ORIGINAL ARTICLE

Sustainability-Oriented STEM Professional Development Program: Developing Teachers' Competencies

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Abstract: This study examines the effects of a six-day sustainability-oriented STEM professional development (PD) program on teachers' conceptual understanding of sustainability and sustainable development, their sustainability literacy, and their capacity to integrate these concepts into STEM instructional practices. A qualitative holistic case study design was employed, drawing on comparative analysis of pre- and post-program data. The participants consisted of 16 volunteer teachers from different subject areas with varying levels of professional experience. Data were collected using a researcher-developed open-ended questionnaire comprising 10 items and were analyzed through qualitative content analysis involving open coding and thematic comparison. The findings indicate that prior to the program, teachers' understandings of sustainability and sustainable development were largely fragmented and predominantly focused on environmental dimensions, while STEM was commonly perceived as a discipline-based approach. Following participation in the program, most teachers developed more multidimensional and systems-oriented perspectives integrating environmental, economic, and social dimensions. These conceptual shifts were reflected in instructional practice, as teachers demonstrated increased competence in designing planned, problem-based STEM activities grounded in the engineering design process and explicitly aligned with sustainability themes. However, a small number of teachers exhibited limited or no change in specific conceptual or instructional dimensions, highlighting the non-linear and context-dependent nature of professional learning in sustainability education. Overall, the results suggest that sustainability-oriented STEM PD can support transformative learning by strengthening the alignment between conceptual understanding, sustainability literacy, and pedagogical implementation, underscoring the importance of practice-oriented and interdisciplinary professional development designs.

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The authors affirm that artificial intelligence did not contribute to the process of preparing the work. Ethical Statement.

Introduction

THE CHALLENGES faced by contemporary societies have been intensified by climate change, depletion of natural resources, biodiversity loss, and increasing social inequalities (United Nations, 2015). As a result, sustainability has become a central priority for global communities. Sustainability is defined as an approach that seeks to meet present needs without compromising the ability of future generations to meet their own needs, while balancing environmental, economic, and social dimensions (Evans et al., 2017; Ferreira et al., 2019). The United Nations' 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) provide a comprehensive framework and action plan to address these challenges. Among these objectives, Quality Education (SDG 4) plays a pivotal role in equipping individuals with the knowledge, skills, and values necessary to advance sustainable development (UNESCO, 2020).

To build a sustainable future, education systems must move beyond approaches focused solely on transmitting knowledge. Instead, they should create learning environments that enable individuals to critically and systematically analyze complex socio-scientific issues (Felix et al., 2025). In this context, sustainability education aims not only to raise environmental awareness but also to help individuals understand the interrelationships among the environmental, social, and economic dimensions of sustainable development, enabling informed decision-making (Chen & Wu, 2024; UNESCO, 2017). This approach emphasizes the development of higher-order cognitive skills, such as critical thinking, systems thinking, and collaborative problem-solving, while prioritizing interdisciplinary and practice-based learning environments (Gamage et al., 2022).

Such interdisciplinary perspectives naturally intersect with STEM-based pedagogies. Educational approaches that integrate science, technology, engineering, and mathematics (STEM) closely align with the objectives of sustainability education (Awad et al., 2025; Routray & Mohanty, 2024). STEM education provides a practical framework that enables students to connect scientific knowledge with engineering design processes to address real-world environmental, social, and economic challenges. This interdisciplinary structure facilitates the integration of sustainability-related themes– such as energy efficiency, renewable energy, and waste management– into instructional practice, while supporting the development of students' systems thinking and problem-solving skills (Fathurohman et al., 2023; Okonkwo et al., 2024).

The literature emphasizes that for sustainability education to be implemented effectively, teachers must have both strong conceptual knowledge and practice-oriented pedagogical competencies (Bürgener & Barth, 2018; Ferreira et al., 2019; Robinson et al., 2022). Sustainability literacy requires teachers to understand the interdependent relationships among environmental, economic, and social systems and to integrate these relationships into instructional processes in a comprehensive and coherent manner (Barth & Rieckmann, 2016; Evans et al., 2017). However, existing research indicates that teachers often conceptualize sustainability primarily in environmental terms and face challenges incorporating its economic and social dimensions into pedagogical practice (Bürgener & Barth, 2018; Ferreira et al., 2019; Robinson et al., 2022). This research gap underscores the need for practice-based professional development (PD) programs that enable teachers to approach sustainability from an interdisciplinary and systems-oriented perspective (Mogensen & Schnack, 2010; UNESCO, 2017).

STEM teachers' competencies constitute a multidimensional construct in the context of sustainability-oriented instruction. These competencies include integrating interdisciplinary content knowledge, applying the engineering design process, creating problem-based learning environments, systems thinking, and fostering students' higher-order cognitive skills (Ferreira et al., 2019; Milner-Bolotin & Martinovic, 2025). However, previous studies indicate that teachers' experiences with STEM-sustainability integration are often limited, and current practices tend to remain largely theoretical rather than applied (Gamage et al., 2022; Routray & Mohanty, 2024). Although the number of studies focusing on integrating STEM pedagogy and sustainability education has increased, qualitative evidence on how teachers experience and implement this integration in classroom practice remains scarce (Bürgener & Barth, 2018; Robinson et al., 2022).

Recent studies indicate that integrating sustainability education with STEM pedagogy strengthens teachers' systems thinking, critical analysis, creative problem-solving, and innovative design skills (Gamage et al., 2022; Li, 2025; Tarlochan et al., 2025). However, research also shows that teachers continue to conceptualize sustainability primarily in environmental terms and tend to approach STEM practices in a fragmented way (Bürgener & Barth, 2018; Robinson et al., 2022). This persistent tendency underscores the need for structured PD initiatives that help teachers engage with sustainability from a systems-oriented, holistic perspective (Barth & Rieckmann, 2016; Ferreira et al., 2019).

