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DEVELOPMENT ARTICLE

Weaving STEAM with threads: teacher professional development with e-textile projects

Mustafa Sat [1] · **Kursat Cagiltay**[2]

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Abstract
The impact of educational e-textiles on student outcomes in STEAM education programs is a growing area of interest. Despite the potential of e-textile projects to enhance STEAM education, their effect on K-12 teachers' professional development remains underexplored. This study investigates middle school teachers' perceptions of their experiences with wearable e-textile-supported STEAM projects, their ability to translate those experiences into classroom practices, and their attitudes toward integrating these projects into the curriculum. Mixed-methods research with a convergent design was employed in two e-textile-supported STEAM teacher training camps, involving 20 and 19 in-service science teachers, respectively. Qualitative and quantitative data were collected using post-intervention surveys, semi-structured interviews, and a follow-up survey. The findings revealed that the program increased teachers' confidence in STEAM project design, fostered creativity and interdisciplinary learning, and improved STEAM knowledge and skills. In addition, teachers reported being well-equipped to integrate the learned practices in their classrooms, with a positive shift in their attitudes toward integrating such interdisciplinary approaches into the curriculum. The findings also revealed high teacher satisfaction with the program and a sustained interest in STEAM practices. This research provides valuable insights for future efforts to support the adoption of e-textiles in STEAM science classrooms by highlighting their role in teacher professional development.

Keywords Professional development · e-textile projects · K-12 teachers · STEAM education

✉ Mustafa Sat
mstfsat@gmail.com

Kursat Cagiltay
cagiltay@gmail.com

[1] Faculty of Education, Lifelong Learning and Adult Education, Kırıkkale University, 71450 Yahşihan, Kırıkkale, Turkey

[2] Faculty of Education, TED University, Ankara, Turkey

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Introduction

The STEAM movement represents an innovative educational approach that integrates artistic endeavors (arts) with traditional STEM subjects (science, technology, engineering, and mathematics). This model emphasizes transdisciplinary learning experiences in which knowledge is shared seamlessly across subjects (White & Delaney, 2021). STEAM, rooted in the hands-on principles of maker education (Peppler, 2013), aims to develop comprehensive knowledge by integrating elements from various disciplines, thereby fostering meaningful and contextualized learning (Aguilera & Ortiz-Revilla, 2021).

Electronic textiles, also known as e-textiles, are fabrics augmented with electronic components (e.g., sensors, LEDs, conductive threads, and microcontrollers) to create systems that can sense, emit light, or display information. The commitment to integrating STEAM into the curriculum has led to the implementation of innovative instructional technologies, particularly e-textiles, across various educational settings (Fields & Kafai, 2023; Hébert & Jenson, 2020). Given their interdisciplinary nature, e-textiles enable educators to integrate multiple science concepts into the curriculum. These concepts include electricity, circuitry, computer science, and computational thinking (Fields et al., 2019; Tofel-Grehl et al., 2017, 2021). Consequently, it is imperative to incorporate maker skills, particularly STEAM practices supported by e-textiles, into initial and ongoing teacher training (Valente & Blikstein, 2019).

It has been widely recognized that in-service teachers need to possess a deep understanding of the content they teach, as well as of the technologies and pedagogies they use (Koehler & Mishra, 2009). However, acquiring and maintaining this multifaceted knowledge base remains a significant challenge for teachers (Nadelson & Seifert, 2017). This challenge is compounded by difficulties in mastering specific subject domains and in effectively implementing integrated frameworks such as STEAM in the classroom (Kim & Bolger, 2017; Margot & Kettler, 2019). As emphasized in the Organization for Economic Co-operation and Development (OECD) report, the solution lies in continuous and comprehensive professional development (PD) interventions tailored to STEAM integration (OECD, 2022). Furthermore, educational literature emphasizes the necessity for PD programs that enhance teachers' understanding of STEAM education and equip them with the necessary tools to effectively implement it in the classroom (Silva-Hormazábal & Alsina, 2023). Therefore, investigating the effects of e-textile-supported PD on teachers could reveal its potential to enhance STEAM integration in their development.

STEAM education with e-textiles

The New Media Consortium (NMC) identified STEAM as a growing trend in K-12 education (Johnson et al., 2015), with an increasing number of institutions worldwide emphasizing and adopting interdisciplinary learning that combines STEM and the arts (Belbase et al., 2022). e-textile projects have the potential to be powerful tools for STEAM education (Buechley et al., 2013). The importance of sustaining e-textile-supported STEAM activities both within and beyond the classroom has been widely recognized (Fields & Kafai, 2023). Studies on e-textiles in STEAM education have demonstrated their significance in promoting STEAM and fostering diverse skills and competencies among students (Guimeráns-Sánchez et al., 2023). While e-textiles offer exciting possibilities for STEAM

education, creating effective educational materials requires addressing technical limitations and prioritizing usability, safety, and visual appeal to ensure their success (Kara & Cagiltay, 2023).

STEAM education integrates three key elements: problem-based learning, technology, and collaboration (Herro & Quigley, 2017). These elements work together to create a dynamic learning environment. e-textile projects have been shown to bring these three elements together in meaningful and engaging ways (Peppler, 2016). According to Peppler (2013), "The creative problem solving, flexible thinking, and risk taking integral to e-textile design are ideal byproducts of a STEAM-powered approach to education, which aims to balance technical expertise with artistic vision" (p. 40). As part of STEAM education, teachers can use these hands-on projects to better convey their standards-based lessons to students (Peppler et al., 2016).

Although teachers play a crucial role in the success of STEAM integration, they need the requisite knowledge and skills to effectively develop and implement STEAM activities in their courses (Anisimova et al., 2020). What they need is practical training in STEAM practices and access to the necessary resources to establish collaborative learning environments within their schools (Şahinkarakaş & Toköz Göktepe, 2022). Nevertheless, resources are scarce to support their implementation of STEAM interventions in their teaching practices (Fields & Kafai, 2023; Lo, 2021). Therefore, this study aims to equip teachers with the essential knowledge, skills, and attitudes to successfully integrate STEAM practices into their teaching methods through wearable e-textile-supported PD.

Studies on e-textiles-supported STEAM PD

e-textiles are an innovative and creative approach in STEAM PD, offering teachers unique opportunities to participate in engaging learning experiences. Several studies explore how wearable e-textile technology can equip teachers with the pedagogical knowledge, skills, and classroom practices needed to integrate engaging STEAM curricular units into their classrooms. For instance, in Searle et al.'s (2016) study, a four-day PD was given to eleven middle school science teachers to use e-textile projects in the context of a middle school science unit on energy. The study found that e-textile projects are effective in helping teachers develop coding skills, broaden their understanding of computational concepts, and foster enthusiasm for teaching these skills to students. Moreover, in the study by Fields et al. (2017), two computer science (CS) teachers participated in a three-day PD program where they first learned to design and create six e-textile projects and then implemented them over eight weeks in their high school classrooms. Similarly, Searle et al. (2023) conducted a 4-day PD program to improve the knowledge of 4 K-12 teachers regarding e-textile content and inquiry-based teaching methods. Following PD, teacher participants implemented an integrated CS and computational thinking unit that incorporated e-textile projects.

