LUMAT
International Journal on Math, Science and Technology Education



Research article

# In-service teachers' readiness, challenges and support needs for implementing steam teaching in schools

Sanna Rantanen[1,2], Xiaoshan Huang[2] and Sari Harmoinen[3,2]

[1] University of Lapland, Finland
[2] University of Turku, Finland
[3] University of Oulu, Finland

**Abstract:** STEAM education has received growing research interest as a pedagogical approach that supports multidisciplinary learning, creativity and authentic problem-solving in schools. In the Finnish basic education context STEAM aligns closely with the National Core Curriculum, which emphasises transversal competencies and multidisciplinary learning modules. Despite this alignment the practical implementation of STEAM teaching remains complex and places significant demands on teachers' pedagogical competence, collaboration, and professional support. This study explores in-service teachers' (N=10) perceptions of STEAM education, their readiness to implement STEAM teaching and the challenges and support conditions shaping STEAM implementation in everyday school contexts. Semi-structured interviews were conducted with ten in-service teachers from primary, lower secondary and upper secondary schools who had experience with or interest in STEAM teaching. The interview data were analysed using reflexive thematic analysis supported by qualitative data analysis software. The findings indicate that teachers view STEAM positively, but experience challenges related to multidisciplinary lesson design, assessment of integrated learning, subject-specific constraints, and limited opportunities for collaborative planning. Teachers' readiness to implement STEAM was closely linked to their pedagogical content knowledge, particularly multidisciplinary PCK, as well as access to sustained professional development and collaborative support structures such as co-teaching. The results highlight a gap between conceptual understanding of STEAM and the practical ability to apply it. The study contributes to research on STEAM education by focusing on teachers' perspectives and identifying key pedagogical and organisational conditions that support sustainable STEAM implementation in schools.

**Keywords:** STEAM education, teachers' readiness, multidisciplinary teaching, PCK

Correspondence: sanna.ma.rantanen@utu.fi


Received 22 January 2026 / Accepted 7 June 2026 / Published 9 June 2026
Published by the University of Helsinki, Finland and LUMA Centre Finland.

## 1 Introduction

The Finnish education system is widely recognised for its strong commitment to educational equity, student well-being, and a highly qualified teaching profession. These values are articulated in the Finnish National Core Curriculum for Basic Education (2014), which provides a flexible, competence-based framework rather than a tightly prescribed, subject-based curriculum. The curriculum emphasises transversal competencies, phenomenon-based learning, multidisciplinary learning modules, and the active role of students in their own learning (Finnish National Agency for Education, 2014). A central aspect of this framework is the shift from subject-based knowledge transmission toward the development of broader competencies, including multiliteracy, technological skills, participation, collaboration, and creative problem-solving. Together, these principles create supportive conditions for the adoption of multidisciplinary pedagogical approaches in schools (Finnish National Agency for Education, 2014; OECD, 2019). In the Finnish National Core Curriculum, integrative teaching is framed as a means of fostering students' ability to understand relationships among phenomena and to develop broad, cross-curricular competencies through multidisciplinary learning modules, an approach that aligns closely with STEAM education in its emphasis on interdisciplinary learning and the integration of knowledge across subject areas (Finnish National Agency for Education, 2014, 31; Drake & Reid, 2018; McPhail, 2018).

One of the pedagogical approaches to implement the multidisciplinary learning model is STEAM education, an interdisciplinary approach that integrates knowledge and practices from science, technology, engineering, the arts, and mathematics to support creative, authentic problem solving (Quigley et al., 2020). Within this curricular context, STEAM education can be understood as a pedagogical approach that aligns well with the intentions of the Finnish curriculum (Finnish National Agency for Education, 2014). By integrating science, technology, engineering, arts, and mathematics, STEAM supports multidisciplinary inquiry, design-based learning, and authentic problem-solving. Although STEAM education is often discussed in relation to interdisciplinary integration, this study adopts the term multidisciplinary to reflect the curricular and organisational realities of Finnish schools, where cross-subject projects are typically implemented through multidisciplinary learning modules defined in line the national curriculum (Finnish National Agency for Education, 2014). Schools are required to implement at least one multidisciplinary learning module each year, typically organised around a shared theme and integrating content from multiple subjectsSTEAM approaches provide concrete pedagogical structures for such modules, enabling teachers to connect disciplinary knowledge with real-world phenomena while fostering creativity, collaboration, and student engagement (Milara et al., 2020).

Curriculum organization and school autonomy also influence how STEAM teaching is implemented. Finnish teachers have extensive freedom to design lessons, assessments, and learning environments, but this autonomy also requires significant pedagogical expertise, particularly when planning multidisciplinary projects that cross subject boundaries (Haapaniemi et al., 2021). While multidisciplinary learning is encouraged, the everyday organisation of schooling often limits what can be implemented in practice. Subject-specific time allocations and structured scheduling can restrict opportunities for collaborative planning, co-teaching, and extended project work (Wang et al., 2020). Although the curriculum supports STEAM principle, its implementation relies heavily on local decisions, resources, and teacher collaboration within each school (Finnish National Agency for Education, 2014).

Assessment practices in Finland also support the implementation of STEAM education. The Finnish curriculum emphasises formative, process-oriented assessment, self-assessment, and peer assessment, aiming to guide learning rather than merely measure outcomes (Finnish National Agency for Education, 2014). These principles resonate strongly with STEAM's emphasis on iterative design, creativity and collaborative problem-solving (Perignat & Katz-Buonincontro, 2019). However, despite the curriculum support, multidisciplinary projects can pose challenges for assessment. Teachers need to negotiate how to evaluate learning that spans multiple subjects, how to assess group processes and creative outputs, and how to align STEAM projects with subject-specific criteria in the national curriculum. The lack of established assessment methods ~~models~~ for multidisciplinary learning is frequently identified as a challenge in both Finnish and international contexts (Finnish National Agency for Education, 2014; Margot & Kettler, 2019), particularly in aligning integrated learning outcomes with subject-specific requirements and assessing broader competencies such as creativity and collaboration.