Practice-based PD programs have been shown to deepen teachers' conceptual understanding of sustainability and strengthen the integration of STEM and sustainability within instructional practice (Milner-Bolotin & Martinovic, 2025; Okonkwo et al., 2024). However, studies that systematically document how this transformation occurs through qualitative data comparing pre- and post-program findings remain limited (Ferreira et al., 2019; Gamage et al., 2022). Consequently, existing research highlights the need for comprehensive investigations that examine both the conceptual and practical dimensions of teachers' PD in sustainability-oriented STEM pedagogy.

This study addresses a research gap by examining the effects of sustainability-oriented STEM education on teachers' conceptual knowledge and instructional competencies, using a qualitative research design with systematic pre- and post-program comparisons. Instead of an experimental pretest–posttest approach, the study uses comparative qualitative data to capture changes in teachers' understanding and classroom practice during a structured PD program. The originality of this study lies in its analysis of teachers' competency development not only as individual knowledge acquisition, but as an interrelated process involving interdisciplinary coherence, systems thinking, and the implementation of sustainability-oriented STEM practices. Additionally, by conceptualizing sustainability literacy within a systems-literacy framework, the study offers an integrative perspective that aligns with and extends current directions in the literature (Li, 2025; Milner-Bolotin & Martinovic, 2025).

Accordingly, the present study seeks to address the following research questions:

1. In what ways does sustainability-oriented STEM education influence teachers' conceptual understanding of sustainability and sustainable development?
2. To what extent, and in what ways, do teachers' understandings of sustainability literacy change before and after participating in the PD program?
3. In what ways does the educational process affect teachers' competencies in planning and implementing sustainability-oriented STEM practices?

Method

Research Design

This study used a qualitative approach to examine in depth the effects of sustainability-oriented STEM education on teachers' conceptual understanding and pedagogical implementation competencies. Rather than employing an experimental pretest–posttest design, the study was structured as a holistic single-case study within a qualitative research framework.

In the study, pre- and post-program data were not used for quantitative effect comparison; instead, they were used to comparatively and descriptively examine changes in teachers' conceptualizations and practice-oriented perceptions related to sustainability, sustainable development, and STEM integration before and after participation in the PD program. In this respect, the study is a case study based on qualitative data comparisons conducted before and after the program.

Table 1. Participants' Demographic Characteristics.

Variable	Category	f
Gender	Female	13
	Male	3
Teaching Field	Preschool Education	3
	Primary School Teaching	5
	Science Education	8
Graduate Education Level	Master's Degree	10
	Doctoral Degree	6
Institution Type	Public School	9
	Private School	4
	Science and Art Center	3
Participation in STEM-related Projects/Training	Yes (TÜBİTAK 4004–4005 and others)	6
	No	10
Age	20–29	6
	30–39	4
	40 and above	6
Professional Experience (Years)	1–5 years	4
	6–10 years	4
	11–15 years	4
	16 years and above	4

The research design followed the holistic single-case study framework as defined by Yin (2018). The case examined is the PD process of a group of teachers who participated in a sustainability-oriented STEM education program. This approach enables a comprehensive examination of the program's effects on teachers within its specific contextual conditions. Hence, the purpose of the study is not to achieve statistical generalization but to provide an in-depth description and interpretation of teachers' conceptual changes, the development of systems thinking, and shifts in pedagogical implementation competencies experienced throughout the sustainability-oriented STEM education process.

Participants

The participants were 16 volunteer teachers from diverse subject areas and with varying levels of teaching experience and enrolled in the sustainability-oriented PD program on STEM education. This PD program was conducted as part of STEM education for teachers supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under a call coded 2237A. **Table 1** presents the participants' demographic characteristics.

As shown in **Table 1**, the participants taught in preschool education (f = 3), primary school teaching (f = 5), and science education (f = 8), with the majority being female (f = 13). Ten teachers were pursuing master's degrees, and six were enrolled in doctoral programs. The participants were employed in public schools (f = 9), private schools (f = 4), and Science and Art Centers (f = 3). Six had previously participated in a STEM-related project or training program. The distribution of participants by age and professional experience indicates a balanced sample suitable for examining the effects of sustainability-oriented STEM education across different levels of teaching experience.

Data Collection Instrument

The data collection instrument was a form developed by the researcher, containing 10 open-ended questions on sustainability, sustainable development, STEM education, and teacher competencies (***Appendix 1***). The form was administered before and after participation in the PD program. The open-ended questions were intended to elicit teachers' conceptual understandings, instructional experiences, and perceptions of PD (Patton, 2015).

To establish the content validity of the instrument, a structured expert review process was conducted. The draft questionnaire was evaluated by two academics with recognized expertise in sustainability education, STEM education, and teacher professional development. The experts were asked to rate each item using a four-point scale (1 = not appropriate, 4 = highly appropriate) with respect to its relevance to the research objectives, conceptual clarity, adequacy of coverage, and suitability for the target participant group.

Based on the experts' ratings, item-level content validity indices (I-CVI) were calculated in accordance with established content validity guidelines (Polit & Beck, 2006). Items with I-CVI values below the acceptable threshold (.80) were revised in response to the experts' qualitative feedback to enhance clarity and alignment with the study objectives. Following these revisions, all items met the recommended I-CVI criteria, and the scale-level content validity index (S-CVI/Ave) was calculated as .92, indicating a high level of content validity (Polit et al., 2007).

Revisions primarily targeted items related to instructional implementation and the frequency of STEM practices in order to improve the precision of expected responses. Specifically, items addressing the frequency of STEM implementation were refined to elicit clearer descriptions of regularity and associated content areas, while items focusing on STEM–sustainability integration were revised to prompt more concrete, practice-based examples. The finalized instrument was administered using the same set of questions in both the pre- and post-program phases, ensuring methodological consistency and supporting the credibility and dependability of the qualitative comparisons.

Implementation Process

The sustainability-oriented STEM education in this study was conducted as part of a six-day PD program supported by the TÜBİTAK 2237-A Scientific

Table 2. Content of Sustainability-Oriented STEM PD Program.