In another study by Nakajima and Goode (2019), five CS teachers received training in an e-textiles curriculum to integrate e-textile projects into their CS courses as a computing pedagogy. The study findings showed that engaging in hands-on making experiences enhanced teachers' content knowledge and skills and sparked their enthusiasm to implement new pedagogical approaches in their classrooms. Moreover, using a design-based research approach, Tofel-Grehl et al. (2018) conducted multiple iterations of the PD workshop with 46 K-12 teachers, focusing on integrating computational thinking and STEM content through e-textiles in their classrooms. The study reported that although science teachers successfully integrated

core STEM skills and practices, they had difficulty understanding basic coding and lacked content knowledge, particularly in implementing hands-on projects involving circuits and electricity.

STEAM PD

PD is widely recognized as a crucial first step in promoting STEAM teaching within schools (Herro & Quigley, 2017) and mitigates the challenges associated with STEAM implementation. Teachers often value PD because it equips them with knowledge and skills that can be readily applied in their classrooms, its transformative effect on teaching methodologies, and the opportunity to collaborate with colleagues (Romero-Ariza et al., 2021). In addition, they seek PD to explore innovative solutions to classroom challenges and to modify their teaching practices (Nakajima & Goode, 2019).

Research has shown that PD can equip teachers with the skills and knowledge needed to integrate STEAM education into their classrooms. This includes enhancing their understanding of STEAM concepts for instructional purposes (Herro & Quigley, 2017) and improving their pedagogy, self-efficacy, and arts-integration practices, ultimately encouraging them to implement STEAM in their courses (Boice et al., 2021). Beyond content knowledge, research by Herro et al. (2018) suggests that well-designed STEAM PD programs positively impact instructional approaches, formative assessment, collaboration, and, ultimately, student engagement. It can also help individual teachers refine their instructional practices (Herro et al., 2022). However, a study by Quigley and Herro (2016) found that although teachers who participated in STEAM PD incorporated some strategies, fully implementing concepts such as transdisciplinary teaching, arts integration, and collaboration remained challenging.

While the PD benefits are well-established, a significant barrier to widespread STEAM integration in classrooms persists: the need for PD focused on applying STEAM practices to specific content (Geum & Bae, 2012). A recent review study highlights the need for ongoing training to enrich courses with interdisciplinary approaches, particularly in the context of e-textiles for STEAM education (Guimeráns-Sánchez et al., 2023). Engaging teachers in designing e-textile STEAM projects and allowing them to apply their subject-matter knowledge through PD could be a promising strategy for integrating STEAM more effectively into classrooms. Therefore, this study examined the effect of STEAM PD supported by e-textiles on in-service teachers by addressing the following research questions.

1- What are the perceived benefits of the e-textile-supported PD program for science teachers?
2- What are in-service science teachers' perceptions regarding their developed ability to transfer learning experiences of the PD program to the classroom?
3- What are the attitudes of in-service science teachers towards integrating e-textile-supported STEAM projects into the curriculum?

Methodology

This study adopted a mixed-methods, convergent design to triangulate evidence from semi-structured interviews and survey data (Creswell & Clark, 2011). In convergent designs, qualitative and quantitative strands are collected within a comparable time frame, analyzed

independently using strand-appropriate procedures, and subsequently integrated to generate a more comprehensive understanding of the research problem (Fetters et al., 2013). The Middle East Technical University Human Research Ethics Committee granted ethical approval. Figure 1 provides an overview of the research process, delineating the main phases of data collection and analysis and indicating the points at which the qualitative and quantitative findings were integrated for interpretation.

Context of the program

A five-day PD program was organized at a university in partnership with the Center for Science, Technology, Engineering, and Mathematics Education (CSTEM) and the Audiovisual Systems Research and Application Center (ASRAC). The PD was conducted through two separate camps, each accommodating a different group of middle school science teachers.

A dedicated website was established as the primary platform for sharing program updates and essential information, and for accepting program applications. The program's announcement was sent out via email and shared across multiple social media platforms. Applications were collected via a Google Form that included questions on demographics, reasons for participation, and prior experience with e-textiles and STEAM approaches.

The researchers employed a purposive sampling technique to choose teachers who fulfilled specific criteria: (1) having little or no previous involvement in hands-on STEAM projects with wearable e-textiles, (2) being early career or inexperienced teachers, (3) showing a keen interest in STEAM fields, particularly arts and crafts, and (4) being from

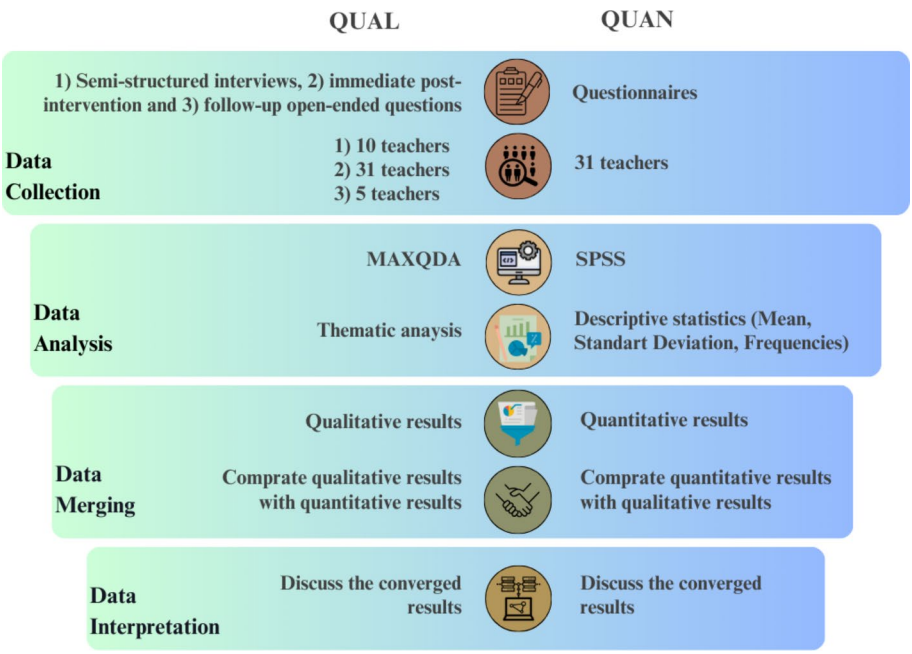


Fig. 1 Overview of the research process

public schools situated in rural and socioeconomically disadvantaged regions of the country (Patton, 2002).

The program implementation

The program focused on assisting science teachers in designing and developing STEAM projects using e-textile technology, with an emphasis on integrating art, design, and technology. In essence, the projects aimed to improve understanding of electricity and circuitry concepts in science subjects.

