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Research article

Professional development in STEM for science teachers: Examining improvements in lesson planning and implements†

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Abstract: In recent years, there has been an increasing emphasis on STEM education and the need for effective professional development (PD) programs to increase teachers' competencies in planning and implementing STEM activities. In this study, the aim was to investigate in depth the effect of a comprehensive STEM PD program on science teachers' competencies in STEM lesson plan preparation and classroom implements. The research design was a holistic single case. The study group consisted of 10 science teachers working in public secondary schools. The STEM PD program included an 80-hour training consisting of four stages in a 6-month period. During the PD program, the teachers prepared at least two STEM lesson plans and carried out STEM classroom implements. The data source of the study consisted of the lesson plans prepared by the teachers and the researchers' observations (observation form and field notes) of the teachers' classroom implements. The results show that the STEM PD program, developed within the scope of this research, contributed to the preparation of lesson plans and in-class implements by teachers. It is recommended that teachers engage in both theoretical learning and practical workshops, distributed across multiple sessions, to enable planning, execution, and experience sharing. The process of identifying deficiencies during implementation and receiving feedback from peers and experts is highlighted as a key strength of the program.

Keywords: design-based learning, professional development, science teacher, STEM lesson planning, STEM classroom implements

1. Introduction

The problems faced nowadays by individuals are often complex and interdisciplinary. Remote-controlled human–machine interface applications, data science applications in disease diagnosis, and renewable energy needs are just a few of the problems we face today. In order to find solutions to these problems, a single discipline-oriented approach is not sufficient. Therefore, a comprehensive and broad perspective is needed to develop effective solutions to complex and interdisciplinary problems. In this context, interdisciplinary learning approaches such as STEM integration stand out as an important educational reform at the global level [1–3].

In STEM education, students are presented with real-life problems. These problems are interdisciplinary, involving science, technology, engineering, and mathematics. Students are expected to solve the problems using processes similar to those of the professionals in these disciplines [3]. Since real-life problems faced by students are related to more than one discipline, the foundation of STEM education is to handle STEM disciplines in harmony with real life, removing the boundaries between disciplines and integrating them with each other [4–6]. In addition, STEM education contributes to the development of 21st-century skills [7,8] and supports the development of career perception with a positive attitude toward STEM fields [9]. The fact that these elements are among the critical needs of this century and can be developed with STEM education makes STEM education more important each day. Many suggestions can be found in the literature about how STEM education, an interdisciplinary approach, should be implemented in the classroom [4,10–12]. Regardless of the approach to be adopted, for STEM activities to be sustainable in the classroom, teachers need to have the knowledge and skills to strengthen their lessons with interdisciplinary connections [3]. Many recent studies draw attention to the need to expand STEM teacher education in order to bring STEM education and students together [13–18]. It is emphasized in these studies that if support is not provided, teachers will avoid implementing STEM activities in classes or will not be able to carry out the applications correctly. This support can be provided to teachers through professional development (PD) programs.

Many studies that draw attention to the necessity of teacher education discuss how it should be conducted and suggest that research on this subject should be continued. The ineffectiveness of short-term training programs [15,19–21], the importance of implements that include at least 80 lesson hours [22,23], mentoring [24], cooperative learning, teachers' participation in training together [1,21], and teachers' in-class implement and evaluation of the results [1,14,25,26] were the issues addressed in STEM PD program research. As these studies have shown, research on the reflection of STEM PD programs on classroom implements will fill an important gap in the literature [1].

In this study, the aim is to investigate in depth the effect of a comprehensive 6-month, 80-hour STEM PD program on science teachers' competencies in STEM lesson plan preparation and classroom implements. The problem of the research is as follows:

How does the STEM PD program affect science teachers' competencies in preparing STEM lesson plans?

How does the STEM PD program affect science teachers' classroom implements?

1.1. STEM education

STEM is a learning approach based on the holistic teaching of two or more disciplines of science, technology, engineering, and mathematics in the context of real-life problems [2,27,28]. In studies on how to integrate STEM disciplines, emphasis is placed on “authentic” problems that are appropriate to the nature of the problems handled by real-world scientists, engineers, applied mathematicians, and technology professionals [29]. Moore et al. [3] examined STEM definitions in 109 different studies in the STEM field and stated that most emphasized the need for complex, authentic, and real-world problems. Moreover, Sanders [28] drew attention to the fact that the integration of STEM disciplines must be in the context of a problem situation.