Day	Main Theme	Application Examples (Brief Description)	Theoretical	Practical
Day 1	Introduction to Sustainability and STEM	Pre-program data collection; sustainability concepts; global environmental issues; fundamentals of STEM	8 hrs (80%)	2 hrs (20%)
Day 2	STEM Methods and Green Engineering	Problem- and project-based learning; 5E model; "Melting Woolly Mammoth" (thermal insulation design)	4 hrs (40%)	6 hrs (60%)
Day 3	Energy and Socioscientific Issues	Renewable energy; sustainable cities; "Sustainable Greenhouse"; digital storytelling	3 hrs (38%)	5 hrs (62%)
Day 4	Sustainable City and Lesson Design	Sustainable city model design; STEM lesson planning	3 hrs (38%)	5 hrs (62%)
Day 5	21st-Century Skills and Clean Water STEM	Critical and creative thinking; water filter design activity	3 hrs (60%)	2 hrs (40%)
Day 6	Project Presentations and Evaluation	Mathematical modeling; project presentations; peer assessment; post-program data collection	2 hrs (40%)	3 hrs (60%)
Total	—	—	**23 hrs (43%)**	**30 hrs (57%)**

Education Activities Support Program. The content of the PD program is presented in **Table 2**.

As shown in **Table 2**, the PD program in the study consisted of 53 hours, with 43% allocated to theoretical sessions and 57% to practice-based activities. The first two days focused on establishing participants' theoretical foundations in sustainability, global environmental issues, and the STEM approach, while the following days emphasized applying this knowledge to real-world, engineering design–based practices.

The hands-on activities included engineering design process–based applications focused on sustainable development themes, such as the "Melting Woolly Mammoth" (thermal insulation), "Sustainable Greenhouse," "Sustainable City Model," and "STEM Application for Clean Water" (water filter design). The project presentations and evaluation sessions held on the final day of the program helped teachers consolidate their learning outcomes related to STEM-sustainability integration and complete the professional reflection process.

Data Analysis

The qualitative data were analyzed using qualitative content analysis, following the procedures outlined by Miles, Huberman, and Saldaña (2014). The analysis was conducted through multiple iterative stages to ensure systematic coding, analytic rigor, and transparent theme development.

In the first stage, all pre- and post-program responses were read repeatedly to achieve thorough familiarization with the data. Open coding was then employed to identify meaningful units within the teachers' written responses. These initial codes were generated inductively and were grounded in recurring concepts, expressions, and instructional descriptions related to sustainability, sustainable development, STEM education, and classroom practices.

In the second stage, conceptually similar codes were clustered and organized into broader categories. This categorization process was informed by both the study's research questions and relevant literature on sustainability education, sustainability literacy, and STEM pedagogy. Through constant comparison across participants and between the pre- and post-program datasets, higher-order themes were developed to capture patterns in teachers' conceptual understanding and instructional implementation.

The coding framework explicitly distinguished between conceptual-level categories (e.g., teachers' definitions and understandings of sustainability, such as single-dimensional versus multidimensional conceptions) and implementation-level categories (e.g., the presence, quality, and characteristics of STEM- and sustainability-oriented instructional practices, such as example-free implementation versus planned, example-based implementation). This distinction provided the analytical foundation for the themes presented in the *Findings* section and informed the summary structure of **Table 10**. Specifically, **Table 10** was designed to synthesize overall trends by aggregating codes related to both the level of sustainability-related content knowledge and the nature of instructional implementation, thereby enabling a holistic comparison of changes observed before and after the professional development (PD) program.

To ensure traceability while maintaining confidentiality, each participating teacher was assigned a unique identifier (T1–T16), which was used consistently throughout the analysis and reporting of findings. This approach enabled systematic comparison of individual teachers' responses across the pre- and post-program phases while preserving participant anonymity. The same coding framework was applied consistently to both datasets, supporting systematic within-participant and cross-phase analyses of changes in teachers' responses.

Validity and Reliability

To ensure the trustworthiness of the qualitative findings, strategies addressing credibility, dependability, and confirmability were employed. Credibility was enhanced by using pre- and post-program data, which enabled the examination of change over time and supported consistent interpretations across datasets. Additionally, incorporating direct teacher quotations during coding grounded the findings in participants' perspectives.

Dependability was strengthened by involving two independent researchers with expertise in qualitative research in the coding process. The researchers coded the data independently, and intercoder reliability was calculated using the formula proposed by Miles, Huberman, and Saldaña (2014) (reliability = agreement / [agreement + disagreement]), resulting in a reliability coefficient of 87%. This value exceeds the commonly accepted 80% threshold in qualitative research, indicating a reliable coding process. Coding discrepancies were discussed until consensus was reached, and the coding framework was finalized accordingly.

Confirmability was supported by maintaining a transparent and systematic data analysis procedure, including documentation of coding decisions and theme development. The involvement of multiple researchers in the analysis process further reduced potential researcher bias and ensured that the findings were grounded in the data rather than individual interpretations.

Ethics Committee Approval and Permission

Ethical approval for this research was obtained from the university's Ethics Committee of Scientific Research and Publication in Social and Human Sciences (Meeting No. 2025/19; Decision No. 29, dated December 29, 2025).

Findings

This section presents the findings from teachers' responses collected before and after the sustainability-oriented STEM PD program. The findings are examined across two dimensions: conceptual competence and instructional implementation competence. Overall, the results show changes in teachers' understanding of sustainability- and STEM-related concepts, as well as their capacities to integrate and apply their knowledge in instructional practices.

Findings Related to Conceptual Competence

This subsection presents changes during the PD program in teachers' knowledge and awareness of sustainability, sustainable development, the Sustainable Development Goals (SDGs), STEM, and sustainability literacy. The findings are based on a comparative analysis of teachers' pre- and post-program responses to Questions 2, 3, 4, 5, and 10 of the open-ended questionnaires.

Conceptual Competence in Sustainability

Table 3 presents the findings on participants' understanding of the concept of sustainability.

As shown in **Table 3**, before the program, most participants (f = 10) defined sustainability in a one-dimensional way, primarily focusing on envi-

Table 3. Conceptual Competence in the Sustainability.