The program encompassed seven structured e-textile projects, including the design of badges, wristbands, necklaces, color-changing star clusters, light-sensing lighthouses, heat-sensing thermometers, color-sensing scarves, and a single unstructured (open-ended) project. PD sessions commenced each day at 9:00 am and concluded at 5:00 pm. The first three projects enabled teachers to explore serial and parallel circuits and to become familiar with e-textile materials. The other projects incorporated various sensors and programming, allowing teachers to explore functional circuit designs and basic programming with Arduino microcontrollers. Table 1 presents the program's designated flow.

The program was held in a large hall located within the ASRAC. The hall provided ample space for teachers to move around comfortably and engage effectively in their STEAM projects. Figure 2 shows the hall's layout, with each group assigned a dedicated table and a central shared table for project materials. A team of five facilitators, along with the researcher, consistently supported the project groups throughout the program.

The program supplied e-textile materials, necessary tools and equipment for the design and crafting process, and comprehensive guidance and support to ensure the successful implementation of teachers' e-textile projects. Figure 3 shows some of the e-textile components used, such as LilyPad LEDs, LilyPad Arduino USB, Light Sensor, LilyPad Pixel Board, Temperature Sensor, Buzzer, Color Sensor, and Conductive Thread.

The hands-on projects integrated problem-based scenarios and engineering design stages adapted from Hynes et al. (2011). Figure 4 displays the design thinking stages that teachers, working in groups of two or three, followed when designing and creating their projects. Some of the projects developed by teachers are shown in Fig. 5.

Participants

The study included two separate groups of middle school science teachers. The first group consisted of 20 teachers—12 women and 8 men—aged 23 to 45. The second group comprised 19 teachers—12 women and 7 men—aged 23 to 52. Both groups had up to 25 years of teaching experience, mostly between 1 and 10 years. The teachers were chosen from schools across 13 regions of Turkey, representing a range of socioeconomic backgrounds. Detailed information about the participants' teaching experience and age is provided in Table 2.

Data collection instruments

Various data-collection tools were used to examine teachers' experiences with PD and their attitudes toward interdisciplinary approaches in K-12 settings. One of the tools was a study-specific multi-subscale questionnaire (74 closed-ended and nine open-ended questions).

Table 1 The flow of the program

Day	Activities
Day 1: Introduction and overview	Welcome ceremony
	An informative and motivational speech by two faculty members from the Department of Fashion and Textile Design about fashion and design
	Introduction to the training camp, its objectives, and schedule
	Lunch break
	Introduction to e-textile technologies, including conductive threads, microcontrollers, and sensors
	Hands-on activities to familiarize teachers with basic e-textile components
Day 2: Guided project development	Introduction to the schedule and objectives for the day's activities
	Participants worked on structured projects
	Lunch break
	Participants refined and developed their projects
Day 3: Guided project development	Introduction to the schedule and objectives for the day's activities
	Introduction to microcontrollers (e.g., Arduino) and programming
	Coding basics for e-textile projects
	Lunch break
	Participants worked on structured projects
Day 4: Guided project development	Introduction to the schedule and objectives for the day's activities
	Participants worked on structured projects
	Lunch break
	Participants refined and developed their projects
Day 5: Project showcase and evaluation	Introduction to the schedule and objectives for the day's activities
	Participants worked on open-ended STEAM projects
	Lunch break
	Groups presented their project designs, highlighting the integration of art, design, and technology
	Awarding certificates of completion
	Celebrating achievements and collaboration

The questionnaire was initially drafted with 83 items to target the constructs in this study. Afterwards, two domain experts in science and ICT reviewed the items for relevance, clarity, and suitability to the context. After this review, the instrument was revised, resulting in a refined 48-item version (39 closed-ended questions and nine open-ended questions). Teachers' responses were gathered using a 7-point Likert scale, from 1 (strongly disagree) to 7 (strongly agree). The questionnaire measured four main areas: perceived benefits of the program, ability to transfer learning to practice, likelihood of participating in similar activities, and overall enjoyment and satisfaction.

The second instrument was a 16-item questionnaire using a 5-point Likert scale, from "strongly disagree" (1) to "strongly agree" (5). The questionnaire's structure and psychometric properties were validated by Karahan et al. (2017), who confirmed a single underlying factor and demonstrated its reliability and validity.

To supplement quantitative data collection, the study used a qualitative approach that combined methods. This included nine open-ended questions added to closed-ended



Fig. 2 E-textile project implementation space

survey items and semi-structured interviews. This multi-faceted approach aimed to capture participants' experiences, perspectives, and behaviors in their own words. Qualitative data collection enabled a more detailed understanding of the research phenomenon by allowing participants to share their unique insights and perspectives.

The interview protocol included twelve open-ended questions. Prompts were designed to capture participants' specific experiences with the program. To ensure the reliability and validity of the questions, they underwent an iterative review and supervision process involving two STEM/STEAM pedagogy experts and a doctoral student.

Furthermore, after a designated period following the program's conclusion and participants' return to their institutions, a follow-up survey was sent to participants as a Word document attachment. This survey aimed to assess their perceptions of how effectively they transferred the program's learning and to identify any challenges they faced in applying it. The follow-up survey consisted of five open-ended questions, such as (a) "*Have you applied or implemented the activities you engaged in the program within or outside of school settings? If yes, please provide details regarding the context (e.g., location), how the activity was implemented, and with whom it was implemented.*" and (b) "*Please elaborate on the extent to which the program's teachings benefited you in implementing these activities.*"

Data collection and analysis procedures

Upon completing the program, participants completed a paper-based survey comprising two questionnaires and several open-ended questions. They were encouraged to respond thoroughly based on their personal experiences and perspectives. Quantitative responses from the questionnaires were entered into IBM SPSS for analysis. In SPSS, the data were



Fig. 3 E-textile components used in the study

prepared and managed through screening procedures (e.g., checks for completeness and outliers) and summarized using descriptive statistics (means, standard deviations, and frequencies). Although 39 teachers from two cohorts participated, some survey forms with incomplete or missing responses were excluded. As a result, the quantitative tables and analyses in this study are based on the complete post-survey responses.