Despite the conceptual alignment between curriculum and STEAM, research suggests that the practical implementation of STEAM remains complex. Although STEAM is not explicitly defined in the Finnish curriculum, related multidisciplinary and transversal approaches are embedded within it, which may lead teachers to conceptualise STEAM in different ways. Teachers often report uncertainty about how to plan and assess integrated projects, how to reconcile subject-specific goals with broader competencies, and how to manage resource-intensive teaching practices within existing school structures. International research reflects many challenges related both to STEAM implementation and to how teachers conceptualise STEAM. Ishartono et al. (2021) found that teachers' understanding of STEAM varies widely and attitudes range from enthusiastic to hesitant. Studies also highlight a persistent need for professional development, structural support and clear instructional models to address teachers' concerns about content knowledge, pedagogical approaches, and interdisciplinary coordination (Duong et al., 2024; Conradty & Bogner, 2020).

STEAM offers significant opportunities to understand teachers' readiness, the availability of school-level support, and the practical pedagogical conditions for multidisciplinary teaching. The purpose of this article is to explore how in-service teachers conceptualise and implement STEAM teaching within the Finnish basic education system, and what challenges and support needs emerge in their everyday practice.

## 2 STEAM teaching and learning

In many implementations, STEAM learning takes the form of open-ended, project-based tasks in which students work collaboratively, iterate on ideas, and connect disciplinary concepts to real-world phenomena (Hsiao & Su, 2021). Evidence from prior research suggests that well-designed STEAM learning can enhance engagement and foster competencies such as creativity, critical thinking, and connections between school knowledge and real-world contexts (Rahmawati et al., 2022).

At the level of instructional design, STEAM projects typically require systematic integration work, which involves aligning disciplinary knowledge, pedagogical approaches, assessment strategies, and learning materials into a coherent whole (Margot & Kettler, 2019). For example, interdisciplinary curricula blend objectives from multiple disciplines around a common problem, align activities with curriculum requirements, and make assessment criteria explicit for both process and product (Quigley et al., 2020). From a teacher's perspective, this means STEAM is not merely a motivational supplement but a demanding design task that requires coordinating goals, activities, tools, collaboration structures, and assessment decisions into a coherent sequence (Spyropoulou et al. 2025). This framing is central for the present study because the teachers' interview accounts are expected to reflect not only beliefs about STEAM but also the design and coordination work that makes STEAM feasible.

Together, these core components – disciplinary knowledge integration, pedagogical approaches, assessment practices, and instructional design and coordination – illustrate the multifaceted nature of STEAM education as both a conceptual framework and a pedagogical practice. The following sections explore how multidisciplinary subject knowledge, pedagogical knowledge, and institutional support shape teachers' readiness to implement STEAM approaches in everyday school contexts.

### 2.1 Teacher readiness and professional development for STEAM

Teacher readiness shapes how STEAM teaching is implemented in classroom practice (Boice et al., 2024). Readiness of STEAM teaching is typically treated as a multidimensional construct that includes affective dispositions, cognitive resources, self-efficacy, and commitment to STEM/STEAM implementation (Papagiannopoulou et al., 2023). Among these dimensions, teachers' self-efficacy is particularly influential because it affects their willingness to adopt STEAM pedagogies and persist when implementation involves uncertainty and iteration. Evidence suggests that targeted professional development can strengthen self-efficacy and support teachers in adopting roles that are common in STEAM, such as facilitator, coach, and co-learner (Romero-Ariza et al., 2021). Despite this, many teachers remain insufficiently prepared to integrate STEAM without additional support, and this limited readiness often appears as uncertainty about how to design interdisciplinary lessons, align projects with curriculum standards, and move from general endorsement to concrete enactment (Belbase et al., 2021).

Given the design-intensive nature of STEAM teaching, teacher readiness cannot be understood only as a matter of attitudes or intentions, but must also be examined in relation to teachers' instructional competence. A central component of such enactment-focused readiness is teachers' knowledge for designing and guiding multidisciplinary learning. In this study, we shift attention from readiness as a general disposition to readiness as instructional competence, focusing on teachers' pedagogical content knowledge (PCK) for STEAM education, the professional development that supports its development, and the collaborative strategies teachers use in practice to compensate for limitations in individual PCK. Here pedagogical content knowledge (PCK) refers to teachers' capacity to transform subject knowledge into teachable, integrated learning experiences within multidisciplinary STEAM contexts.

## 2.2 Pedagogical content knowledge for STEAM

Pedagogical content knowledge (PCK) is a foundational construct in teacher education that refers to the integration of subject-matter knowledge and pedagogical knowledge needed to teach specific content effectively (Gudmundsdottir & Shulman, 1987). In STEAM, which integrates science, technology, engineering, arts, and mathematics, the relevance of PCK expands from disciplinary teaching to pedagogical connections across disciplines within project-based work (Herro & Quigley, 2017). For example, a project on sustainable city planning may require the teacher to connect scientific concepts, mathematical reasoning, and engineering design constraints through instructional practices that help students build coherent cross-disciplinary understanding. In this sense, STEAM implementation draws on both disciplinary PCK, i.e., teaching key ideas within a domain, and multidisciplinary PCK, i.e., linking domains pedagogically through a shared problem or design challenge. Multidisciplinary PCK can thus be understood as knowledge of how to design, sequence, and scaffold learning activities that meaningfully connect disciplinary ideas within a shared project or design challenge (Mehddi et al., 2025).

STEAM instruction is often enacted through student-centered approaches such as problem-based learning, inquiry, and design challenges, which require teachers to facilitate open-ended exploration while still making disciplinary learning goals explicit (Thibaut et al., 2018). Such pedagogical approaches requires an overarching understanding of how to link disciplines pedagogically. Teachers often report challenges in coordinating content and pedagogy across domains, particularly when one or more domains fall outside their primary expertise (Cochran et al., 1993, as cited in Herro & Quigley, 2017). Successful integration requires not only strong disciplinary teaching knowledge, but also knowledge of how to connect disciplines pedagogically within coherent project structures (Galanti & Holincheck, 2022).