Theme	Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
Conceptual Competence in Sustainability	Single-dimensional definition (environment only)	T1, T3, T4, T6, T8, T9, T10, T12, T13, T14	10	T4, T9	2
	Multi-dimensional definition (environment–economy–society)	T2, T5, T7, T11	4	T1, T2, T3, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15	14
	Emphasis on future generations	T5, T6, T8	3	T5, T6, T8, T9, T10, T12, T13, T15, T16, T4, T3, T11, T1	13
	Conceptual ambiguity / incomplete expression	T2, T4, T7, T9, T10, T11	6	T7	1

Note: One participant may have been coded under more than one category.

ronmental protection. This was followed by responses indicating conceptual ambiguity (f = 6), multidimensional definitions (f = 4), and references emphasizing future generations (f = 3). These findings indicate that teachers' conceptual frameworks regarding sustainability were limited prior to the program. For example, one teacher (T3) stated in the pre-program phase, "*Sustainability means protecting the environment and avoiding harm to nature*," reflecting this narrow conceptualization.

Following the program, teachers approached sustainability from a more comprehensive perspective. As articulated by another teacher (T5) in the post-program phase, "*I now understand more clearly that sustainability is a concept based on the relationships among the environment, the economy, and society*." This statement illustrates the conceptual shift observed after the program.

However, **Table 3** also shows that not all participants demonstrated change across all conceptual dimensions. Specifically, two teachers (T4 and T9) continued to define sustainability in a single-dimensional manner following the program, and one teacher (T7) still displayed conceptual ambiguity in the post-program responses. These cases indicate that, despite an overall shift toward more multidimensional and future-oriented understandings, some participants' conceptualizations remained largely consistent with their pre-program perspectives.

Overall, these findings suggest that sustainability-oriented STEM education supported teachers in moving beyond viewing sustainability solely as an environmental concept, fostering a more comprehensive understanding that recognizes the interrelationships among environmental, economic, and social dimensions. At the same time, the persistence of unchanged conceptual patterns among a small number of participants underscores variability in

Table 4. Knowledge of Sustainable Development.

Theme / Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
Inability to provide a definition	T1, T2, T3, T4, T5, T6, T8, T9	8	T9	1
Explanation limited to the economic dimension	T7, T10, T11, T12, T13	5	T5, T7	2
Holistic explanation (economic–social–environmental)	T14, T15, T16	3	T1, T2, T3, T4, T5, T6, T7, T8, T10, T11, T12, T13, T14	13

teachers' responses to the program. Taken together, these findings indicate that teachers increasingly conceptualized sustainability from a systems-oriented perspective.

Knowledge of Sustainable Development and the Sustainable Development Goals

The findings on participants' knowledge of sustainable development and the Sustainable Development Goals (SDGs) are presented in **Tables 4** and **5**.

As shown in **Table 4**, before the program, a substantial proportion of participants (n = 8) struggled to define sustainable development, with responses primarily focusing on the economic dimension (n = 5). These findings indicate that teachers' conceptual clarity about sustainable development was limited prior to the program. For example, one teacher (T7) stated in the pre-program phase, "*I think it is mostly related to economic development*," reflecting a limited understanding.

Following the program, teachers conceptualized sustainable development more comprehensively, incorporating environmental, economic, and social dimensions. As another teacher (T12) expressed, "*Sustainable development is an approach in which the economy, the environment, and society are addressed together*," clearly demonstrating the development of a more holistic understanding of the concept.

However, **Table 4** also indicates that change was not uniform across participants. Specifically, one teacher (T9) was still unable to articulate a definition of sustainable development in the post-program phase, and two teachers (T5 and T7) continued to frame the concept primarily in economic terms. These findings suggest that, while most participants demonstrated a shift toward more holistic explanations following the program, a small number of teachers retained conceptions similar to those expressed prior to their participation.

Overall, these results indicate that sustainability-oriented STEM education facilitated a shift from economically narrow interpretations of sustainable development toward a more integrated understanding that acknowledges

Table 5. Knowledge of the Sustainable Development Goals (SDGs).

Theme / Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
No prior knowledge	T1, T2, T3, T4, T5, T6, T7, T8, T10	9	T2	1
Awareness of the SDGs	T9, T11, T12, T13, T14	5	T1, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15	14
Linking the SDGs to instructional content	T15, T16	2	T3, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T16	12

the interconnections among environmental, economic, and social dimensions. At the same time, the persistence of unchanged or only partially developed conceptualizations among a small number of participants underscores variation in the extent to which teachers' understandings evolved over the course of the program.

As shown in **Table 5**, the findings indicate that teachers' awareness of the Sustainable Development Goals (SDGs) was limited before the program. Before the program, a large proportion of participants (f = 9) reported not knowing the SDGs. In contrast, fewer participants (f = 5) reported familiarity with the goals, and only a small number (f = 2) could relate the SDGs to instructional content. This limited awareness is reflected in the pre-program statement of one teacher (T6), who noted, "*I had not previously examined the Sustainable Development Goals*."

Following the program, teachers began addressing the SDGs within instructional contexts. One teacher (T9) stated, "*I realized that the Sustainable Development Goals can be linked to learning outcomes*," while another teacher (T11) remarked, "*I now think that I can integrate the SDGs into my teaching by connecting them with STEM activities such as energy, clean water, and city planning*." These statements indicate that teachers developed a more structured understanding of how to integrate the SDGs into STEM instructional activities.

However, **Table 5** also indicates that change was not uniform across all participants. Specifically, one teacher (T2) continued to report having no prior knowledge of the Sustainable Development Goals (SDGs) in the post-program phase. Moreover, although many teachers demonstrated increased awareness of the SDGs, some did not advance to explicitly integrating the SDGs into their instructional content, highlighting variation in the depth of change across participants.

Overall, the findings indicate that the program reduced teachers' conceptual ambiguities regarding sustainable development and strengthened their capacity to integrate the Sustainable Development Goals into instructional practices in a functional manner. This shift suggests that teachers be-

Table 6. Conceptual Knowledge of Sustainability Literacy.