Additionally, after completing the program, semi-structured interviews were conducted with a criterion-based purposive subsample of participants who showed high levels of interest and engagement during the activities (Patton, 2002). This method was used to gather rich reflections on teachers' learning experiences and their perceptions of the applicability of e-textile activities. Six teachers (three male, three female) from the first camp and four teachers (two male, two female) from the second camp participated in the interviews. The interviews were conducted in person and lasted 23–53 min. In addition, a follow-up survey was sent as an attachment to 32 participants. Although 25 participants responded, only 5 completed and returned the survey. The remaining ten participants did not respond. Because follow-up participation was voluntary and limited, these responses

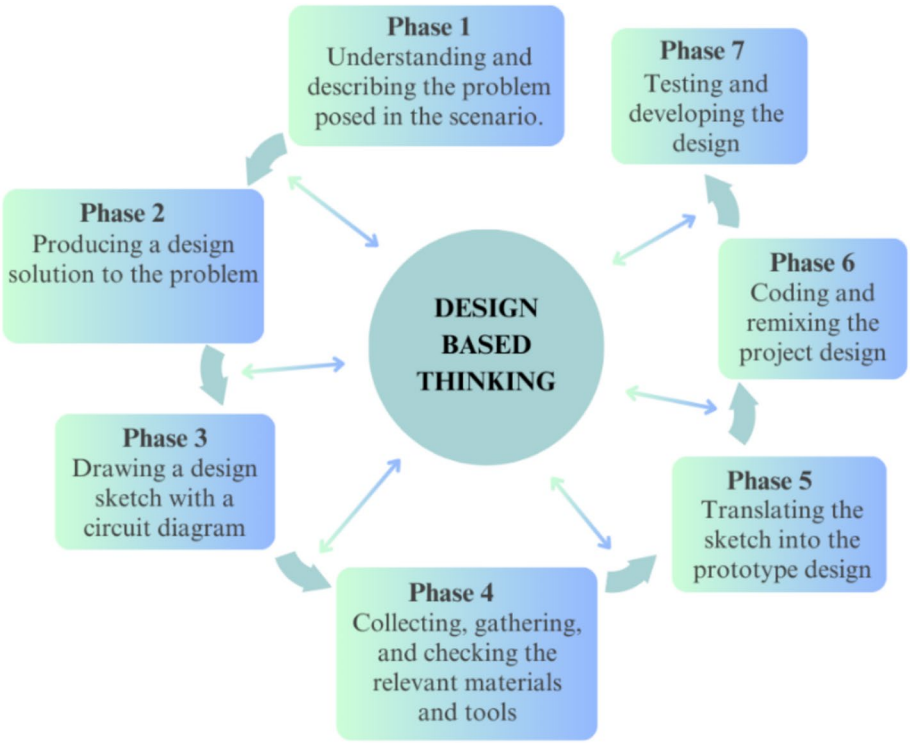


Fig. 4 Design-based thinking stages

were treated as supplementary qualitative data and interpreted with caution. The follow-up survey included five open-ended questions designed to elicit participants' reflections on and experiences with the e-textile activities they carried out in their schools following the PD program.

The qualitative data included interview transcripts and written responses to open-ended questions. All qualitative materials were imported into MAXQDA for analysis. Two researchers independently used structural coding, a technique that organizes qualitative data by identifying recurring concepts and patterns and grouping excerpts accordingly (Bogdan & Biklen, 2007). They began the study by thoroughly familiarizing themselves with the entire dataset through repeated readings. The unit of analysis was a meaning unit, defined as a phrase, sentence, or short segment that expresses a single idea relevant to the research questions. Each meaning unit was examined to identify key concepts, and provisional codes were assigned using labels created by the researchers. As the analysis continued, new concepts were identified and assigned new codes, while similar segments were grouped under existing labels through an iterative, constant comparison process.

After the initial coding phase, the researchers created a codebook to ensure consistent application of codes across the entire corpus. The codebook included code labels, operational definitions, inclusion/exclusion criteria, and brief sample excerpts to demonstrate its intended use. Using this refined codebook, both researchers independently coded the dataset and then met to compare their coding decisions and resolve any discrepancies through discussion. Disagreements were resolved through a mutual agreement protocol,



Fig. 5 Project samples created by teachers

Table 2 Participants' teaching experience and age in the first and second group

Teaching experience (years)	Age range	First group (n)	Second group (n)
Below 1	21–25	3	5
1–5	26–30	7	8
6–10	31–35	5	4
11–15	36–40	3	1
16–20	41–45	1	–
21–25	46–50	1	–
25+	51+	–	1

and code definitions were repeatedly refined as needed to clarify them (Creswell & Poth, 2016). Next, the codes were combined into broader categories and organized into candidate themes based on the identification of conceptual patterns and relationships among codes.

Thematic analysis was conducted by examining these themes in relation to the dataset to ensure internal consistency and clear distinctions among them. Through consensus, final labels and definitions for the themes were established. After coding the ten interview transcripts, thematic redundancy was observed at the category level.

Findings

The findings are organized by themes. Within each theme, quantitative findings are presented along with qualitative evidence to illustrate and support participants' perspectives.

Benefits of STEAM activities

Table 3 presents participants' views on the PD's effectiveness in improving various aspects of their teaching and learning. The findings indicated highly positive perceptions across all items measured, with average scores ranging from 5.74 to 6.77.

As shown in Table 3, participants demonstrated the highest levels of agreement regarding the program's facilitation of interdisciplinary learning, with 83.9% *strongly agreeing* that cross-disciplinary integration was effectively supported. The program's overall perceived value was high, with 74.2% of participants *strongly agreeing* that they experienced multiple benefits from their participation. Many participants also *agreed* or *strongly agreed* that they gained substantial understanding of design-oriented thinking methodologies (90.3%), principles for designing STEAM instructional activities (96.8%), and improvements in their domain-specific knowledge and pedagogical skills (96.8%). Additionally, 80.6% of participants *strongly agreed* that the program had the potential to improve students' fine motor skills through e-textile-based activities.

Participants' reflections provided rich qualitative support for these quantitative findings, particularly regarding the development of creative skills and the discovery of latent abilities. A participant articulated the emergence of previously dormant competencies through the e-textile activities: *"I saw that skills that I had never had could slowly emerge, and I, who hadn't picked up a needle and thread since I was in the army, can now sew. So, the activities showed how to connect a thread to a needle, which color goes with which color, which things can be used more vividly, or how to transform the design into three dimensions. The activities showed that we can think in three dimensions, but it is atrophied because we don't use it. I saw that the inclusion of art in the activities improved these skills."* Another participant echoed this sentiment regarding artistic development, stating: *"As a person with a weak artistic and aesthetic side, I think that this program has developed something in us, it has shown that we have a skill and a talent."* These qualitative accounts suggest that the program not only developed technical and pedagogical competencies but also facilitated participants' recognition of their own creative potential, which may have been previously underestimated or underdeveloped.

Participants strongly endorsed the program's effectiveness in developing their creative capacities (77.4%) and encouraging the practical application of STEAM knowledge and competencies (77.4%). These quantitative findings were corroborated by participants' reflections, which emphasized how the design-oriented activities unlocked creative potential. A participant illustrated the intrinsic link between the program's design tasks and creativity: *"I think the activities definitely developed our creativity because there is design involved. This is not something that can happen without design and creativity. For*

Table 3 Perceived benefits of the PD program (N = 31)