When STEM education is implemented in the classroom, it is often carried out with student-centered approaches such as problem-based learning [30], project-based learning [31], and design-based learning (DBL) [32]. In problem-based learning, learners are faced with an interdisciplinary and complex problem that is applicable to real life and has more than one solution; learners must review their existing knowledge to solve the problem, determine what information they need for a solution, acquire new information, and reconstruct existing knowledge. In this process, learners gain knowledge and skills while searching for a solution to the problem [33]. In project-based learning, the process starts with a project task that is also interdisciplinary and has a real-life context. STEM project-based learning (PBL) is a current instructional strategy that is student-driven, interdisciplinary, collaborative, and technology-based. In a STEM PBL activity, students need to find and define a problem while exploring a project topic [34]. The subject of the project is interdisciplinary in nature, and students can construct their own knowledge by understanding the disciplines in depth [35]. DBL starts with a design problem that includes a set of criteria and constraints within a real-life context. The process is carried out by students defining the problem, determining the criteria and constraints, developing possible solutions, selecting the best solution, and presenting the solution by testing. Used as a common approach in STEM education, DBL builds on the integration of the designing process of real-life engineers into classroom implements to solve real-life problems [12,36]. Students need to acquire scientific, mathematical, and technological skills to solve these real-life problems by using engineer-like designs as tools, providing real-life context for both science and mathematics. DBL enables students to transfer a knowledge base to complex problems [36], motivates students, and improves their engineering knowledge through experiencing the design process [27,36].

1.2. STEM PD programs

The global quest to integrate STEM approaches into curricula has led to a focus on PD for teachers. In studies conducted with teachers, it was determined that they had positive views toward the STEM approach, but their self-efficacy in implementing the STEM approach was low [37–39]. Several studies evaluated the development and implementation of PD programs for STEM education [13–16,20,40]. In some, short-term PD programs were conducted, and their inadequacy was noted, together with the lack of hands-on activities [13,14,40]. For example, it was found that science teachers who participated in a short-term PD program made progress in developing problem situations to prepare lesson plans, but they had deficiencies [40]. STEM PD programs spread over a period of at least 2 years were also shown to increase teachers' interest in implementing STEM activities in their classrooms [15,19]. Researchers who implemented long-term STEM PD programs emphasized teachers' participation in hands-on STEM activities [15,19].

In the planning and evaluation of STEM PD programs, focusing only on the development of STEM pedagogical knowledge is a factor that causes these programs to fail, as they fail to meet individual teacher needs [17,41]. It is important to focus on the needs of individual teachers, to focus on how to transfer STEM pedagogy into the classroom through lesson plans and implements, and to design and evaluate the PD program accordingly. On the other hand, as stated in a systematic analysis of experimental studies in which STEM PD programs were implemented, the effectiveness of PD programs is mostly obtained through methods such as interviews and questionnaires [13]. Therefore, it is understood that individual needs cannot be determined, and individual results cannot be monitored. For example, Kelley et al. [20] conducted a long-term PD program. The findings of the study are limited to the fact that the program increased the self-efficacy of science teachers but had no significant effect on engineering technology teachers. It is important to determine whether the PD program meets the needs of engineering technology teachers or assess the impact of STEM PD programs on teachers' implements in the classroom. This is essential both for developing a PD program that addresses individual teacher needs and for evaluating the effectiveness of the approach in classrooms. The important issue here is to go beyond teacher perceptions and explore performance-based outcomes (such as lesson plans and implementation achievements) of PD programs [13,42]. Therefore, there is a need for observation protocols for evaluating classroom implements.

1.3. Context and significance of the research

This study aims to fill important gaps in the literature by examining the effects of STEM PD programs in depth. The literature shows that the duration of PD programs affects teacher gains [43]. Since teachers' beliefs and behaviors and thus their classroom implements are expected to improve during the PD process, it is necessary to plan enough time to allow for this change [44,45]. It is a frequently emphasized problem in literature that PD programs for STEM education are generally short-term and insufficient to improve teachers' professional competencies [42]. Sustainable STEM PD duration is highly correlated with teacher outcomes [42]. In this study, a comprehensive STEM PD program lasting 6 months and 80 hours in total was examined, and its effects on teachers' STEM lesson plan preparation and classroom implements were examined with a performance-based approach. The research goes beyond teachers' perceptions of the effectiveness of PD programs and focuses on concrete and measurable data through the analysis of STEM lesson plans and observation protocols on classroom implements. In addition, the study takes into account the criticisms in the literature that focusing only on STEM pedagogical knowledge is insufficient to meet individual teacher needs; as such, it aims to develop an inclusive STEM PD program that will meet the individual needs of teachers and improve their STEM pedagogical competencies. The performance-based evaluation of the implements within the scope of the program and the fact that recommendations will be made for STEM PD programs according to these evaluations make this study different and innovative.

As a result, this study will provide a comprehensive framework to understand how STEM PD programs can affect teachers' STEM lesson planning and implements in classrooms based on in-depth data. The performance-based evaluation of the effects of long-term and applied PD programs, which are generally ignored in the literature, makes this study important and valuable both theoretically and practically.

2. Methodology

In this study, the aim is to investigate in depth the effect of a comprehensive 6-month, 80-hour STEM PD program on science teachers' competence in STEM lesson plan preparation and STEM classroom implements. In the study, the competencies of science teachers in STEM lesson planning and classroom implements were examined in depth during a comprehensive STEM PD program. The research was conducted using a case study design. Yin [46] considers the case study as a comprehensive research method and defines it as a research model in which multiple data sources are used and the researcher’s effect is minimal. In this research, STEM lesson planning and classroom implements by science teachers were handled as a holistic single case, with each science teacher forming an analysis unit. The research was planned in a holistic single-case design.