Theme / Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
No prior knowledge	T1, T2, T3, T4, T5, T6, T7, T8, T9, T10	10	T2	1
Recognition of the concept	T11, T12, T13, T14	4	T1, T4, T6, T10, T11	5
Guiding students	T15, T16	2	T3, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T15	12

gan to view sustainable development not merely as an abstract policy framework, but as a pedagogical resource actively employed in teaching and learning. At the same time, the persistence of limited or unchanged responses among a small number of participants highlights variation in the extent to which teachers engaged with and internalized SDG-related content over the course of the program.

Conceptual Competence in Sustainability Literacy

The findings from the analysis of participants' responses on sustainability literacy are presented in **Table 6**.

As shown in **Table 6**, before the program, most teachers reported not knowing the concept of sustainability literacy (f = 10). This lack of awareness is clearly reflected in the pre-program statement of one teacher (T3), who noted, "*I had not previously heard of the concept of sustainability literacy*."

Following the program, teachers conceptualized sustainability literacy as a comprehensive competence that integrates environmental, economic, and social dimensions. For example, one teacher (T8) described sustainability literacy as "*a competence that enables students to make informed decisions by evaluating the relationships among these dimensions*," indicating the development of a systems literacy–oriented understanding. These findings suggest that the program strengthened teachers' conceptual awareness and supported the emergence of a guidance-oriented professional role, in which teachers view themselves as facilitators of students' sustainability-related learning.

However, **Table 6** also shows that change was not uniform across all participants. Specifically, one teacher (T2) continued to report having no prior knowledge of sustainability literacy in the post-program phase. Furthermore, while many teachers progressed toward describing sustainability literacy in terms of a guiding role for students, some participants remained at the level of conceptual recognition and did not explicitly articulate a guid-

Table 7. Conceptual Knowledge of STEM Education.

Theme / Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
Fragmented or incorrect definition	T1, T2, T3, T4, T6, T8, T10	7	T3	1
Emphasis on interdisciplinary integration	T5, T7, T9, T11, T12, T13	6	T1, T2, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16	15
Problem-based learning / engineering design process	T9, T11, T12, T13	4	T2, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15	13

ance-oriented pedagogical role. These findings point to variation in the depth of both conceptual and pedagogical change among participants.

Overall, these results indicate that sustainability-oriented STEM education enhanced teachers' sustainability literacy not only in terms of conceptual knowledge, but also with respect to systems thinking and the competencies required to guide students' learning processes. At the same time, the persistence of limited or unchanged responses among a small number of teachers highlights variation in the extent to which participants engaged with and internalized the concept of sustainability literacy over the course of the program. Taken together, these findings suggest that teachers' increasing tendency to conceptualize sustainability as a relational and dynamic system reflects an evolution of sustainability literacy into a pedagogical competence.

Conceptual Knowledge of STEM

The findings on participants' conceptual knowledge of STEM are presented in **Table 7**.

As shown in **Table 7**, before the program, teachers predominantly conceptualized STEM in a fragmented way, often limiting it to science experiments or the use of technology (f = 7). This limited conceptualization is reflected in the pre-program statement of one teacher (T2), who noted, "*When I think of STEM, I mostly think of coding activities conducted in science classes*."

Following the program, teachers conceptualized STEM as an interdisciplinary, problem-based, and sustainability-oriented instructional approach. For example, one teacher (T9) stated, "*STEM is a process that enables students to solve a problem by using multiple disciplines together,*" clearly illustrating this conceptual shift. In addition, another teacher (T6) remarked, *"STEM allows sustainability-related topics to be integrated with the engineering design process*," indicating that the program fostered a more comprehensive understanding of STEM.

However, **Table 7** also indicates that change was not uniform across all participants. Specifically, one teacher (T3) continued to offer a fragmented or partially inaccurate definition of STEM in the post-program phase. Moreover, although most teachers emphasized interdisciplinary integration following the program, some participants did not explicitly reference problem-based learning or the engineering design process in their post-program responses, suggesting variation in the depth of conceptual change.

Overall, these findings indicate that the program facilitated a shift from teachers fragmented and discipline-bound perceptions of STEM toward a problem-based approach grounded in the engineering design process. At the same time, the persistence of limited or unchanged conceptualizations among a small number of participants underscores variation in the extent to which teachers internalized and articulated key components of STEM education. Taken together, these findings suggest that STEM evolved from being perceived primarily as a teaching method to being understood as a comprehensive pedagogical framework for addressing sustainability-oriented real-world problems.

Findings Related to Instructional Implementation Competence

This subsection examines changes in teachers' competencies in integrating and implementing sustainability and STEM concepts into instructional processes. The findings are based on an analysis of responses to Questions 6, 7, 8, and 9 of the open-ended questionnaires. These questions were designed to explore teachers' capacities to guide STEM practices, the types of activities students implemented, the inclusion of sustainability-related content in lessons, and the extent to which such content was integrated into STEM-based activities.

STEM Implementation Competence

The findings on participants' STEM implementation competence are presented in **Table 8**.

As shown in **Table 8**, before the program, many teachers either did not implement STEM activities at all (f = 8) or engaged in irregular, example-free practices (f = 5). This pattern indicates that teachers had limited experience with pedagogical planning for STEM implementation. This limitation is clearly reflected in the pre-program statement of one teacher (T10), who noted, "*I did not implement STEM activities in a planned manner in my lessons*." Similarly, another teacher (T7) stated, "*I sometimes conduct small STEM activities in science classes, but not regularly,*" suggesting a lack of a systematic approach to implementation.

Table 8. Competence of STEM Implementation.

Theme / Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
No implementation	T1, T2, T3, T4, T6, T8, T9, T10	8	T3	1
Irregular or example-free implementation	T5, T7, T11, T12, T13	5	T5, T11	2
Planned and example-based implementation	T14, T15, T16	3	T1, T2, T4, T5, T6, T7, T8, T9, T10, T11, T12, T13, T15	13

Following the program, teachers shifted toward planned and example-based STEM practices. For instance, one teacher (T15) reported, "*I planned a STEM activity addressing energy conservation through the engineering design process*," indicating that STEM activities were increasingly aligned with lesson objectives and sustainability themes. In addition, another teacher (T12) remarked, "*I can now design at least one STEM activity in each unit and link it to the intended learning outcomes*," demonstrating a marked improvement in teachers' planned implementation competence.