Item	M	SD	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
The program benefited me in many ways	6.74	0.44	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	8 (25.8)	23 (74.2)
Thanks to the program, I learned how to design and develop a project by following the design-oriented thinking steps	6.58	0.67	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (9.7)	7 (22.6)	21 (67.7)
The e-textile supported STEAM activities in the program would improve students' fine muscle skills	6.71	0.69	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	1 (3.2)	4 (12.9)	25 (80.6)
The activities in the program developed my creative skills	6.77	0.43	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	7 (22.6)	24 (77.4)
The activities in the program allow for interdisciplinary learning	6.77	0.56	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (6.5)	3 (9.7)	26 (83.9)
The activities in the program encourage the use of knowledge and skills in STEAM areas	6.77	0.43	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	7 (22.6)	24 (77.4)
Thanks to the program, I got an understanding of how STEAM activities should be designed	6.61	0.67	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	0 (0.0)	9 (29.0)	21 (67.7)
Through the activities in the program, I improved my knowledge and skills in STEAM fields	6.74	0.51	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	6 (19.4)	24 (77.4)
I learned a lot about electricity concepts in the program	6.45	0.68	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (9.7)	11 (35.5)	17 (54.8)
I learned how to code with Arduino in the program	5.74	1.21	0 (0.0)	0 (0.0)	2 (6.5)	3 (9.7)	6 (19.4)	10 (32.3)	10 (32.3)

Values are n (%). Percentages are based on N = 31. Response scale: 1 = Strongly disagree to 7 = Strongly agree

example, in the last activity, we were going to come up with a design ourselves. We are thinking about what to do. Creating something original made us receptive to new ideas and open to manufacturing processes." Echoing the creativity-focused findings, participants also highlighted the iterative nature of this creativity, noting that even failures contributed to their development: *"I think the activities in the program unleashed and developed our creativity. Everything we did is actually the product of creativity. Even though we failed in many things, my groupmates and I corrected them later, but creativity had a big impact. You say that better designs can be done over time."*

Perceived learning outcomes related to electrical concepts received favorable ratings, with 54.8% *strongly agreeing* that they gained significant knowledge of electrical principles. However, Arduino programming instruction received the lowest endorsement and showed the greatest variability among all measured items. 32.3% *strongly agreed* that they learned Arduino coding skills, while 9.7% reported a *neutral* stance.

Transfer of knowledge and experiences

Table 4 shows participants' views on the transferability and classroom use of program learning. The findings indicate a generally positive outlook across all items, with average scores ranging from 5.68 to 6.71, indicating a strong readiness to incorporate e-textile–supported STEAM activities in schools.

As outlined in Table 4, participants showed the highest agreement on the integration and ongoing use of STEAM-focused wearable e-textile activities. To illustrate, 74.2% of participants *strongly agreed* that these activities should be included in the curriculum. Furthermore, participants expressed high confidence in applying the program's outcomes in their professional practice. Specifically, 71.0% *strongly agreed* that they could design similar activities using wearable e-textile technologies. Additionally, 67.7% *strongly agreed* that they could use wearable e-textiles across different fields. The perceived transferability to school settings was also significant, with a large proportion of participants *agreeing* or *strongly agreeing* that they could apply what they learned at school (80.6%) and that they felt capable of transferring the knowledge and skills to their students (80.6%). Participants' reflections provided qualitative evidence supporting these quantitative findings, especially regarding classroom applicability and the sense of having a solid foundation for implementation. A participant noted, "*I can apply all these activities in my electricity lesson. I can apply a simple electrical circuit with the technological materials provided. Of course, I need to improve myself a little more. Maybe I need to learn different activities, but I have the necessary foundation here, and that would be enough. The rest is up to me. Adding different ideas,* etc.*, varies according to the person.*"

Participants also strongly supported the instructional value of wearable e-textiles for teaching electricity concepts. As shown in the table, all participants *agreed* or *strongly agreed* that they could benefit from wearable e-textile technologies in teaching electricity. 93.5% of participants similarly *agreed* or *strongly agreed* that they had gained the ability to use STEAM-focused e-textile activities to teach electricity concepts. Follow-up reports of post-camp implementation confirmed these findings. A participant described the implementation of e-textile products at a school science fair, noting: "*I organized a science fair… We designed bracelets, necklaces, badges, and color-changing scarves… 5th-grade students had a lot of fun and learned while doing the activities. They understood the electric circuit very well thanks to these activities.*"

Table 4 Perceived ability to transfer knowledge and experiences to the classroom (N = 31)

Item	M	SD	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
I can apply what I learned in the program in my school	6.29	0.94	0 (0.0)	0 (0.0)	0 (0.0)	2 (6.5)	4 (12.9)	8 (25.8)	17 (54.8)
I consider myself competent enough to transfer the knowledge and skills I learned in the program to my students	6.19	1.22	1 (3.2)	0 (0.0)	0 (0.0)	0 (0.0)	5 (16.1)	9 (29.0)	16 (51.6)
I can benefit from wearable e-textile technologies to teach electricity concepts in my lessons	6.52	0.51	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	15 (48.4)	16 (51.6)
I developed the ability to utilize STEAM-focused e-textile activities to teach electricity concepts	6.45	0.62	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (6.5)	13 (41.9)	16 (51.6)
STEAM-focused e-textile activities should be integrated into the curriculum	6.65	0.71	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	1 (3.2)	6 (19.4)	23 (74.2)
Through the knowledge and skills, I learned in the program, I can design similar activities using wearable e-textile technologies	6.71	0.46	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	9 (29.0)	22 (71.0)
With what I learned in the program, I can use wearable e-textile technologies in different fields	6.65	0.55	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	9 (29.0)	21 (67.7)
I can adequately transfer the art dimension to my STEAM-focused e-textile designs	5.68	1.25	0 (0.0)	1 (3.2)	0 (0.0)	4 (12.9)	8 (25.8)	8 (25.8)	10 (32.3)

Values are n (%). Percentages are based on N = 31. Response scale: 1 = Strongly disagree to 7 = Strongly agree

However, compared with the generally strong endorsement seen across most items, the art-integration dimension had the lowest level of support and the most variation. Only 32.3% of participants *strongly agreed* that they could effectively incorporate the artistic dimension into their STEAM-focused e-textile designs, whereas 12.9% were *neutral*. This pattern suggests that teachers felt somewhat prepared to implement and adapt e-textile–supported STEAM activities, though some may require additional scaffolding to incorporate aesthetic and artistic elements into their designs confidently.

Future engagement in STEAM practices

Table 5 presents participants' views on their future involvement in STEAM activities after the PD program. The findings consistently show positive intentions across all items, with average scores ranging from 6.52 to 6.90, indicating strong dedication to ongoing participation and continued use of program practices.

As shown in Table 5, participants demonstrated the highest agreement regarding their future involvement in STEAM activities and the continued use of e-textile–supported professional learning. 93.5% of participants *strongly agreed* that similar training opportunities should be offered regularly, showing strong support for ongoing STEAM-focused professional development. Additionally, participants demonstrated a strong willingness to reengage in similar learning experiences; specifically, 80.6% *strongly agreed* that they would like to participate in such programs again.

Furthermore, participants expressed a need for support in integrating such training programs into school settings, with 67.7% *strongly agreeing* that similar initiatives could be carried out as school-based activities. Additionally, participants showed high confidence in applying the program's learning outcomes in student-centered ways. 67.7% of participants *strongly agreed* that they could lead similar projects with their students, using the knowledge gained from the program. Participants also indicated their plans for ongoing professional growth and innovation. Specifically, all participants *agreed* or *strongly agreed* that they are dedicated to further developing the skills they acquired and to starting new projects aligned with that knowledge. Overall, these findings clearly show that participants are committed to the immediate start and continual development of STEAM education.