2.1. Participants

The study involved 10 science teachers, selected in two stages. Initially, a PD program was announced province-wide by the National Education Directorate in northern Turkey, with 600 teachers registering online. In the online registration form, an open-ended question asked why they wanted to participate in the training. The responses were analyzed and, in line with the purpose of the study, we focused on the applications of teachers who drew attention to situations such as being open to innovations to support classroom teaching, being open to applying new methods and techniques in the classroom, and being willing to share their experiences with their colleagues after the training. In addition, other reasons arose, such as obtaining a training certificate and adding that they had received training to their background. In order to identify volunteer teachers, the applications of those who only stated reasons such as adding training to their CV or receiving a certificate were not evaluated. Considering the physical facilities of the research, 25 teachers were selected for the training courses. It was considered that evaluating the lesson plans of all 25 teachers and monitoring their in-class implements would cause data saturation and make the research process difficult. In qualitative research, the adequacy of sample size is measured by the depth of data; therefore, there is a number of participants that best represents the research topic [47]. The number of participants must not be too large to cause data saturation, nor should it be too small to make it difficult to obtain information [48]. Although there is no “magic number” in achieving saturation, the conceptual understanding and skills of the researcher play a critical role in determining the saturation point [49]. In this context, in the second stage, 10 teachers were selected from the initial 25 for in-depth data collection, ensuring maximum diversity in duty location, school type, gender, and STEM training status using maximum variation sampling. In addition, while determining the study group, teachers were informed about the research process, and care was taken to ensure that teachers were volunteers and available for observation. Another issue in selecting the participants was the representation in terms of working in public and private schools.

The demographic characteristics of the participants are presented in Table 1.

Table 1. Demographic characteristics of the participants.

Teacher	STEM PD experience	Gender	Professional experience (years)	Public school experience	Private school experience
Teacher 1	30 h training	Male	17	17	-
Teacher 2	None	Female	22	20	2
Teacher 3	None	Female	15	8	7
Teacher 4	Workshop	Female	10	10	-
Teacher 5	30 h training	Male	21	21	-
Teacher 6	None	Male	10	-	10
Teacher 7	None	Female	17	17	-
Teacher 8	30 h training	Female	5	3	2
Teacher 9	None	Male	12	11	1
Teacher 10	30 h training	Female	13	13	-

After participant selection, a form was provided to explore their definitions of the STEM approach, their views on the elements related to STEM education in the science curriculum in their country, and their views on how STEM education could be implemented in science classes. Their STEM definitions, their associations with the science curriculum, and their views on its applicability showed that some teachers had partial knowledge on these issues, while others did not. In addition, none of the participants had previously prepared a lesson plan or implemented a STEM activity in their classes. One teacher has only private school experience, and 5 teachers had only public school experience; 4 teachers had both private and public school experience.

2.2. STEM PD program and data collection process

The STEM PD program was designed based on criteria derived from literature, emphasizing continuous support throughout the process [44,45], teachers' development and implementation of lesson plans, sharing experiences with colleagues [50], classroom implement observation, feedback provision [14,25,26], and material outcomes [14]. The program consists of four stages in a total of 80 hours, including feedback sessions between stages for teachers' lesson plans and classroom implements. The output of the PD program is as follows: Science teachers prepare and implement a STEM lesson plan aligned with the science curriculum to be used in their classroom teaching. The content of the program is summarized in Table 2. After the program content is prepared, feedback on the content is received from two experts who conduct STEM PD programs and scientific research, are educated at the doctoral level, and whose doctoral thesis studies were related to STEM approaches. After feedback, the duration of the content on how to integrate the technology discipline is increased, and an inquiry-based STEM lesson plan preparation session is added. In addition, teachers' opinions on the suitability of the program for the purpose of the research are obtained.

Table 2. STEM PD program.

	Day	Period (hours)	Learning content
1. STAGE	**1. Day**	3 (TC)	Theoretical content about STEM
		3 (TC)	Science curriculum and STEM
		2 (W)	
	2. Day	2 (TC)	Science and mathematics disciplines in STEM
		2 (W)	
		2 (TC)	Engineering integration
		2 (W)	
	3. Day	2 (TC)	Technology integration
		2 (W)	
		2 (TC)	Problem-based learning and STEM
		2 (W)	
	4. Day	2 (W)	Problem-based learning and STEM
		2 (TC)	5E learning model
		1 (W)	5E learning model/examining STEM lesson plans
		2 (TC)	Project-based learning
		1 (W)	Project-based learning/review of sample STEM lesson plans
	5. Day	1 (TC)	Inquiry-based learning
		1 (W)	Inquiry-based learning/review of sample STEM lesson plans
		3 (W)	STEM lesson planning
		2 (TC)	Measurement and evaluation in STEM
		1 (W)	
Implements of the lesson plans prepared by the teachers in their classes and monitoring the applications (4 weeks)			
2. STAGE	6. Day	4 (W)	Teachers' implementation experience, suggestions for improving implementations
		4 (W)	Project-based STEM lesson plan preparation/evaluation of lesson plans
	7. Day	4 (W)	Teachers' implementation experience, suggestions for improving implementations
		4 (W)	Inquiry-based STEM lesson plan preparation/review of plans
Implementations of the lesson plans prepared by the teachers in their classes and monitoring the applications (4 weeks)			
3. STAGE	8. Day	4 (W)	Teachers' implementation experience, suggestions for implementations
		4 (W)	Prepare a problem-based STEM lesson plan/review of plans
	9. Day	4 (W)	Teachers' implementation experience, suggestions for improving implementations
		4 (W)	Preparation of DBL STEM lesson plans/review of plans
Implementations of the lesson plans prepared by the teachers in their classes and monitoring the applications (4 weeks)			
4. STAGE	10. Day	4 (W)	Teachers' implementation experience, suggestions for implementations
		4 (W)	Coding and robotics implementations in STEM

TC: Theoretical content; W: workshop.