Contemporary frameworks such as technological pedagogical content knowledge (TPACK) further extend PCK by including technology knowledge as a component of effective teaching (Mishra & Koehler, 2006). In STEAM contexts that incorporate digital tools or making practices, teachers may benefit from TPACK in selecting and using technologies that support content learning and creative production (Miller-Ray, 2019). However, the extent to which technology is required varies by project design and local resources. Therefore, in this study we focus on PCK while acknowledging that technological competence can become a relevant part of enactment in technology-rich STEAM contexts, including makerspace-oriented activities (Leavy et al., 2023).

### 2.3 Professional development in supporting PCK development for STEAM

Research on STEAM professional development indicates that teachers can develop more multidisciplinary pedagogical content knowledge when they receive sustained, practice-connected support (Boice et al., 2021). Evaluations of intensive STEAM training programs have reported that teachers leave professional development with greater confidence and clearer strategies for designing lessons that deliberately connect multiple disciplines, which in turn supports the implementation of integrated STEAM projects (Tan & Wei, 202). Conversely, when teachers have limited opportunities to develop STEAM-specific teaching knowledge, they often understand the value of STEAM but remain uncertain about how to translate interdisciplinary principles into classroom practice (Herro & Quigley, 2017). This pattern points to a recurring gap between conceptual endorsement of STEAM and procedural capacity to enact it.

A key source of this enactment challenge is teachers' subject specialisation. Integrated projects require teachers to identify meaningful connections across domains and to maintain balance so that one subject does not dominate while others remain superficial (Thibaut et al., 2018). This difficulty becomes more pronounced when key content lies outside teachers' primary expertise. While professional development could support the PCK development, individual teachers rarely have deep expertise across all STEAM disciplines. These findings position professional development and, where relevant, collaborative planning and co-teaching as key mechanisms for strengthening teachers' integrative PCK and reducing the enactment gap in STEAM implementation.

### 2.4 Collaboration and co-teaching in STEAM education

STEAM teaching often depends on collaborative arrangements that distribute expertise and reduce the burden of designing integration alone. Collaboration can take several forms, including co-teaching, interdisciplinary planning teams, professional learning communities, and partnerships with external experts such as artists, engineers, or scientists (Li et al., 2022). Co-teaching refers to instruction collaboratively implemented by two or more teachers who share responsibility for planning, teaching, and assessment (Friend & Cook, 2010). Effective co-teaching involves joint planning, reflection, and adaptation rather than simply dividing tasks by subject (Fluijt et al., 2016). In STEAM projects co-teaching can make integration more feasible because teachers can pool disciplinary strengths. This co-teaching approach requires teachers of different subjects to share roles, plan and work together across disciplinary boundaries to achieve shared multidisciplinary learning objectives (Exter et al., 2020). Li et al. (2022) demonstrated in a primary school study that cooperative teaching led to more cohesive STEAM experiences and improved student outcomes, as teachers could model interdisciplinary thinking together.

Beyond the classroom, collaboration also forms a professional learning community. Through co-planning, peer observation, and shared reflection, teachers engage in ongoing dialogue about how to connect curriculum areas and address the practical challenges of integration (Wu et al., 2021). Evidence indicates that teachers can learn instructional skills from colleagues and improve their practice through structured peer interaction, suggesting that collaboration can function as both positive workplace atmosphere and embedded professional development (Papay et al., 2020). The collaborative conversation also helps in connecting curriculum areas and solving the practical challenges of integration (Wu, 2021).

Teachers' collaboration structures can also be broadened to collaborate with universities, industry, and peer networks, which can provide expertise, resources, and feedback loops for refining instructional models over time (Aksela, 2019). It commonly involves cross-department teams and in some cases, external partners (e.g., artists or engineers) who contribute to planning and strengthen disciplinary balance. In this study, STEAM is approached primarily as a multidisciplinary and collaborative framework for teaching and learning.

## 3 Challenges in implementing STEAM education

STEAM teaching typically involves open-ended inquiry and design work, which makes uncertainty and iteration a normal part of learning (Spyropoulou, 2025). Prior research suggests that STEAM classrooms are more likely to succeed when students experience a psychologically safe environment in which they can explore, take risks, and learn from failure (Harris & de Bruin, 2017). By extension, teachers also need supportive conditions that allow them to experiment with STEAM approaches without fear of negative consequences when lessons do not work perfectly, because implementation often requires trial, revision, and adaptation (Mäkelä et al., 2022).

Research has identified multiple, interacting barriers that make STEAM implementation difficult. These include limited teacher readiness for multidisciplinary integration (Belbase et al., 2021), weak collaboration cultures and lack of meaningful cross-disciplinary cooperation (Schernoff et al., 2017), insufficient shared instructional guidance (Thibaut et al., 2018), lack of clear assessment models for interdisciplinary work (Giffney et al., 2025), and structural constraints such as subject-based timetables and limited instructional resources (Duong et al., 2024; Conradty & Bogner, 2020). Because STEAM projects can also introduce practical unpredictability such as technical glitches, material limitations, and variation in student readiness, teachers may need flexibility, resilience, and the capacity to iteratively adjust plans during enactment (Tan & Wei, 2024). Taken together, these findings indicate that STEAM's implementation is not determined by teachers' attitudes alone, but depends on a combination of teacher capacity, organizational structures, and available support mechanisms.

Although prior literature has thoroughly reported the barriers and general support needs, fewer studies provide empirically grounded, practice-level descriptions of what STEAM enactment and readiness look like in everyday school contexts, and how specific support conditions develop or constrain that readiness in practice. The present study focused on this gap to reveal what STEAM teachers can realistically adopt, adapt and implement within real-world school contexts.

Given this background, the research questions are:

1. How do in-service teachers conceptualise and integrate STEAM teaching in their classrooms?
2. What conditions enable or hinder in-service teachers' STEAM implementation?

# 4 Method

## 4.1 Participants

This study involved in-service teachers (N=10) from primary (classroom teachers), lower secondary, and upper secondary (subject teachers) schools, representing a range of subject backgrounds. Participants were identified through professional networks and STEAM-related educational projects all over in Finland. Participants were selected using purposeful sampling, based on their experience with or interest in implementing STEAM education in school contexts. All participants had prior experience in designing or implementing STEAM-related projects and expressed an interest in developing their STEAM teaching practices. Detailed demographic variables such as age or years of STEAM teaching experience were not systematically collected in the present study. This sampling approach was considered appropriate for generating in-depth insights into teachers' practical experiences of STEAM implementation.