However, **Table 8** also indicates that change was not uniform across all participants. Specifically, one teacher (T3) continued to report no implementation of STEM activities in the post-program phase. Additionally, two teachers (T5 and T11) remained at the level of irregular or example-free implementation, indicating that, despite overall improvement, some participants' instructional practices exhibited limited change relative to their pre-program responses.

Overall, the findings indicate that sustainability-oriented STEM education substantially strengthened teachers' implementation competence, enabling them to design STEM activities in a planned, purposeful, and learning-outcome–aligned manner. At the same time, the persistence of unchanged or only partially developed implementation practices among a small number of teachers highlights variation in the extent to which participants translated program experiences into classroom practice. Despite this variation, the overall pattern of change suggests that teachers began to approach STEM practices not as isolated or temporary activities, but as sustainable pedagogical practices embedded within their instructional planning.

Integration of STEM and Sustainability

The findings from participants' responses about the integration of STEM and sustainability are presented in **Tables 9** and **10**.

As shown in **Table 9**, before the program, most teachers did not address STEM and sustainability concepts in an integrated way (f = 9). This situation is reflected in the pre-program statement of one teacher (T1), who

Table 9. STEM–Sustainability Integration.

Theme / Code	Pre-Program: Teacher Codes	Pre-Program: f	Post-Program: Teacher Codes	Post-Program: f
No integration	T1, T2, T3, T4, T6, T8, T9, T10, T11	9	T2	1
Limited integration	T5, T7, T12, T13	4	T5, T7, T9	3
Explicit and deliberate integration	T14, T15, T16	3	T1, T3, T4, T5, T6, T7, T8, T10, T11, T12, T13, T15	12

noted, "*I did not address sustainability topics together with STEM activities*."

Following the program, teachers linked STEM practices with sustainability-oriented problems. For example, one teacher (T6) stated, "*I integrated the topic of energy efficiency into a STEM activity,"* while another teacher (T9) explained, *"I planned a STEM project focused on the conservation of water resources.*" These statements indicate that the integration of STEM and sustainability became more deliberate after the program.

However, **Table 9** also indicates that change was not observed uniformly across all participants. Specifically, one teacher (T2) continued to report no integration of STEM and sustainability in the post-program phase. In addition, three teachers (T5, T7, and T9) demonstrated only limited integration after the program, indicating that, although integration increased overall, some participants' practices remained at a partial or surface level compared to others.

Overall, these findings suggest that, by the end of the program, teachers began to view STEM and sustainability not as separate instructional domains, but as complementary and mutually reinforcing pedagogical approaches. At the same time, the persistence of limited or unchanged integration practices among a small number of participants highlights variation in the extent to which teachers translated program experiences into interdisciplinary classroom practice. Taken together, these findings indicate a strengthening of teachers' interdisciplinary thinking competencies and their ability to more deliberately incorporate sustainability-oriented problem-solving processes into classroom practice.

Findings Related to Knowledge of Sustainability-Oriented Content and Its Transformation into STEM Practices

As shown in **Table 10**, the findings illustrate changes in teachers' knowledge of sustainability-related instructional content and their competencies in trans

Table 10. Knowledge of Sustainability-Oriented Content and STEM Practices.

Theme	Code	Pre-Program (f)	Post-Program (f)	Description
Content Level	Limited / environmentally focused	15	4	Limited to recycling and environmental protection
Content Level	Holistic (environment–economy–society)	7	13	Energy, biodiversity, and social dimensions
Implementation Level	No STEM implementation / example-free	12	3	Inability to provide concrete implementation examples
Implementation Level	Planned and example-based STEM practices	4	11	Based on the engineering design process
Implementation Level	Real-life problem–based	3	10	Project- and problem-based STEM activities

Note: Teacher codes are not included in this table. The table was designed to provide a holistic summary of general trends in teachers' sustainability-related content knowledge and STEM implementation competencies before and after the sustainability-oriented STEM education program. Detailed findings based on teacher codes are presented in the text through direct quotations.

forming this content into STEM-based practices before and after the sustainability-oriented STEM education program.

As shown in **Table 10**, the findings provide a comprehensive overview of the changes in teachers' knowledge of sustainability-related instructional content and their STEM implementation competencies before and after the sustainability-oriented STEM education program. Before the program, teachers' knowledge of sustainability content was mainly limited to environmental aspects such as recycling and environmental protection. At the same time, their awareness of the economic and social dimensions remained limited. This is reflected in the pre-program statements of one teacher (T1), who noted, "*There is no specific sustainability-related content in my lessons,*" and another teacher (T3), who stated, "*I mostly focus on topics related to environmental protection*." During the same period, a substantial proportion of teachers either did not implement sustainability-oriented STEM activities or were unable to provide planned and concrete examples of such practices. For instance, one teacher (T10) remarked, "*I did not implement STEM activities in my lessons in a planned manner*," highlighting this limitation at the implementation level.

Following the program, teachers approached sustainability-related content more comprehensively, incorporating energy, biodiversity, and economic and social dimensions. This shift is clearly illustrated by the post-program statement of one teacher (T9), who noted, "*I can now integrate sustainability into my lesson plans by relating it to energy, the economy, and social life*." In addition, an increase was found in sustainability-oriented STEM practices that were planned, connected to real-life problem situations, and grounded in the engineering design process. For example, one teacher (T15) stated, "*I planned a STEM activity addressing energy conservation through the engineering design process*," while another teacher (T9) explained, "*We designed an insulated house model to promote energy conservation*," providing concrete evidence of this shift in practice.