Within the scope of the STEM PD program, the process of teachers' lesson planning and implement development unfolded as follows: After the first stage of the program, teachers were tasked with preparing lesson plans, and researchers provided feedback on these plans. Teachers who were unable to finalize their plans by the end of the first stage continued to be contacted through the WhatsApp social media tool. Subsequently, teachers made necessary corrections and shared them with the researchers. Once the researchers approved the final versions of the lesson plans, participants were expected to implement the lesson plan in the classroom. In-class implements were observed by the researchers within the framework of the observation form. Following this observation, observation forms were shared with the teachers, and feedback was provided on each item. Furthermore, teachers immediately shared their experiences both verbally and with images from the implementation process on the social media group where all participants of the research were present. After a 4-week break from the first stage, the second stage began, in which teachers both shared their classroom implement experiences and enriched their theoretical knowledge. The processes after the first phase continued until the end of phase 4. In the 4-week breaks between each stage, the teachers worked on their plans. They asked questions about their plans and received feedback through the social media platform where all participants were present. After phase 4, in-class observations and feedback were spread over a 6-month period. Teachers implemented their lesson plans in the classrooms of the schools where they worked.

Within the scope of the program presented in Table 2, the program was carried out by the second author of the study. It also provided feedback on teachers' lesson plans. The second author has various scientific articles, book chapters, and a doctoral thesis on STEM education. She has provided STEM teacher training in research projects. She has conducted and published research based on the analysis of teachers' lesson plans. She is also conducting a research project funded by the National Science and Technology Research Council to observe teachers' classroom implementations and improve their lesson plan preparation competencies. The first author has a master's degree in science education. He planned the STEM PD program with the trainer and took part in issues such as the execution of the process and the establishment of communication with the teachers. He participated in the entire educational process. Also, he observed the classroom implements of the teachers, filled the observation form, and kept field notes.

2.3. Data collection tools

The data source consists of data obtained by observation (lesson observation form and field notes) and lesson plans.

2.3.1. Lesson plans

Lesson plans were developed by teachers during the STEM PD program. Teachers prepared and implemented STEM lesson plans and developed their lesson plans through group work during the PD program. Teachers did not work with the same group members in all stages of the PD program (stages 1–4). Therefore, the development of lesson planning competencies of each participant was analyzed separately.

2.3.2. Lesson observation

Researchers developed a checklist to observe teachers' classroom implements. The checklist was reviewed by two experts in science education and STEM and was developed based on the DBL process, since teachers prepared all lesson plans in accordance with DBL [27,36]. The form prepared by the researchers was finalized by taking the opinions of two experts who conduct research on DBL in science education. Some of the items in the checklist, which includes behaviors that teachers should exhibit during in-class implementation, are as follows: Is the problem situation presented in an understandable way? Has the teacher given students the opportunity to understand the problem? Has the teacher given the opportunity to produce different solutions for the problem?

2.3.3. Field notes

Sherman and Webb [51] defined field notes as comprehensive records detailing observed phenomena, emphasizing activities, individuals, spatial elements, objects, and chronological events. In this study, researchers took notes during classroom observations to describe teacher implements and evaluate lesson observations collaboratively. Field notes served as a supporting data source for teachers' STEM implements, forming a general framework during observations. The points observed and noted for each item in the observation form were recorded by the researcher. Researchers noted and evaluated observations holistically alongside lesson data.

2.4. Analysis of data

2.4.1. Analysis of lesson plans

It was found that all teachers planned their lesson plans according to the DBL. In this context, the descriptive analysis framework proposed by Bozkurt Altan and Hacıoğlu [40] was used. Lesson plans were analyzed by both researchers based on the framework in Table 3.

Table 3. Descriptive analysis framework for the evaluation of DBL [40].