## 4.2 Data collections

The interview data were collected in May 2024. Each interview lasted approximately 45–60 minutes and was conducted remotely via Microsoft Teams. The interviews were recorded with the participants' consent and transcribed verbatim for analysis. They were informed that all responses would be processed and reported anonymously and in accordance with good scientific practices.

The data was collected through semi-structured interviews, which enabled a thorough examination of teachers' views, attitudes, and experiences regarding STEAM education. The interviews focused on how teachers interpret and apply STEAM principles in their classrooms. Teachers shared the challenges they face and the skills, knowledge, and support they consider essential for effective implementation.

The research data was stored securely in accordance with the organization's data protection practices. Transcribed interview files are stored in a protected file system that can only be accessed by the research team. The data was anonymized prior to analysis, and individual respondents cannot be identified in the final research report.

## 4.3 Data analysis

The data were analysed using NVivo-software. Data-driven thematic analyse allows for the identification, analysis, and reporting of patterns within qualitative data (Braun & Clarke, 2022). The approach combines a structured thematic focus with openness to participants' subjective meanings, making it suitable for examining teachers' experiences of STEAM education.

The interview data were first coded using a data-driven approach. Initial codes were generated from recurring patterns and significant statements in the transcripts. These codes were subsequently reviewed and grouped into broader categories, from which the main themes were identified. Themes that appeared consistently across multiple interviews were prioritised in the final analysis.

This study employed researcher triangulation to enhance the credibility of the analysis. All researchers participated in the coding and interpretation process to ensure a more balanced and objective understanding of the data. According to Nowell et al. (2017), researcher triangulation is an essential technique for ensuring the credibility of qualitative research. In the step-by-step approach to thematic analysis, researcher triangulation is a means of ensuring reliability at several stages, such as in the creation of initial codes, the review, definition and naming of themes (Nowell et al. 2017). In this research themes are pedagogical knowledge, curriculum, technology, co-teaching and assessment. Researchers analysed independently the transcribed interview material. The analysis process involved initial independent coding, after which the researchers collaboratively compared, discussed, and refined the codes and themes. The researchers systematically compared their findings and discussed any differences. The inclusion of different perspectives added depth to the analysis and helped uncover multiple interpretations of the phenomenon under study. Lack of consensus on all themes was considered a reflection of the richness of the data rather than a weakness of the analysis.

# 5 Results

## 5.1 Conceptualising STEAM teaching

The analysis of the interview data revealed several key themes related to how teachers perceive and approach STEAM teaching in practice. The participants described a range of competencies and considerations they deemed essential for implementing STEAM education effectively in the classroom. These included pedagogical skills, understanding and interpreting the curriculum, careful planning, technological proficiency, co-teaching practices, assessment strategies, collaboration networks, and various forms of professional support. Together, these themes reflect the multifaceted nature of STEAM teaching as experienced and conceptualised by educators and highlight the complex interplay between teacher expertise, institutional structures, and pedagogical innovation. These themes and related examples of teachers' views are presented in table (Table 1) below.

Pedagogical knowledge were described as including the ability to guide and motivate students, manage collaborative classroom work, give clear instructions, use a variety of teaching methods and learning environments and adapt instruction to students' needs and classroom situations. Curriculum was also considered an essential competence, as teachers emphasised the need to master subject content and align it with curricular goals and multidisciplinary learning. Technology was seen as useful, though not essential for STEAM teaching. While some teachers expressed uncertainty or fear of failure, others highlighted learning through collaboration with colleagues or even students. Participants consistently emphasized co-teaching as both necessary and beneficial, noting that it supports authentic multidisciplinary learning, aligns with curricular expectations, and provides opportunities for sharing expertise, addressing student needs, and enhancing teacher well-being.

Participants described both assessment-related challenges and collaborative support structures as central factors influencing the implementation of STEAM teaching. Assessment is perceived in varied ways among teachers. While some participants felt that assessment functions well in interdisciplinary settings, others described it as complex and challenging. A key concern was the lack of clear and consistent assessment models, which led to uncertainty and hesitation about how to evaluate student learning. Collaboration was identified as an important element in successful STEAM implementation. Teachers highlighted the value of building networks across schools, educational levels, and municipalities to share knowledge, receive peer support, and exchange best practices. Co-teaching, mentoring, and support from STEAM developer teachers were mentioned as effective ways to strengthen professional competence.

**Table 1.** Key themes related to STEAM teaching identified in the interviews.

| Theme | Description | Example from interview |
|---|---|---|
| Pedagogical knowledge | Ability to guide and motivate students, manage teamwork, give clear instructions, adapt to situations, and use diverse methods and environments. | "Teachers learn together with the students." (T9)<br>"These are not quick things, they are more like ways of working." (T5)<br>"I try to understand the meaning behind it and bring it into my own subjects... with the kind of expertise I already have." (T5)<br>"The pedagogical skills of a teacher are the ability to give work instructions, form groups, clearly explain what to do, motivate students, and then provide guidance. " (T4)<br>"You have to step out of your comfort zone... it might fail the first time. That's normal." (T3)<br>"I always think about what goals need to be achieved and how we collect different forms of evidence throughout the project." (T1) |
| Curriculum | Teachers must master the content they teach and be able to align it with the curriculum and multidisciplinary learning. | "In my opinion, transversal competences and broad-based learning modules include many components that come from various areas."(T4)<br>"That's how it's directed in the curriculum in the sense that we have the criteria and the objectives within each discipline." (T10)<br>"Well, actually, if the teacher reads through it, or if every teacher should have read through it, then STEAM will show it there." (T3)<br>"Teachers have a freedom, they have to follow the curriculum." (T8) |
| Technology | Basic knowledge of technology and programming, and their pedagogical application in teaching. | "You really have to adapt quickly... I've wanted to include programming and different kinds of software." (T7)<br>"You need to have some kind of understanding of things like 3D printers or coding, if that's the direction the project takes." (T6)<br>"It's perfectly fine to use them, but it's not a necessity, because I see that STEAM is also about doing some laboratory work with a microscope." (T4) |
| Co-teaching | Teachers work in systematic collaboration by planning, implementing, and evaluating teaching together, integrating content from different subjects and drawing on each other's expertise to achieve shared learning goals. | "It's just rewarding that it's not. It's just a good thing."(T4)<br>"Sharing their expertise and ideas. I don't have such extensive knowledge that I would necessarily be able to organize such a multidisciplinary whole on my own, but I do think it's important."(T2)<br>"I was working with people who knew their own thing. We could talk about the students and the issues that the students were facing and then it was just more fun. So I think it has an overall benefit to both how to get your subject taught, but also that how you feel in the working. So it has a well-being effect as well." (T10) |
| Assessment | Teachers monitor the progress, collect feedback from the students and evaluate their student's successes and areas for improvement. | "The teacher creates a framework for assessment in such a way that the skills can be demonstrated by the children in a variety of ways." (T6) |