Enjoyment and satisfaction

Table 6 presents perceptions of enjoyment and satisfaction after participants' involvement in the training program. The findings show consistently positive ratings across all measured items, with mean scores ranging from 1.10 to 6.77, signifying high perceived usefulness and enjoyment, along with minimal reluctance to participate in camp activities.

As shown in Table 6, participants expressed the highest levels of agreement regarding the camp's perceived usefulness and the enjoyment of participating. 80.6% of participants *strongly agreed* that the camp was highly beneficial and that they enjoyed the experience. Participants also showed strong positive engagement with the program's practical part, with 71% *strongly agreeing* that they enjoyed the STEAM activities. Additionally, many participants expressed satisfaction with how the program was run, with 90.3% *agreeing* or *strongly agreeing* that the camp was well organized. Participants' reflections provided qualitative evidence supporting these quantitative findings, particularly regarding the extent to which the camp met professional standards and its relevance to classroom practices. A participant stated, "*I expected the camp to improve my professional skills, to give me the*

Table 5 Future engagement in STEAM practices (N = 31)

Item	M	SD	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
Similar programs should be organized frequently	6.90	0.40	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	1 (3.2)	29 (93.5)
I would love to participate in this or similar professional development programs again	6.77	0.50	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	5 (16.1)	25 (80.6)
Similar professional development programs should be organized as in-school activities	6.52	1.00	0 (0.0)	1 (3.2)	0 (0.0)	0 (0.0)	1 (3.2)	8 (25.8)	21 (67.7)
I will be able to make similar projects with my students using the knowledge I gained at the program	6.61	0.62	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (6.5)	8 (25.8)	21 (67.7)
I am planning to improve the skills I acquired at the program	6.74	0.44	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	8 (25.8)	23 (74.2)
I am planning to develop new projects in line with the knowledge I gained at the program	6.77	0.43	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	7 (22.6)	24 (77.4)

Values are n (%). Percentages are based on N = 31. Response scale: 1 = Strongly disagree to 7 = Strongly agree

Table 6 Perceived enjoyment and satisfaction with the program (N = 31)

Item	M	SD	Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree
The program was generally useful	6.77	0.50	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	5 (16.1)	25 (80.6)
I enjoyed doing activities in the program	6.65	0.61	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (6.5)	7 (22.6)	22 (71.0)
The program was boring for me	1.19	0.40	25 (80.6)	6 (19.4)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
I had fun during the program	6.77	0.50	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	5 (16.1)	25 (80.6)
I did the activities in the program reluctantly	1.10	0.30	28 (90.3)	3 (9.7)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
I would not recommend this program to my colleagues	1.61	1.80	27 (87.1)	1 (3.2)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (9.7)
It was fun to do the activities in the program	6.58	0.76	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.2)	2 (6.5)	6 (19.4)	22 (71.0)
The program was well organized	6.55	0.68	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (9.7)	8 (25.8)	20 (64.5)
The program did not meet my expectations	1.29	0.64	24 (77.4)	6 (19.4)	0 (0.0)	1 (3.2)	0 (0.0)	0 (0.0)	0 (0.0)

Values are n (%). Percentages are based on N = 31. Response scale: 1 = Strongly disagree to 7 = Strongly agree

knowledge to use STEAM activities in my classes, and to attract more attention by applying the activities to my students. I think my expectations were met. I believe I can apply these activities in my school." Another participant highlighted the perceived practicality and motivational potential of the activities for students, noting: "*It was a practical and effective camp. The activities were quite unusual and intriguing for designing simple electrical circuits. I believe that students will be motivated to engage in these activities.*"

Conversely, responses to negatively framed statements showed minimal negative affect and reluctance. Importantly, many participants *strongly disagreed* with statements suggesting that the camp was uninteresting (80.6%) or that they were hesitant to engage in the activities (90.3%). Additionally, perceptions of unmet expectations were rare, with 96.8% *disagreeing* or *strongly disagreeing* that the camp fell short of their hopes. Overall, these findings suggest that participants experienced high satisfaction and enjoyment during the activities, with very little evidence of disengagement or dissatisfaction.

Teacher attitudes towards interdisciplinary curriculum integration: readiness, recognition, and challenges

Table 7 presents participants' attitudes toward integrating an interdisciplinary approach, such as STEAM practices, into the school curriculum. The findings reveal broad support for interdisciplinary teaching, along with clearly expressed implementation challenges.

As shown in Table 7, 94.4% of participants *agreed* or *strongly agreed* that interdisciplinary elements already appeared in their curriculum unintentionally. Additionally, all participants *agreed* or *strongly agreed* that they intentionally incorporated content and materials from other disciplines to support student learning, indicating deliberate efforts to foster cross-disciplinary connections. The perceived educational value of an interdisciplinary curriculum was also high, with 63.9% of participants *strongly agreeing* that such a curriculum would improve students' learning.

Regarding preparedness and openness to change, most participants (86.1%) *agreed* or *strongly agreed* that their professional training was sufficient to implement interdisciplinary approaches, while a small minority (5.56%) expressed uncertainty or felt inadequately prepared, indicating variability in perceived training adequacy. Consistent with an openness to innovation, resistance to curriculum change seemed limited, as 77.8% *disagreed* or *strongly disagreed* with statements reflecting discomfort about implementing such changes, while 22.2% remained neutral. Participants also demonstrated strong willingness to engage in capacity building, with 100% *agreeing* or *strongly agreeing* that they would be willing to receive training in foundational concepts of interdisciplinary curricula.

Despite these positive orientations, participants also identified significant barriers to implementation. Although curriculum-related constraints were seen as moderate, resource limitations emerged as the main obstacle. 38.9% of participants *agreed* or *strongly agreed* that the existing curriculum standards hindered the adoption of new concepts. In contrast, 88.9% *agreed* or *strongly agreed* that limited resources (such as time and funding) made it difficult to implement new approaches, like e-textiles-supported STEAM activities. Supporting these findings, qualitative accounts further explained these challenges, highlighting inadequate learning spaces and materials, insufficient instructional time, students' underdeveloped sewing and handcrafting skills, exam-focused performance pressures, parents' limited awareness of STEAM practices, and the relatively high cost of wearable e-textile technologies. For instance, a participant stated, *"The lack of suitable classes, working space, laboratories, and materials, and in short, not having suitable conditions, will make*

Table 7 Attitudes of teachers towards interdisciplinary approach and its integration into school curriculum (N = 36)