Feature	Feature description	Not suitable	Must be improved	Acceptable
Limitation	Possible obstacles to the successful design are defined.	Possible obstacles have not been identified.	At least one potential obstacle has been identified, but the evaluation process is not clearly articulated.	At least one potential obstacle has been identified. The process for evaluating the limitation is clearly articulated.
Criterion	The qualities of a successful design are defined.	The criteria have not been determined.	At least one criterion has been identified, but the evaluation process is not clearly articulated.	At least one criterion is clearly defined. The process for evaluating the criteria is clearly stated.
Clarity	The design problem is expressed clearly and understandably.	In the design problem, what is required of the students is not clearly and explicitly stated.	The design problem is recognizable but not clear to students.	The design problem is clear and understandable for students.
Student context	The relevance of the problem to real life and the social and cultural environment in which the students live.	The problem situation is not suitable for real life and context.	The problem relates to real life but is not suitable for the students' context.	The problem is appropriate to real life and students' context.
Multiple solutions	The design problem allows us to produce more than one solution.	There is only one solution to the design problem.	Multiple solutions exist, but the lesson plan focuses on a single solution.	The design problem is clearly stated, allowing for multiple solutions.
Science learning outcomes	The design problem can include science learning outcomes.	Science learning outcomes are not clearly stated.	Science learning outcomes are stated, but the content does not support their development.	Science learning outcomes are specified, and the content supports their development.
Testable	The design problem allows the product/solution to be presented successfully.	There are no plans to test the success of the design.	There is a plan to test the success of the design, but the implementation process is not clearly articulated.	Planning for testing the success of the design has been made, and the implementation process has been clearly articulated.
STEM disciplines	The design problem requires knowledge or skills in at least one of the other STEM disciplines.	Other STEM disciplines are not integrated into the problem.	The problem involves at least one other STEM discipline. However, there is no application in the lesson plan.	The problem involves at least one other STEM discipline and has applications in the lesson plan.
Scientific research inquiry	The design problem allows the use of research-inquiry processes.	The lesson plan did not include research-inquiry processes.	The design problem enables the use of research and inquiry processes, but the plan does not include practices.	Research-inquiry processes are included in the lesson plan.
Engineering process	The design problem has eligibility that enables us to use the stages of the design process.	The lesson plan was not planned according to the design process.	The lesson plan follows the design process but omits some stages.	The lesson plan is planned according to the design process and includes all phases.

Table 3 presents the 3-point rating scale for each criterion, based on which both researchers analyzed each plan.

The criteria presented in Table 3 can be explained as follows: The *limitation* and *criterion* features refer to the criteria that must be present in a successfully developed design and the obstacles against such a design. The problem situations presented in the lesson plans should include criteria and constraints. *Clarity* refers to the clarity and comprehensibility of the problem situation and of what is desired in the problem by the students. *Student context* refers to the relevance of the problem situation presented in the lesson plan to students' prior knowledge and experience. *Multiple solutions* refer to the suitability of the problem presented in the lesson plan to develop different solutions. The problem should not lead students to a single and correct solution. *Science learning outcomes* refers to the compatibility of the problems and activities presented in the lesson plan with the learning outcomes targeted in the science course. *Testable* refers to the elements related to the testability of the prototype for the problem. Students' products and solutions should be planned to be testable to provide feedback on their suitability for the problem. *STEM disciplines* refers to the extent to which the lesson plan includes other disciplines other than science. *Engineering process* is related to the extent to which all DBL stages are included in the lesson plan.

The lesson plans prepared by the teachers according to the criteria presented in Table 3 were analyzed separately by both researchers to ensure inter-rater reliability. Each researcher independently analyzed the lesson plans using predetermined criteria and documented the analysis systematically. During the analysis process, the teacher who developed the lesson plans was contacted to clarify any ambiguities. Following the independent analyses by both researchers, the analyses were compared to identify areas of agreement and disagreement. Differences were discussed in detail through an iterative process of reconciliation that enabled different perspectives to be reconciled. After detailed deliberations, a final consensus was reached, and necessary revisions were made accordingly. This rigorous approach ensured a high degree of consistency and objectivity in the evaluation process. In this way, inter-rater reliability was ensured.

2.4.2. Analysis of lesson observation forms

The data collected with the lesson observation form were analyzed through a descriptive analysis, since the analysis was carried out based on a checklist created by the researchers during the lesson observations. Each question was checked as observed/not observed. For example, if the teacher guided the students to realize what was required in the problem, it was decided that the item "Has he given students the opportunity to understand the problem?" was observed. For the item "Has he given the opportunity to produce different solutions for the problem?", it was expected that the teacher would direct the students to produce not one but more than one solution.

2.4.3. Analysis of field notes

The researcher shared the field notes with the consultant after each observation; afterward, the checklist (lesson observation form) was discussed. A consensus was reached on how the researcher completed the checklist. This was also presented as a supporting data source to describe the implementation process.

2.5. Validity and reliability of research

Internal validity was ensured through triangulation, which involves using multiple data sources or methods to clarify a topic [52]. In this research, data were collected from various sources, including teachers' lesson plans and observations. Member checks were conducted where researchers reviewed field notes and observation forms with participants for approval. Observations were conducted in a natural environment to minimize participant bias. One researcher observed lessons in order to manage time and maintain consistency. Observation notes were shared and reviewed by another researcher for consistency. To align with research questions, data collection and analysis techniques were harmonized [53]. Lesson plans were analyzed separately by two researchers and finalized through consensus [54]. Triangulation, peer examination, and audit trail methods were employed for reliability [54].

3. Findings

3.1. How are science teachers' competencies in preparing STEM lesson plans during the STEM PD program?

Science teachers' competencies in preparing STEM lesson plans during the STEM PD program are shown in Table 4.