## 5.2 Teachers' support in STEAM education

Teachers emphasised the need for different forms of support (Table 2) in implementing STEAM education. Leadership and school atmosphere were seen as essential with particular value placed on encouragement from principals, a positive culture, and the freedom to experiment with new ideas. Adequate time and resources for planning, collaboration, and mentoring, such as opportunities for experienced teachers to support newly graduated colleagues, as well as co-teaching practices were also considered important. Continuous professional development through workshops, peer networks, and internal training, as well as support from STEAM lead teachers, helped sustain pedagogical growth. Motivation was strengthened by opportunities to innovate, participate in projects or competitions, and receive recognition for development efforts. Practical resources, such as materials and funding, were seen as necessary enablers. Finally, collaboration across educational levels and municipalities, alongside multidisciplinary learning units and student involvement (e.g., peer tutoring), supported a more integrated and sustainable approach to STEAM teaching.

**Table 2.** Teachers support in STEAM education.

| Theme | Description | Example from interview |
|---|---|---|
| Collaborative support structures | Multiple collaborative structures supported teachers, including mentoring by experienced colleagues, inter-school and inter-city networks and cooperation with external experts enabling interdisciplinary teaching. | *Mentoring:* "Mentor schools… how we get it from one municipality to another." (T1)<br>*Networks:* "Support from the city." (T5)<br>"In large cities, cooperation brings strength… small municipalities could also be involved." (T6)<br>*Collaboration with teachers and experts:* "Network creation and projects." (T7)<br>"Time to… brainstorm what could be done." (T9) |
| Organizational and developmental support | Support from school leadership, access to professional development, resources, planning time, and the sharing of teaching materials facilitated teachers' engagement in STEAM education. | *Leadership:* "It's the principal's support… he encourages it… 'Go ahead and do it.'" (T4)<br>*Training & resources:* "STEAM training and resources for planning… which often lack due to time constraints." (T2)<br>"We have STEAM developer teachers… who get some kind of training." (T5)<br>*Sharing practices:* "Material available so the student could get started independently…" (T7) |

## 5.3 Teachers perceived benefits and key insights in STEAM teaching

Throughout the interviews, many teachers spontaneously shared observations and ideas they considered positive or enabling factors in STEAM teaching. These were elements they had noticed in their own practice that, in their experience, made its implementation easier or more rewarding. These points emerged inductively from the data and reflected various conditions, resources, and approaches perceived as supporting the use of STEAM in everyday teaching. Unlike the support structures discussed in the previous section, these insights reflect teachers' experienced benefits and professional meanings associated with STEAM teaching rather than formal organisational conditions.

Identifying such enabling factors is valuable as they provide practical insights into the circumstances and practices that can promote the wider adoption and long-term sustainability of STEAM approaches in schools. The fact that these perspectives arose without a specific question suggests that teachers regard them as particularly relevant to the successful implementation of STEAM. Documenting these perceptions not only deepens the understanding of how STEAM works in everyday school contexts but also offers valuable guidance for policymakers, school leaders, and those supporting teachers' professional development. Based on the analysis, these factors can be summarised into categories, which are presented below together with illustrative quotations.

Teachers also shared broader insights into how STEAM operates in their everyday practice. A central observation concerned the changing role of the teacher. STEAM encouraged them to move beyond familiar routines, engage with new content areas and accept uncertainty as part of their work. As one teacher (T8) noted, *"failure is always a learning opportunity"*. Many described this as professionally rewarding, noting that co-learning with students and experimenting with new approaches strengthened their confidence, creativity and pedagogical flexibility. Teachers also highlighted collaboration and co-teaching as important positive benefits. Multidisciplinary projects created opportunities to plan together, exchange ideas, and draw on colleagues' expertise. As one teacher (T5) noted, *"the best work emerges when teachers themselves become enthusiastic and start developing and creating ideas together"*. This collegial support made STEAM implementation more manageable and helped sustain motivation.

Based on the interview data, teachers described STEAM practices as being strongly supported by enthusiasm, pedagogical courage, and collaborative learning cultures. Effective STEAM implementation was associated with teachers adopting facilitative roles, tolerating uncertainty and viewing failure as a productive part of learning. STEAM's key strengths lie in making student learning visible in diverse ways and in supporting curriculum goals through integrated, future-oriented practices. One teacher (T6) described *"how students' learning and competence can become visible in multiple ways through STEAM projects"*. While structural supports enhance implementation, the most decisive factors are school culture and teachers' perceived autonomy.

## 6 Discussion

The aim of this study was to examine how in-service teachers conceptualise and implement STEAM teaching in school contexts, as well as to identify the conditions that enable or constrain its enactment. The findings indicate that teachers generally view STEAM as a pedagogically meaningful and motivating approach that supports integrated and future-oriented learning. At the same time STEAM teaching was experienced as complex and demanding, requiring careful planning, coordination across subject boundaries and a willingness to work under conditions of uncertainty.