Item	M	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Some elements in my curriculum feature an interdisciplinary approach, although they were unplanned	4.17	0.61	0 (0.0)	1 (2.8)	1 (2.8)	25 (69.4)	9 (25.0)
I purposely incorporate material from other disciplines to prepare students for my curriculum	4.22	0.42	0 (0.0)	0 (0.0)	0 (0.0)	28 (77.8)	8 (22.2)
An interdisciplinary curriculum would enhance student's learning	4.64	0.49	0 (0.0)	0 (0.0)	0 (0.0)	13 (36.1)	23 (63.9)
My professional training prepared me to use an interdisciplinary approach in the classroom	4.00	0.83	1 (2.8)	1 (2.8)	3 (8.3)	23 (63.9)	8 (22.2)
I feel uncomfortable implementing curriculum change in my classroom	1.89	0.75	12 (33.3)	16 (44.4)	8 (22.2)	0 (0.0)	0 (0.0)
I am willing to be trained/re-educated on the basic concepts of an interdisciplinary curriculum	4.72	0.45	0 (0.0)	0 (0.0)	0 (0.0)	10 (27.8)	26 (72.2)
I would find it difficult to work with teachers from other disciplines	2.08	0.81	7 (19.4)	22 (61.1)	4 (11.1)	3 (8.3)	0 (0.0)
Required curriculum, such as graduation standards, make it difficult to implement new ideas	2.97	1.13	2 (5.6)	14 (38.9)	6 (16.7)	11 (30.6)	3 (8.3)
Lack of resources, such as money and time, makes it difficult to implement new approaches	4.03	0.94	1 (2.8)	3 (8.3)	0 (0.0)	22 (61.1)	10 (27.8)
An interdisciplinary curriculum is just another "educational reform" that will not work	1.61	0.69	17 (47.2)	17 (47.2)	1 (2.8)	1 (2.8)	0 (0.0)
Teachers in the other disciplines involved in this survey view my discipline area as less valuable than theirs and wouldn't be interested in an interdisciplinary approach involving my curriculum area	2.11	0.75	6 (16.7)	22 (61.1)	6 (16.7)	2 (5.6)	0 (0.0)
My curriculum is more important for students than some other disciplines involved in this survey	2.72	1.09	3 (8.3)	16 (44.4)	7 (19.4)	8 (22.2)	2 (5.6)
An interdisciplinary approach would waste valuable class time from my discipline area	1.67	0.59	14 (38.9)	20 (55.6)	2 (5.6)	0 (0.0)	0 (0.0)
An interdisciplinary curriculum would improve upon my current curriculum	4.36	0.54	0 (0.0)	0 (0.0)	1 (2.8)	21 (58.3)	14 (38.9)
An interdisciplinary curriculum would support the learning goals of our high school	4.25	0.60	0 (0.0)	0 (0.0)	3 (8.3)	21 (58.3)	12 (33.3)
My current curriculum emphasizes a holistic learning experience for students	3.50	1.03	0 (0.0)	8 (22.2)	8 (22.2)	14 (38.9)	6 (16.7)

Values are n (%). Percentages are based on N = 36. Response scale: 1 = Strongly disagree to 5 = Strongly agree

it challenging to implement interdisciplinary practices like STEAM activities." Another participant noted the presence of contextual inequities between schools: "*I see that such activities can be done more easily in central schools, especially those located at the center of provinces, as they have more opportunities and the parents who live there are a bit more conscious of these activities. Schools in urbanized areas encourage their students or financially support them. That is why better projects take place in such schools. But I am in a small region, a village school. Our conditions, therefore, are not good. In this regard, lots of work and effort must be taken to spread these activities around.*"

Participants generally did not see collaboration with other disciplines as difficult. 80.5% of participants *disagreed* or *strongly disagreed* that working with teachers from other fields was challenging, while only 8.3% *agreed*. However, participants highlighted the instructional benefits of collaboration for effective implementation. A participant illustrated this instructional necessity as follows: *"When I teach science subjects, the fashion teacher should come and talk about fashion, the visual arts teacher might come and talk about aesthetic perception, and the ICT teacher should come and talk about how circuits are built. We have to be together in this."*

Participants showed little skepticism about the viability of the interdisciplinary approach. 94.4% of participants *disagreed* or *strongly disagreed* with the idea that an interdisciplinary curriculum was just another educational reform likely to fail. Most participants also rejected views of disciplinary devaluation. For example, 77.8% of participants *disagreed* or *strongly disagreed* that other disciplines considered their area less valuable. However, participants held mixed views regarding the disciplinary hierarchy. Although 52.8% *disagreed* or *strongly disagreed* that their discipline was more important than others, 27.8% *agreed* or *strongly agreed*. Finally, participants strongly opposed the idea that an interdisciplinary approach would waste instructional time. Specifically, 94.4% *disagreed* or *strongly disagreed* that it would waste valuable instructional time. Conversely, participants saw high perceived benefits. Many *agreed* or *strongly agreed* that an interdisciplinary framework could improve their current curriculum (97.2%) and support the school's learning goals (91.7%). In contrast, views on the current curriculum's holistic nature were more moderate. Only 55.6% *agreed* or *strongly agreed* that their curriculum emphasized a holistic learning experience, while 44.4% remained *neutral* or *disagreed*.

In conclusion, the findings primarily support interdisciplinary curriculum integration, highlighting perceived benefits, readiness for further training, and low reform skepticism, while emphasizing that resource constraints—rather than curricular limits—are the most significant perceived barrier to implementation.

Discussion and conclusion

This study examined the experiences of in-service middle school science teachers who participated in a PD program that used e-textiles to support teachers' acquisition of knowledge and skills for designing STEAM-oriented classroom learning activities. The findings collectively affirm the program's success, demonstrating high levels of teacher confidence in STEAM project design, strong perceived competence in implementing the learned practices in the classroom, and widespread positive attitudes toward integrating these activities into the curriculum.

The study's findings indicated high teacher satisfaction with the PD program. From a professional development perspective, high levels of satisfaction are pedagogically

significant, as they are closely associated with sustained engagement, openness to instructional innovation, and willingness to implement newly acquired practices in classroom contexts. Nearly all teachers reported that the program was beneficial, enjoyable, and well organized, exceeding their expectations and eliciting strong endorsements. These findings align with Nakajima and Goode (2019), in which teachers reported satisfaction with a PD program that met their goals. The overwhelmingly positive responses from teachers in this study underscore the value of such a well-designed program, as also indicated by Herro and Quigley (2017).

The development of creative skills and understanding of design-oriented thinking were among the most highly endorsed benefits of the program, along with enhanced STEAM content knowledge. These findings corroborate prior research emphasizing the role of maker-based activities, such as e-textiles, in fostering creativity and problem-solving (Peppler, 2013), understanding STEAM concepts (Herro & Quigley, 2017), and integrating arts-based practices (Boice et al., 2021). The qualitative data, which articulate the emergence of previously 'dormant' competencies, support the view that e-textiles can stimulate creative potential that is typically not addressed in traditional science training. Notably, this study extends existing knowledge by underscoring design thinking and creativity as salient perceived outcomes of participation. By foregrounding design thinking as a perceived outcome, the study contributes to the STEAM PD literature by highlighting how iterative problem-solving, prototyping, and reflective redesign can serve as central pedagogical mechanisms rather than ancillary skills in interdisciplinary teacher learning. In addition, consistent with studies reporting pedagogical shifts following STEAM PD (Boice et al., 2021), this study's findings indicated perceived improvements in teachers' pedagogical practices and interdisciplinary learning orientations, as well as increased interest in using e-textiles in STEAM activities. As a result, the findings suggest that e-textile projects may serve as a catalyst for teachers to refine, adapt, and integrate new pedagogical strategies within their existing instructional repertoires, rather than requiring comprehensive curricular change.