As presented in Table 4, the teachers (T1, T2, T3, T5, T6, T7) who prepared lesson plans after receiving 40 hours of training in the PD program (at the end of Phase 1) were found to have deficiencies in their plans in terms of clarity of the problem, inclusion of criteria and constraints, and the criteria of suitability for the engineering design process. For example, Teacher-1 prepared the first lesson plan on pressure. In the activity, students were asked to design a rocket that would stay in the air the longest, not exceeding a certain cost, by utilizing the pressure laws of gases and liquids. In this respect, it was determined that the student context, multiple solutions, science achievements, testable and scientific research inquiry features were at an acceptable level. However, although the statement that the rocket should stay in the air for the longest time was included, criteria such as how high it should go and how long it should stay in the air were not mentioned. In addition, a material cost template was not presented, although the cost was specified as having to be low. In this context, it was determined that the limitations, criteria, clarity, and engineering process features should be improved. It was determined that the plan met the criteria of integration of science, mathematics, and engineering disciplines.

After the second stage, the teachers received feedback on their first lesson plans, had the opportunity to review the feedback given to each other on a common social media platform, applied ready-made plans even though they did not develop plans, and received 16 hours of training. As presented in Table 4, it was determined that all of the teachers who prepared lesson plans after Stage 2 had no deficiencies in their plans in terms of any criteria (T1, T2, T3, T4, T5, T6, T7, T8, T9, T10). Although some of these teachers (T4, T8, T9, T10) prepared their first lesson plans after Stage 2, it was determined that their plans were appropriate in terms of the criteria examined.

After Stage 2, teachers were involved in a process similar to Stage 1, participating in a 16-hour sharing experience and lesson plan preparation. After Stage 3, the lesson plans of the teachers who developed plans (T2, T3, T4, T7, T10) were also found appropriate in terms of all the criteria examined.

It was found that teachers integrated science and engineering disciplines into their plans from the first stage. They also integrated mathematics and technology disciplines into their plans.

Table 4. Findings from the teachers' lesson plans.

Teachers' lesson plan*	Stage**	Limitations	Criterion	Clarity	Student context	Multiple solutions	Science learning outcomes	Testable	Disciplines **	Scientific research inquiry	Engineering process
T1.1	1	I	I	I	A	A	A	A	S, E, M	A	I
T1.2	2	A	A	A	A	A	A	A	S, M, E	A	A
T2.1	1	I	I	I	A	A	A	A	S, T, E, M	A	I
T2.2	2	A	A	A	A	A	A	A	S, T, E, M	A	A
T2.3	3	A	A	A	A	A	A	A	S, T, E, M	A	A
T3.1	1	I	I	I	A	A	A	A	S, E, M	A	I
T3.2	2	A	A	A	A	A	A	A	S, E, M	A	A
T3.3	3	A	A	A	A	A	A	A	S, E, M	A	A
T4.1	2	A	A	A	A	A	A	A	S, E, M	A	A
T4.2	3	A	A	A	A	A	A	A	S, E, M	A	A
T5.1	1	I	I	I	A	A	A	A	S, T, E, M	A	I
T5.2	2	A	A	A	A	A	A	A	S, T, E, M	A	A
T6.1	1	I	I	I	A	A	A	A	S, T, E, M	A	I
T6.2	2	A	A	A	A	A	A	A	S, T, E, M	A	A
T7.1	1	I	I	I	A	A	A	A	S, E, M	A	I
T7.2	2	A	A	A	A	A	A	A	S, E, M	A	A
T7.3	3	A	A	A	A	A	A	A	S, E, M	A	A
T8.1	2	A	A	A	A	A	A	A	S, T, E, M	A	A
T9.1	2	A	A	A	A	A	A	A	S, E, M	A	A
T10.1	2	A	A	A	A	A	A	A	S, E, M	A	A

A: acceptable; I: must be improved; S: science; T: technology; E: engineering: M: mathematics.

**In the column Teachers' lesson plan, T means Teacher. The second number is the number of teachers participating. The number next to it indicates the number of lesson plans prepared by the teacher. For example, T3.2 refers to the second lesson plan of the teacher coded T3.*

***It indicates after which stage of the PD program the lesson plan was prepared.*

****The findings in this column indicate which STEM discipline was integrated into the lesson plan.*

3.2. How do science teachers' competencies to implement STEM lessons change during the STEM PD program?

The findings regarding the development of science teachers' competencies to implement STEM lessons during the STEM PD program are presented in Table 5.

Table 5. Findings from teachers' classroom implements.