Teachers in this study conceptualised STEAM not as a discrete instructional method but as a broader pedagogical orientation that organises teaching around authentic, multidisciplinary problems. This understanding aligns with previous research describing STEAM as an open-ended, design-based approach that emphasises creativity, problem solving, and the integration of disciplinary knowledge (Quigley & Herro, 2020). At the same time, the findings reveal a clear tension between the pedagogical promises of STEAM and the practical demands of its implementation. While participants highlighted the motivational and meaningful nature of STEAM teaching, they also described the approach as time-intensive and pedagogically demanding. This duality reinforces earlier research suggesting that open-ended STEAM approaches can function both as a source of engagement and as a significant source of complexity in classroom practice (Rahmawati et al., 2022). These interpretations raise important questions about what kinds of professional knowledge, skills, and support teachers need to implement STEAM teaching in practice. Instead, STEAM teaching appeared to require a broader form of teacher readiness that includes pedagogical competence, curriculum interpretation, and the ability to manage multidisciplinary planning and assessment.

A central explanation for the challenges associated with STEAM implementation in this study lies in the demands placed on teachers' pedagogical content knowledge. While participants demonstrated strong disciplinary teaching knowledge, they also described difficulties related to integrating multiple subjects, aligning curricular goals, and designing coherent learning sequences within multidisciplinary projects. The findings highlight that STEAM teaching places demands on teachers' pedagogical content knowledge that go beyond traditional, discipline-specific PCK. In multidisciplinary STEAM contexts teachers simultaneously attend to subject-specific learning objectives, pedagogical strategies, collaboration structures and assessment practices, often under conditions of uncertainty.

The challenges teachers described were therefore not simply a matter of limited expertise within individual disciplines but rather reflected the complexity of designing and structuring learning experiences that meaningfully connect disciplinary ideas within a shared project or problem. Some teachers described challenges in combining subject-specific curriculum goals into shared multidisciplinary projects and in finding assessment practices that supported different subject areas simultaneously. This interpretation is consistent with earlier research that identifies integrative pedagogical content knowledge as a central challenge in interdisciplinary and multidisciplinary teaching contexts (Herro & Quigley, 2017; Thibaut et al., 2018).

Given the complexity of integrative pedagogical content knowledge required for STEAM teaching, the findings suggest that individual teachers cannot be expected to develop and sustain such competence in isolation. Instead, professional development and collaborative structures emerged as key enabling conditions for STEAM enactment (Herro & Quigley, 2017). Teachers emphasised the importance of sustained, practice-oriented professional development that supports multidisciplinary lesson design, assessment, and coordination. This aligns with earlier research showing that professional development is most effective when closely connected to teachers' everyday practice and collaborative work (Tan & Wei, 2024).

Collaboration and co-teaching further supported integrative PCK by enabling teachers to distribute expertise and jointly design multidisciplinary learning activities. Prior studies similarly highlight collaboration as a key mechanism for reducing uncertainty and supporting sustainable STEAM implementation (Thibaut et al., 2018). Overall, these findings highlight that professional development and collaboration function as structural conditions rather than optional supports for STEAM teaching.

In addition to enabling enactment, these supportive structures also shaped how teachers experienced the professional benefits of STEAM teaching. Despite the challenges of STEAM education, the results highlight the perceived benefits that help explain teachers' motivation to continue these practices. Teachers described STEAM education as professionally meaningful and emphasized creativity, collaboration, co-teaching and shared learning with students. These benefits seemed to reinforce teachers' professional agency and partially compensate for the demands associated with multidisciplinary STEAM education.

## Conclusions

This study examined in-service teachers' perceptions of STEAM education and the conditions that shape its implementation in school contexts. The findings indicate that teachers perceive STEAM as a holistic pedagogical approach that supports student agency, creativity, collaboration and future-oriented competencies. Rather than viewing STEAM as a single instructional method, teachers conceptualised it as a broader pedagogical orientation centred on authentic, multidisciplinary problem solving.

At the same time, the study demonstrates that the pedagogical potential of STEAM is closely tied to the conditions under which it is implemented. Although teachers generally expressed positive attitudes towards STEAM, its implementation was experienced as complex and demanding. The primary challenges were not related to technological skills but to pedagogical integration, curriculum alignment, multidisciplinary planning, and assessment. These findings highlight that successful STEAM implementation requires more than individual enthusiasm. It depends on a broad conception of teacher readiness that encompasses integrative pedagogical content knowledge, pedagogical competence, and organisational support.

The results further emphasise the central role of collaboration and professional support in sustaining STEAM practices. Co-teaching, mentoring, and professional learning communities enabled teachers to distribute expertise, manage uncertainty, and design coherent multidisciplinary learning experiences. These collaborative structures functioned as essential enabling conditions rather than optional supports, reinforcing the need for school-level leadership that prioritises time, resources, and a supportive culture for pedagogical experimentation.

Importantly, teachers in this study did not perceive their digital competence as a major barrier to STEAM teaching. Rather, the challenges they described were more often related to pedagogical and organisational factors. This finding may be relevant in the context of emerging digital technologies and the increasing presence of AI in education. STEAM education can be understood as providing a pedagogically grounded framework within which digital tools, including AI-based applications, may be integrated in ways that support inquiry, creativity, and problem solving. From the perspective of teacher education, these findings suggest that there may be value in placing greater emphasis on integrative pedagogical content knowledge and pedagogical digital competence in both pre-service and in-service programmes, alongside rather than in place of technical skills training.

This study is limited by its qualitative design and context-specific sample, which restricts the generalisability of the findings. Nevertheless, the results provide in-depth insights into teachers lived experiences of STEAM teaching and the conditions that support or constrain its enactment. The interviews were conducted remotely, and several participants voluntarily shared concrete examples of STEAM practices during the interviews, including materials from school websites and STEAM-related projects. This enriched the interviews and also highlights the potential added value of digital interview environments for sharing multimodal and practice-based materials in future studies. Future research could further investigate the relationships between pedagogical digital competence, the use of AI-based tools, leadership practices, and student learning outcomes across different educational contexts. In conclusion, STEAM education holds significant potential for supporting meaningful, inclusive and future-oriented learning. However, this potential can only be realised when coherent pedagogical expertise, collaborative professional structures, and supportive leadership practices are in place to enable sustainable innovation in school contexts.

## Research ethics

### Author contributions

S.R.: conceptualisation, analysis, investigation, methodology, writing—original draft preparation, writing—review and editing
X.H.: conceptualisation , analysis, writing—review and editing
S.H.: conceptualisation , analysis, writing—review and editing
All authors have read and agreed to the published version of the manuscript.