However, **Table 10** also indicates that change was not uniform across all dimensions or participants. Specifically, despite an overall increase in holistic sustainability-related content knowledge, a small number of teachers continued to emphasize primarily environmentally oriented content in the post-program phase. Similarly, although planned and real-life problem–based STEM practices increased substantially, some teachers remained unable to articulate concrete, example-based sustainability-oriented STEM implementations. Taken together, these patterns suggest that, while the overall trends point to meaningful improvement, variability persisted in the extent to which teachers translated sustainability-related knowledge into STEM instructional practices.

Overall, these findings indicate that sustainability-oriented STEM education strengthened teachers' competencies not only in sustainability-related content knowledge, but also in their ability to translate this knowledge into planned, interdisciplinary, and practice-oriented STEM activities. At the same time, the persistence of limited or unchanged content focus and implementation practices among a small number of teachers underscores variation in the extent to which participants engaged with and applied the experiences offered by the program.

Results and Discussion

This study examined the effects of a sustainability-oriented STEM PD program on teachers' conceptual understanding, instructional implementation competencies, and sustainability literacy through qualitative pre- and post-program comparisons. Taken together, the findings demonstrate a clear overall transformation from fragmented, discipline-bound, and predominantly environmental conceptions toward more multidimensional, systems-oriented, and practice-focused understandings of sustainability, sustainable development, and STEM pedagogy. Following participation in the program, most teachers not only expanded their conceptual frameworks but also translated these developments into planned, example-based, and problem-oriented instructional practices explicitly linked to sustainability themes. This integrated transformation aligns with previous research indicating that sustainability-oriented STEM and STEAM PD can support teachers' movement from surface-level awareness toward more coherent conceptual and pedagogical frameworks (Álvarez & Olatunde-Aiyedun, 2024; Gamage et al., 2022; Milner-Bolotin & Martinovic, 2025; Tarlochan et al., 2025).

More specifically, the pre-program findings revealed that teachers predominantly conceptualized sustainability and sustainable development in single-dimensional or conceptually limited ways, most often emphasizing environmental protection, recycling, or economic growth, while social dimensions and systemic interrelationships remained largely absent. Such environmentally or economically reductionist patterns have been widely documented in the literature, particularly in contexts where teachers have limited exposure to structured education for sustainable development (Bürgener & Barth, 2018; Evans et al., 2017). Following the PD program, however, most teachers began to conceptualize sustainability and sustainable development as interconnected systems encompassing environmental, economic, and social dimensions. In parallel, the Sustainable Development Goals were increasingly perceived not as abstract global policy frameworks but as meaningful pedagogical reference points that could guide lesson planning and instructional decision-making. This conceptual expansion reflects the transformative learning processes emphasized in education for sustainable development frameworks (Sterling, 2010; UNESCO, 2020) and corroborates recent research demonstrating that practice-oriented PD can foster more holistic sustainability understandings among in-service teachers (Álvarez & Olatunde-Aiyedun, 2024; Brandt et al., 2021).

At the same time, the findings indicate that conceptual change was not uniform across all participants. A small number of teachers exhibited limited or no change in their understandings of sustainability, sustainable development, or the SDGs, particularly in relation to systemic integration and instructional application. This pattern is consistent with prior studies emphasizing that professional learning in sustainability education is a nonlinear process shaped by teachers' prior beliefs, disciplinary identities, and instructional contexts (Evans et al., 2017; Timm & Barth, 2021). The persistence of limited conceptual change among some participants suggests that short-term PD, while effective for many, may not be sufficient for all teachers to internalize complex sustainability frameworks without continued opportunities for reflection, reinforcement, and contextualized practice.

A similar pattern emerged in relation to teachers' conceptualizations and implementations of STEM education. Before the program, STEM was commonly approached in a narrow and fragmented manner, often restricted to isolated science experiments, technology use, or coding activities, rather than understood as an interdisciplinary, problem-oriented pedagogical framework. This finding aligns with existing literature indicating that teachers frequently conceptualize STEM as a collection of separate disciplines rather than as an integrated approach grounded in engineering design and real-world problem solving (Acar & Büyükşahin, 2021; Margot & Kettler, 2019). Following the program, however, most teachers demonstrated a marked shift toward conceptualizing STEM as an instructional approach centered on the engineering design process, explicitly linked to sustainability-related real-life problems. This shift enabled teachers to design more planned, example-based, and learning-outcome–aligned STEM activities, reflecting increased pedagogical coherence and interdisciplinary thinking (Gamage et al., 2022; Milner-Bolotin & Martinovic, 2025).

Importantly, changes in conceptual understanding were closely mirrored by changes in instructional implementation competencies. Teachers who developed more holistic and systems-oriented understandings of sustainability were also more likely to integrate sustainability themes into STEM practices in deliberate and pedagogically meaningful ways. As reflected across the findings, these teachers designed STEM activities grounded in real-life problem contexts, employed the engineering design process, and aligned sustainability content with curricular goals. This finding supports previous research suggesting that conceptual change in sustainability education is most effective when accompanied by opportunities to translate new understandings into pedagogical action (Brandt et al., 2019; Gamage et al., 2022). Through this process, sustainability and STEM began to function as mutually reinforcing pedagogical frameworks rather than as separate or additive instructional components.

Nevertheless, a subset of teachers continued to demonstrate irregular, example-free, or limited STEM implementation following the program. This variation underscores that pedagogical transformation does not occur uniformly and is influenced by factors such as prior teaching experience, confidence in interdisciplinary instruction, perceived curricular constraints, and institutional support structures (Brandt et al., 2019; Evans et al., 2017). These findings highlight the importance of designing PD not only to introduce new conceptual frameworks but also to provide sustained opportunities for practice, feedback, and collaborative reflection.

Finally, the findings related to sustainability literacy further illustrate the multidimensional nature of teachers' professional growth. Prior to the program, sustainability literacy was largely perceived as unfamiliar or was equated with declarative environmental knowledge. Following the program, most teachers began to conceptualize sustainability literacy as a dynamic competence involving systems thinking, cause–effect reasoning, long-term perspectives, and responsibility-oriented decision-making. This shift reflects the development of cognitive, analytical, and value-based dimensions of sustainability literacy emphasized in the literature (Evans et al., 2017; Nash et al., 2025; UNESCO, 2020). However, the persistence of limited change among a small number of participants suggests that developing sustainability literacy is a gradual process that may require extended and iterative professional learning opportunities beyond short-term interventions.