Checklist	**Teacher 1**			**Teacher 2**			**Teachers 3**			**Teachers 6**			**Teachers 7**			**Teachers 9**			**Teachers 10**		
	1.	**2.**	**3.**	**1.**	**2.**	**3.**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Is the problem situation presented in an understandable way?	-	+	They did not implement a plan.	+	+	+	-	+	+	-	+	+	-	+	+	+	+	+	+	+	+
Has the teacher given students the opportunity to understand the problem?	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Has the teacher made students realize what they need to solve the problem?	-	+		+	+	+	-	+	+	-	-	-	-	+	+	+	+	+	+	+	+
Has the planned content been implemented to provide students with the knowledge and skills they should have?	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Has the teacher given the opportunity to produce different solutions for the problem?	+	+		+	+	+	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+
Has the teacher allowed students to use their decision-making skills to choose the best solution?	-	+		+	+	+	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+
Were students given the opportunity to present their solutions?	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

As presented in Table 5, it was determined that T2, T9, and T10 carried out an appropriate process in terms of all criteria in their classroom implements after the first stage. T2, T9, and T10 also conducted an appropriate lesson process in terms of all criteria in their implements after Stage 2 and Stage 3. T1, T3, T6, and T7 did not meet criteria such as presenting the problem in a comprehensible way and making students realize what they needed to solve the problem in their lesson plans after the first stage, but they corrected this situation after the second and third stages. T1 and T6 did not give students the opportunity to choose the best solution in their classroom implements after the first stage, but they corrected this situation after the second and third stages. T6 did not give the students the opportunity to produce more than one solution after the first stage, but then conducted the lessons appropriately in terms of this criterion after the second and third stages.

According to the classroom implement findings obtained from the field notes, it was determined that Teacher-1 had problems with time and classroom management in the first implement and could not finish the activity on time. However, she improved on these issues in the following process. Teacher-2 did not attach importance to the "evaluation and development of solutions" criterion in the first implement due to time concerns. It was determined that she did not feel adequate in terms of evaluation, but with further implements, she ensured time management, improved in evaluation, and gave importance to this criterion. Teacher-3 did not attach importance to the criterion of "evaluating and developing solutions" due to time concerns, considering that this criterion was a waste of time, and it was sufficient to discuss it. Teacher-7 felt the same regarding the criterion of "evaluating and improving the solutions". Teacher-6 could not complete the first implement on time, had difficulties in the management of the groups, could not fulfil the two criteria stated in Table 5 despite showing improvements in time management and classroom management in the following activities, and did not attach importance to the criterion of "evaluation and improvement of solutions", which she considered as a waste of time and thought that it was sufficient to discuss. Teacher-9 was in a hurry in her first implement due to the pressure of the school administration and parents to solve exams and the desire to complete the curriculum and the activities on time. For this reason, she could not meet some of the criteria, but as the negative opinions of the school administration and students decreased as she implemented, it was noted in the field notes that she improved in managing time better and met this criterion. Teacher-10 did not attach importance to the criterion of "evaluation and improvement of solutions" due to time concerns and considered that this criterion was a waste of time, and that it was sufficient to discuss it.

4. Discussion

In this study, the aim was to investigate in depth the effect of a comprehensive 6-month, 80-hour STEM PD program on science teachers' competencies in STEM lesson plan preparation and classroom implements. The findings show that teachers made significant improvements in their lesson planning and classroom implement competencies. The general results of these findings, in comparison with the literature, and some recommendations are discussed below.

4.1. Science teachers' competencies in preparing STEM lesson plans during the STEM PD program

After the first stage of the STEM PD program, significant deficiencies were found in the plans prepared by the teachers, such as clarity of the problem situation, identification of criteria and limitations, and the requirements of the engineering design process. For example, in the lesson plan prepared by a teacher on the topic of pressure, features such as how long the rocket should stay in the air were not clarified, and a template for material cost was not provided. However, in the later stages of the program (Phases 2 and 3), the teachers addressed these deficiencies and met the STEM planning criteria to a great extent thanks to the feedback they received and their sharing with each other on the social media platform. These results are in line with evidence stating that STEM PD programs make significant improvements in teachers' planning skills when they provide effective feedback and support mechanisms [15]. However, this study adds a new dimension to the literature by demonstrating that, beyond individual feedback, collective sharing on social media platforms where teachers share with each other contributes significantly to teachers' learning process. This result is supported by research studies that conclude and suggest that it is important for teachers to share their experiences with each other for PD programs [15,25,26,55]. On the other hand, the shortcomings of the initial plans developed by teachers at the end of a 40-hour, 5-day training, which included theoretical sessions and STEM integration workshops, indicate that short-term, intensive programs such as the first phase of the PD program may be insufficient for plan development. This finding is in line with the idea that STEM PD programs should be longer and more widespread [15,19–21].

In this study, after the first phase of the STEM PD program, deficiencies in the plans prepared by the teachers were identified, and individual learning needs could be recognized by providing individual feedback. For this reason, when individual needs are not taken into account in the activities after the first phase, STEM pedagogy presents deficiencies in general. This result is consistent with the conclusion that focusing only on STEM pedagogical knowledge in STEM PD programs fails in meeting individual teacher needs [17,41]. Based on this result, an important contribution of this study is the conclusion that monitoring the development of individual teachers in STEM PD programs is crucial.

In lesson plans, it was observed that teachers were more successful in integrating science and engineering disciplines, but they had difficulties in integrating mathematics and technology disciplines, especially in the early stages. By the end of the program, there was a general improvement in the integration of these disciplines. This finding is in line with literature stating that the integration of mathematics and technology in STEM implements requires more support than science and engineering [56]. According to the literature, in technology integration in STEM, technology should be an active component of the solution process and not a tool (only instructional technology) [57–60]. On the other hand, it is known that science teachers often do not go beyond using technology as a tool in learning environments suitable for STEM approach [60]. Similarly, in technology-oriented STEM activities implemented in primary and secondary schools between 2015 and 2023, technology generally remained at the level of instructional technology as a tool for teaching science and mathematics [60]. The result of our research is in line with this literature.