A crucial finding is the participants' high perceived learning related to electricity and circuitry concepts. This directly addresses the need for content-specific PD and contrasts with prior studies that identified a lack of content knowledge in circuits and electricity among science teachers in similar PD contexts (Tofel-Grehl et al., 2018). The e-textile projects appear to have provided the necessary context to enhance the teachers' domain-specific understanding meaningfully.

The high perceived ability to transfer knowledge to the classroom and to design similar activities indicates a strong sense of self-efficacy gained from the PD. The qualitative evidence that participants successfully implemented e-textile projects at a school science fair is a powerful indication of the program's utility and the immediate applicability of the foundational skills taught. These findings suggest that teachers recognize the value of e-textiles in STEAM education and strongly support their integration into curricula. Although prior e-textile PD research has corroborated these findings (e.g., Fields et al., 2017; Nakajima & Goode, 2019; Searle et al., 2023; Tofel-Grehl et al., 2018), these studies have focused mainly on computer science teachers or employed small sample sizes. This study, therefore, makes a distinct contribution by demonstrating the effectiveness of an e-textile PD program for a broader range of teachers. This broader applicability is particularly important given ongoing calls for STEAM professional development models that are accessible to teachers across subject areas and levels of prior technological expertise.

The study revealed a high level of teacher motivation to translate their newly acquired e-textile knowledge into classroom practice and continuously develop their STEAM skills.

This enthusiasm for bridging the gap between PD and classroom application by integrating similar training into school activities aligns with previous research (Jones et al., 2017; Nakajima & Goode, 2019; Searle et al., 2016). However, this study uniquely distinguished itself by identifying a firm intention among teachers to sustain and deepen their professional engagement with STEAM practices beyond the immediate PD context. These findings explain the program's effectiveness in motivating teachers not only to use e-textiles but also to embrace STEAM education as a whole. This sustained interest in e-textile projects is important for ensuring long-term program impact and successful STEAM integration into classrooms.

A notable challenge was participants' lower confidence in their ability to adequately transfer the art dimension to their STEAM designs. Although the program successfully stimulated personal creative skills, this finding suggests a gap in the pedagogical training required to formally integrate aesthetic and artistic principles into lesson plans. This difficulty in fully realizing interdisciplinary teaching and arts integration is consistent with the barriers identified by Quigley and Herro (2016). This finding indicates a need to assist teachers in integrating art or to help them seek out experts outside their content area. To facilitate the integration of art into their curriculum, teachers need PD opportunities that connect their subject matter to these art forms. Collaboration with arts specialists could further enhance this process.

Finally, this study found that integrating an interdisciplinary approach, such as STEAM activities supported by e-textiles, into the school curriculum is generally well received, though with some reservations. Thus, although teachers recognized the potential of interdisciplinary curricula to enhance student learning and enrich educational frameworks, they also reported challenges at multiple levels, including institutional constraints (e.g., school conditions and resources) and pedagogical factors (e.g., curriculum rigidity and difficulties with collaboration). These challenges are further compounded by teachers' limited content knowledge in circuits and electricity (Tofel-Grehl et al., 2018) and their challenges in designing practical STEAM projects supported by e-textiles (Sat & Cagiltay, 2025). Addressing these interconnected challenges is essential to the successful implementation of interdisciplinary STEAM approaches in education, thereby ensuring that both teachers and students can realize their benefits.

Although the findings indicate increased confidence, enjoyment, and strong perceived ability to transfer learning, the present study does not provide direct evidence of sustained changes in classroom practice. Transfer and implementation were assessed primarily through self-reports (post-program measures and a limited follow-up survey), rather than systematic classroom observations or longitudinal tracking. Therefore, assertions regarding the degree to which attitudinal and confidence shifts translate into durable instructional change should be approached with caution.

Limitations and future directions

Several limitations should be considered when interpreting the findings of this study. First, a major limitation is the potential selection bias inherent in purposive sampling. Because participants were partly selected for their interest in STEAM-related areas and willingness to attend an intensive PD, they may have been more likely to report high satisfaction, confidence, and perceived usefulness than teachers with less initial interest or readiness. Future studies using more diverse sampling strategies and longitudinal designs could strengthen

the evidence by capturing variations in teacher readiness and documenting sustained classroom implementation over time. Second, the qualitative interview subsample was selected through criterion-based purposive sampling, focusing on teachers who showed relatively high interest and engagement during the PD. While this approach provided rich information, it might have exaggerated enthusiastic perspectives and underrepresented more ambivalent experiences or barriers to implementation. As a result, the qualitative findings should be interpreted as reflecting the attitudes of highly engaged participants in this PD context rather than the full range of participant perspectives. Third, although the multi-subscale questionnaire was created the multi-subscale questionnaire to align with the study's aims and was reviewed and refined by experts, it was not psychometrically validated; thus, the construct validity and internal consistency of the subscales cannot be assured. Consequently, the conclusions based on these measures should be considered preliminary. Future research should involve the development and validation of comprehensive instruments and, where feasible, the replication of findings using established measures.

Furthermore, future research should address the gaps identified in the computational and artistic aspects of the PD. Long-term studies are necessary to evaluate the ongoing implementation of e-textile projects in classrooms and their effects on student outcomes. Additionally, research should examine the effectiveness of PD models that specifically focus on scaffolding arts-based pedagogy to better support comprehensive STEAM integration.

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Data availability The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

Conflict of interest The authors declare they have no financial interests.

Ethical approval The study protocol was reviewed and approved by the Middle East Technical University Human Research Ethics Committee (Approval No: 2018-FEN-103). Participation was voluntary. Prior to data collection, participants were informed about the purpose and procedures of the study, expected time commitment, potential risks/benefits, and their right to withdraw at any time without penalty. Written informed consent was obtained from all participants. For interviews, participants additionally consented to audio recording. To protect confidentiality, identifying information was removed during transcription, and participants were assigned pseudonymous identifiers.

Informed consent Informed consent was obtained from all individual participants included in the study.

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Mustafa Sat is an assistant professor in the Department of Educational Sciences at Kırıkkale University, Türkiye. He received both his master's and doctoral degrees in Computer Education and Instructional Technology from Middle East Technical University. His research focuses on educational technology, artificial intelligence in education, STEAM education, teacher education, and design-based learning environments.

Kursat Cagiltay is a professor in the Department of Educational Sciences at TED University, Ankara, Türkiye, He earned his BS in Mathematics and MS in Computer Engineering from Middle East Technical University. He holds a double PhD in Cognitive Science and Instructional Systems Technology from Indiana University. His research focuses on technology-enhanced learning, human–computer interaction, learning engineering, eye-tracking technologies, and virtual/augmented reality in education.