## Informed consent statement

Informed consent was obtained from all participants prior to participation.

## Data availability statement

The data are stored on the researchers' computers and hard drives. They are duly labeled and stored. They may be accessed with prior authorization.

# Appendix

Semi-structured interview questions

General experiences of implementing the STEAM learning project

1. What are your overall views on STEAM teaching and learning based on your experiences?
2. What do you expect students to learn during this process?

Students' performance and learning process

3. What observations have you made about students' learning processes and learning outcomes in STEAM learning? Did students meet your expectations or exceed them? How did you notice this?
4. Did you observe differences between subject-based learning and STEAM learning? What are your views on the connections between subject learning and STEAM learning?

STEAM planning and design

5. How do you integrate STEAM subjects into your teaching? How do you decide on the learning topics? What factors do you consider when selecting the topics?
6. Could you describe the process of preparing and designing a STEAM learning project? What elements of STEAM teaching do you consider (e.g., learning objectives, learning content, pedagogical approaches, technology, and assessment)? What challenges and support needs are involved in this process?

STEAM teaching competencies

7. What kinds of pedagogical competencies do you consider important in STEAM teaching, particularly in multidisciplinary approaches?
8. How important do you consider teachers' technological and digital skills in STEAM teaching?
9. How is teacher collaboration reflected in STEAM teaching?

STEAM implementation

10. Could you describe your experiences of implementing STEAM projects? What is your role during students' learning processes? What kinds of responsibilities do you have?
11. What concerns do you have during the implementation of STEAM learning projects?
12. What challenges and support needs are involved in this process?

STEAM Learning objectives and problem-solving process

13. If you could discuss with people working in interdisciplinary and transdisciplinary fields, what would you like to know about their work? Why?

Future development

14. What kind of support would you need if you wanted to continue STEAM practices in the future?

STEAM and the curriculum

15. How do you see STEAM education being integrated into the current curriculum?
16. How do you balance traditional subject teaching with a multidisciplinary STEAM approach?
17. Do you have any concrete examples of how you have integrated STEAM education into the curriculum?

## References

Aksela, M. (2019). Towards student-centred solutions and pedagogical innovations in science education through co-design approach within design-based research. *Lumat: International Journal of Math, Science and Technology Education*, *7*(3), 113–139. https://doi.org/10.31129/LUMAT.7.3.421

Boice, K. L., Alemdar, M., Jackson, J. R., Kessler, T. C., Choi, J., Grossman, S., & Usselman, M. (2024). Exploring teachers' understanding and implementation of STEAM: One size does not fit all. *Frontiers in Education*, *9*, 1401191. https://doi.org/10.3389/feduc.2024.1401191

Boice, K. L., Jackson, J. R., Alemdar, M., Rao, A. E., Grossman, S., & Usselman, M. (2021). Supporting teachers on their steam journey: a collaborative steam teacher training program. *Education Sciences*, *11*(3), 105. https://doi.org/10.3390/educsci11030105

Cochran, K. F., DeRuiter, J. A., & King, R. A. (1993). Pedagogical content knowing: an integrative model for teacher preparation. *Journal of Teacher Education*, *44*(4), 263–272. https://doi.org/10.1177/0022487193044004004

Conradty, C., & Bogner, F. X. (2020). STEAM teaching professional development works: Effects on students' creativity and motivation. *Smart Learning Environments*, *7*(1), 26. https://doi.org/10.1186/s40561-020-00132-9

Drake, S., & Reid, J. (2018). Integrated Curriculum as an Effective Way to Teach 21st Century Capabilities. *Asia Pacific Journal of Educational Research*, *1*(1), 31–50. https://doi.org/10.30777/APJER.2018.1.1.03

Duong, N. H., Nam, N. H., & Trung, T. T. (2026). Factors affecting the implementation of STEAM education among primary school teachers in various countries and Vietnamese educators: Comparative analysis. *Education 3-13*, *54*(2), 382–396. https://doi.org/10.1080/03004279.2024.2318239

Exter, M. E., Gray, C. M., & Fernandez, T. M. (2020). Conceptions of design by transdisciplinary educators: Disciplinary background and pedagogical engagement. *International Journal of Technology and Design Education*, *30*(4), 777–798. https://doi.org/10.1007/s10798-019-09520-w

Finnish National Agency for Education. (2014). National Core Curriculum for Basic Education 2014.

Fluijt, D., Bakker, C., & Struyf, E. (2016). Team-reflection: The missing link in co-teaching teams. *European Journal of Special Needs Education*, *31*(2), 187–201. https://doi.org/10.1080/08856257.2015.1125690

Friend, M., Cook, L., Hurley-Chamberlain, D., & Shamberger, C. (2010). Co-Teaching: An Illustration of the Complexity of Collaboration in Special Education. *Journal of Educational and Psychological Consultation*, *20*(1), 9–27. https://doi.org/10.1080/10474410903535380

Galanti, T. M., & Holincheck, N. (2022). Beyond content and curriculum in elementary classrooms: Conceptualizing the cultivation of integrated STEM teacher identity. *International Journal of STEM Education*, *9*(1), 43. https://doi.org/10.1186/s40594-022-00358-8

Giffney, S., & Lane, D. (2025). Towards an integrated model of STEM education in secondary schools: Perspectives of practicing teachers in Ireland. *International Journal of Technology and Design Education*, *35*(5), 1805–1824. https://doi.org/10.1007/s10798-025-09971-4

Gudmundsdottir, S., & Shulman, L. (1987). Pedagogical content knowledge in social studies. *Scandinavian Journal of Educational Research*, *31*(2), 59–70. https://doi.org/10.1080/0031383870310201

Haapaniemi, J., Venäläinen, S., Malin, A., & Palojoki, P. (2021). Teacher autonomy and collaboration as part of integrative teaching – Reflections on the curriculum approach in Finland. *Journal of Curriculum Studies*, *53*(4), 546–562. https://doi.org/10.1080/00220272.2020.1759145

Harris, A., & de Bruin, L. (2017). STEAM education: Fostering creativity in and beyond secondary schools. *Australian art education*, *38*(1), 54–75.