Overall, the findings demonstrate that sustainability-oriented STEM professional development can foster meaningful transformations in teachers' conceptual understanding, instructional implementation, and sustainability literacy. However, the uneven nature of change across participants suggests that short-term interventions alone may not be sufficient to support all teachers in fully consolidating sustainability-oriented pedagogical competencies. Accordingly, these findings point to the need for future professional development models that incorporate sustained support mechanisms, including follow-up activities and collaborative learning structures, to promote the long-term continuity and deepening of sustainability-oriented teaching practices (Evans et al., 2017; Robinson et al., 2022).

Conclusion

This study demonstrates that sustainability-oriented STEM education can substantially enhance teachers' conceptual understanding of sustainability and sustainable development, instructional implementation competencies, and sustainability literacy. Following participation in the professional development program, most teachers moved from fragmented, discipline-bound conceptions toward more multidimensional, systems-oriented, and practice-focused understandings, which were reflected in their ability to design planned, example-based, and real-life problem–focused STEM activities aligned with sustainability themes.

The findings further indicate that conceptual development and instructional implementation progressed in an interconnected manner, suggesting that sustainability-oriented STEM education functions as a transformative learning process that integrates systems thinking, pedagogical reasoning, and classroom practice. At the same time, uneven patterns of change among a small number of participants underscore the non-linear and context-dependent nature of professional learning in sustainability education.

Overall, these results highlight the importance of designing sustainability-oriented STEM professional development not merely as knowledge transmission, but as a sustained and practice-rich process that supports the translation of conceptual change into instructional action. Future initiatives should therefore prioritize ongoing support, opportunities for iterative practice and reflection, and collaborative learning structures to promote the long-term consolidation of sustainability-oriented teaching competencies.

Limitations of the Study

This study was conducted with a specific sample and within a particular educational context; therefore, the generalizability of the findings is limited. The research involved a relatively small group of teachers who participated in a sustainability-oriented STEM education program and did not include educators from a wide range of subject areas or educational levels. In addition, participation in the professional development (PD) program was voluntary, which may have introduced self-selection bias. Teachers who chose to participate may have had higher levels of motivation, prior interest, or more favorable attitudes toward sustainability and STEM education, potentially influencing both their responses and the observed changes.

The study employed a qualitative research design based on pre- and post-program comparisons, and the findings rely primarily on participants' self-reported experiences. While this approach allowed for in-depth exploration of teachers' conceptual and instructional development, it limits the extent to which quantitative inferences or causal conclusions can be drawn. Moreover, the PD program was implemented over a defined time period, and the long-term durability of changes in teachers' competencies and their sustained impact on classroom practice were not examined.

Finally, the institutional and local contexts in which the study was conducted may further constrain the transferability of the findings. Differences in curricular structures, available resources, and professional development conditions across educational settings may influence the applicability of the results to other contexts.

Implications for Practice and Policy

Based on the findings of this study, teacher PD programs should move beyond addressing sustainability and STEM integration solely at a theoretical or awareness-raising level and instead be grounded in practice-based, interdisciplinary learning experiences connected to real-world problems (Caughman, 2022). The results indicate that teachers were more likely to develop holistic and systems-oriented understandings of sustainability when conceptual learning was explicitly linked to concrete instructional applications. In this regard, the systematic integration of STEM activities centered on the engineering design process and explicitly aligned with the Sustainable Development Goals within teacher education programs may support the sustained development of teachers' interdisciplinary thinking, problem-solving abilities, and pedagogical design competencies.

In addition, the findings suggest that although many teachers benefited from the program, a small number demonstrated limited or inconsistent instructional change, particularly in translating conceptual understanding into classroom practice. To address this variability, PD programs should incorporate structured instructional supports, such as sample lesson plans, adaptable activity templates, and assessment tools that teachers can modify to suit their curricular contexts. Providing such concrete resources may help reduce implementation barriers, strengthen teachers' confidence in interdisciplinary instruction, and promote more consistent enactment of sustainability-oriented STEM practices across diverse classroom settings.

From the perspectives of both practitioners and policymakers, the results underscore the importance of positioning sustainability-oriented STEM education as an institutionalized and ongoing component of in-service teacher education rather than as a one-time intervention. Designing PD programs in an interdisciplinary manner that encourages participation from teachers across subject areas can facilitate the holistic integration of sustainability into curricula, instructional strategies, and school culture. Furthermore, to ensure the long-term continuity of sustainability-oriented STEM practices, it is essential to strengthen school-based professional learning communities, mentoring structures, and monitoring and evaluation mechanisms. Such sustained and collaborative support structures are particularly critical for teachers who may require extended time and guided practice to internalize complex sustainability frameworks and translate them into effective instructional practice.

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Appendix 1

Open-Ended Questions in the Questionnaire

1. Have you previously participated in any in-service training, course, or project related to STEM education or sustainability, either within or outside formal professional development programs? If yes, please provide a brief explanation.
2. In your opinion, what is sustainability? Please explain your understanding.
3. In your opinion, what is sustainable development? Please describe your views.
4. Do you have any knowledge of the Sustainable Development Goals (SDGs)? If yes, please explain what you know.
5. In your opinion, what is STEM education? Please describe your understanding.
6. Do you guide your students in implementing STEM education in your lessons? Please explain your response.
7. If you guide your students in STEM education, how frequently do they engage in these practices, and in which content areas? Please describe the activities your students have implemented, providing a few examples.
8. Within the subject(s) you teach, which content related to sustainability (such as units, topics, or concepts) is included? Please specify.
9. If you incorporate STEM education into sustainability-related content in your lessons, please describe these practices and provide a few examples.
10. Do you have any knowledge of sustainability literacy as a skill?
    If so, please explain how you would guide your students in developing this skill in your lessons.