4.2. Development of science teachers' competencies to implement STEM lessons during the STEM PD program

Teachers had difficulties in criteria such as time and classroom management, presentation of the problem, and evaluation of solution alternatives. For example, some teachers considered the solution development phase a waste of time and limited themselves to superficial discussions. However, in the following stages, these teachers improved in time management and classroom management, which contributed to the qualitative improvement of the implements. The literature emphasizes that time management and classroom management play a critical role in the successful implementation of STEM implements [61]. This study shows that the difficulties encountered during STEM implements can be reduced as the implementation is repeated and with critical feedback. The importance of observing classroom implements and providing feedback in STEM PD programs has been emphasized [13,14,25,26]. This result also reveals once again the importance of exploring performance-based outcomes (such as lesson plans and implementation achievements) of STEM PD programs [13]. Performance-based observation findings revealed that time and classroom management is the problem most commonly faced by teachers while implementing STEM activities.

5. Conclusions

The findings of this study suggest that the STEM PD program played an important role in developing science teachers' competencies in planning and implementing STEM lessons. Initially, teachers struggled with key components of STEM lesson planning, such as clearly defining problem situations, setting criteria and limitations, and effectively integrating the engineering design process. However, peer sharing on social media platforms is considered to contribute to supporting teachers' learning beyond individualized feedback. Moreover, the results are in line with the literature on the need for long-term and ongoing support, emphasizing that short-term, intensive PD programs may be insufficient for continuous improvement.

According to the results related to their experiences with classroom implementations, teachers initially encountered difficulties in time and classroom management, problem presentation, and evaluation of solution alternatives. However, these difficulties decreased as they gained experience and received critical feedback. In conclusion, this study confirms the potential of well-structured STEM PD programs to improve teachers' lesson planning and implementation competencies and provides recommendations for the design of future PD programs.

6. Limitations and implications

This research was conducted within the context of a specific STEM PD program, and the findings may not be fully generalizable to other PD initiatives with different structures, durations, or participant demographics. Also, the participants of this study were science teachers. This may limit the applicability of the findings to teachers from other disciplines, such as mathematics or technology, who may have different challenges and support needs in STEM integration. Additionally, while the study highlighted improvements in teachers' planning and implementation skills, the long-term retention of these skills and their impact on student learning outcomes were not assessed, which remains an area for further research. Finally, the study relied on qualitative observations and lesson plan evaluations, which, while valuable, could be complemented by research using quantitative measures to comprehensively assess teachers' progress and the effectiveness of the PD program.

6.1. Implications for policy

The findings of this study provide valuable recommendations for policymakers and researchers designing STEM PD programs. First, education policymakers should consider extending the duration of STEM PD programs to allow for gradual and continuous teacher development. Short-term, intensive programs may provide basic knowledge, but will not be sufficient for meaningful skill acquisition. Second, priority should be given to integrating structured feedback mechanisms to enhance teacher learning, including expert evaluations and peer collaboration through social media or other digital platforms. Furthermore, STEM PD programs should allocate dedicated time and resources for classroom and time management skills training, as these were identified as key challenges during implementation. Another important implication is the need to emphasize interdisciplinary collaboration in STEM education, especially in the integration of mathematics and technology, which was found to be more challenging for teachers. Finally, PD programs should be designed with a focus on personalized learning approaches that address individual teacher needs, rather than relying solely on generalized STEM pedagogical content. Implementing these recommendations can improve the quality of STEM education and ultimately contribute to better student learning experiences in STEM fields.

6.2. Implications for implements

This study highlights several areas where further research is needed to improve the effectiveness of STEM PD programs. First, future studies should investigate the long-term impact of STEM PD programs on teachers' implements and students' learning outcomes. Longitudinal research could provide insights into whether observed improvements in lesson planning and classroom implements persist over time. Second, although this study focused on science teachers, future research should explore the experiences of math and technology educators to understand their unique challenges in STEM integration. Furthermore, quantitative studies using standardized assessment tools can complement the qualitative findings and provide a more comprehensive assessment of teachers' development. In this study, a checklist was used for classroom observations. It may be possible to collect more in-depth data with a system that will enable quantitative data collection. These data can be supported with observation notes. Or, in order to collect more in-depth data, video recordings of classroom implements can be taken and analyzed. Another important research direction is to examine the effectiveness of different peer-sharing platforms and digital collaboration tools in supporting teacher learning. Finally, studies comparing the effectiveness of short-term, intensive PD programs with long-term, continuous PD models would help to identify the most efficient structures for teacher development.

Author contributions

Both authors contributed equally to the process of determining the purpose and method of the research, conducting the applications, data analysis and reporting.

Use of generative-AI tools declaration

Artificial intelligence support has not been received.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics declaration

The author declared that no ethics approval is required for the study.

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