovation (Annandale et al., 2021). Without institutionalized collaboration, teachers struggle to move beyond isolated efforts.

Interestingly, teachers also acknowledged gaps in their knowledge, noting that "*sustainability-oriented STEM learning is still understood only at a superficial level.*" This observation suggests that having awareness alone does not equate to readiness; instead, a deeper conceptual and pedagogical understanding must be intentionally developed. Similar

Table 5 Themes, descriptions, and representative quotes from teachers' qualitative responses.

Theme	Description	Representative Quotes
Training/PD	Teachers highlight the lack of training and workshops on sustainability-oriented STEM learning.	1. Attending training first. 2. Teacher training is needed to understand STEM-ESD teaching methods and how to integrate them into the curriculum. 3. There must be training or workshops whose results can be applied in schools.
Resources	Teachers emphasize the need for facilities, media, and teaching materials.	1. Teaching devices and teaching materials, Smartphone/laptop, LCD, student worksheets. 2. Interactive learning resources such as books, videos, and software are needed to support sustainability-oriented STEM learning. 3. Laboratories or practice rooms should be provided for experiments and projects.
Curriculum	Teachers mention challenges aligning sustainability-oriented STEM learning with curriculum requirements.	1. Almost all science material can be linked. 2. Science materials should be appropriate and in accordance with students' needs. 3. Supporting resources and teacher competence are crucial.
Collaboration	Teachers stress the importance of collaboration and peer networking.	1. Cooperation with local industries should be established to give practical insights into STEM. 2. Perseverance, critical thinking, and collaboration are needed. 3. STEM aims to improve 21st-century skills, including critical, creative, and collaborative thinking.
Knowledge	Teachers reveal limited knowledge and superficial understanding of sustainability-oriented STEM learning.	1. A learning approach that emphasizes the relationship between knowledge and skills in science, technology, engineering, art, and mathematics (STEAM) to solve problems. 2. Education that encourages changes in knowledge, skills, values, and attitudes to create a more sustainable and just society. 3. Sustainability-oriented STEM learning is still understood superficially.
Attitudes	Teachers express motivation, enthusiasm, and positive attitudes toward sustainability-oriented STEM learning.	1. Education should encourage motivation, values, and attitudes to enable a more sustainable society. 2. Sustainability-oriented STEM learning can build enthusiasm and positive attitudes in students. 3. Education should develop awareness and responsibility for sustainability.
Barriers	Teachers identify obstacles such as time, workload, and institutional support.	1. STEM in the learning process aims to overcome challenges in teaching. 2. ESD aims to prepare students to face global challenges. 3. Time and workload challenges make it difficult to design sustainability-oriented STEM lessons.

findings were reported by Herro and Quigley (2017), who noted that teachers often express confidence in theory but lack clarity when applying STEM approaches to sustainability-related issues.

At the same time, teachers expressed positive attitudes and motivation, viewing sustainability-oriented STEM learning as a way to "build enthusiasm and positive attitudes in students" and to promote sustainability awareness. This finding is encouraging, as positive teacher attitudes are recognized as a powerful predictor of successful innovation adoption. Yet, these aspirations are tempered by reported barriers, particularly time and workload constraints, with one teacher stating, *"time and workload challenges make it difficult to design sustainability-oriented STEM learning lessons."* Such barriers are consistent with prior research identifying institutional support and workload management as critical determinants of teacher readiness (Septiyanto et al., 2023).

4. CONCLUSION

This study concludes that science teachers exhibit a moderate level of readiness to implement sustainability-oriented STEM learning, supported by high reliability across the four measured constructs: Knowledge, Skills, Professionalism, and Collaboration. Correlation analysis confirmed meaningful relationships among these dimensions, and the radar plot illustrated relatively stronger profiles in Knowledge and Skills but weaker outcomes in Professionalism and Collaboration. The inferential analysis demonstrated that participation in ESD training significantly improved readiness with a moderate-to-large effect size, whereas STEM training alone did not yield significant differences. The qualitative findings further enriched these results by identifying seven major themes: limited training opportunities, lack of resources, challenges with curriculum alignment, collaboration needs, superficial knowledge, positive attitudes, and systemic barriers such as workload and institutional support. Collectively, these results indicate that while teachers are motivated and possess a foundation of knowledge and skills, their overall readiness remains constrained by systemic limitations. By addressing these systemic gaps, teachers' readiness can be elevated from moderate to advanced levels, thereby ensuring the meaningful integration of sustainability-oriented STEM learning in science education and preparing students with the competencies needed to address future sustainability challenges.

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