Herro, D., & Quigley, C. (2017). Exploring teachers' perceptions of STEAM teaching through professional development: Implications for teacher educators. *Professional Development in Education*, *43*(3), 416–438. https://doi.org/10.1080/19415257.2016.1205507

Hsiao, P.-W., & Su, C.-H. (2021). A Study on the Impact of STEAM Education for Sustainable Development Courses and Its Effects on Student Motivation and Learning. *Sustainability*, *13*(7), 3772. https://doi.org/10.3390/su13073772

Ishartono, N., Sutama, Prayitno, H. J., Irfan, M., Waluyo, M., & Sufahani, S. F. B. (2021). An Investigation of Indonesian In-Service Mathematics Teachers' Perception and Attitude Toward STEAM Education. *Journal of Physics: Conference Series*, *1776*(1), 012021. https://doi.org/10.1088/1742-6596/1776/1/012021

Leavy, A., Dick, L., Meletiou-Mavrotheris, M., Paparistodemou, E., & Stylianou, E. (2023). The prevalence and use of emerging technologies in STEAM education: A systematic review of the literature. *Journal of Computer Assisted Learning*, *39*(4), 1061–1082. https://doi.org/10.1111/jcal.12806

Li, J., Luo, H., Zhao, L., Zhu, M., Ma, L., & Liao, X. (2022). Promoting STEAM Education in Primary School through Cooperative Teaching: A Design-Based Research Study. *Sustainability*, *14*(16), 10333. https://doi.org/10.3390/su141610333

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. *International Journal of STEM Education*, *6*(1), 2. https://doi.org/10.1186/s40594-018-0151-2

McPhail, G. (2018). Curriculum integration in the senior secondary school: A case study in a national assessment context. *Journal of Curriculum Studies*, *50*(1), 56–76. https://doi.org/10.1080/00220272.2017.1386234

Mehddi, F., Kazi, A. S., & Butt, A. I. (2025). From Theory to Practice: How STEAM Professional Development Shapes Teacher Beliefs and Perceptions About Design Thinking Activities. *Sage Open*, *15*(3), 21582440251355779. https://doi.org/10.1177/21582440251355779

Milara, I. S., Pitkänen, K., Laru, J., Iwata, M., Orduña, M. C., & Riekki, J. (2020). STEAM in Oulu: Scaffolding the development of a Community of Practice for local educators around STEAM and digital fabrication. *International Journal of Child-Computer Interaction*, *26*, 100197. https://doi.org/10.1016/j.ijcci.2020.100197

Miller-Ray, J. (2019). Investigating the Impact of a Community Makers' Guild Training Program on Elementary and Middle School Educator Perceptions of STEM (Science, Technology, Engineering, and Mathematics). In M. S. Khine & S. Areepattamannil (Eds.), *STEAM education* (pp. 79–100). Springer International Publishing. https://doi.org/10.1007/978-3-030-04003-1_5

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: a framework for teacher knowledge. *Teachers College Record: The Voice of Scholarship in Education*, *108*(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic Analysis: Striving to Meet the Trustworthiness Criteria. *International Journal of Qualitative Methods*, *16*(1), 1–16. https://doi.org/10.1177/1609406917733847

OECD. (2019). *OECD Learning Compass 2030: A Series of Concept Notes*. OECD Publishing. https://www.oecd.org/content/dam/oecd/en/about/projects/edu/education-2040/1-1-learning-compass/OECD_Learning_Compass_2030_Concept_Note_Series.pdf

Papagiannopoulou, T., Vaiopoulou, J., & Stamovlasis, D. (2023). Teachers' Readiness to Implement STEM Education: Psychometric Properties of TRi-STEM Scale and Measurement Invariance across Individual Characteristics of Greek In-Service Teachers. *Education Sciences*, *13*(3), 299. https://doi.org/10.3390/educsci13030299

Papay, J. P., Taylor, E. S., Tyler, J. H., & Laski, M. E. (2020). Learning Job Skills from Colleagues at Work: Evidence from a Field Experiment Using Teacher Performance Data. *American Economic Journal: Economic Policy*, *12*(1), 359–388. https://doi.org/10.1257/pol.20170709

Perignat, E., & Katz-Buonincontro, J. (2019). STEAM in practice and research: An integrative literature review. *Thinking Skills and Creativity*, *31*, 31–43. https://doi.org/10.1016/j.tsc.2018.10.002

Quigley, C. F., Herro, D., King, E., & Plank, H. (2020). STEAM Designed and Enacted: Understanding the Process of Design and Implementation of STEAM Curriculum in an Elementary School. *Journal of Science Education and Technology*, *29*(4), 499–518. https://doi.org/10.1007/s10956-020-09832-w

Rahmawati, Y., Taylor, E., Taylor, P. C., Ridwan, A., & Mardiah, A. (2022). Students' Engagement in Education as Sustainability: Implementing an Ethical Dilemma-STEAM Teaching Model in Chemistry Learning. *Sustainability*, *14*(6), 3554. https://doi.org/10.3390/su14063554

Romero-Ariza, M., Quesada, A., Abril, A.-M., & Cobo, C. (2021). Changing teachers' self-efficacy, beliefs and practices through STEAM teacher professional development (*Cambios en la autoeficacia, creencias y prácticas docentes en la formación STEAM de profesorado*). *Journal for the Study of Education and Development*, *44*(4), 942–969. https://doi.org/10.1080/02103702.2021.1926164

Roseveare, C. (2023). *Thematic Analysis: A Practical Guide* , by Virginia Braun and Victoria Clarke. *Canadian Journal of Program Evaluation*, *38*(1), 143–145. https://doi.org/10.3138/cjpe.76737

Shernoff, D. J., Sinha, S., Bressler, D. M., & Ginsburg, L. (2017). Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *International Journal of STEM Education*, *4*(1), 13. https://doi.org/10.1186/s40594-017-0068-1

Spyropoulou, N., Mathiopoulos, K., & Kameas, A. (2025). “We Believe in STEAM Education, but We Need Support”: In-Service Teachers’ Voices on the Realities of STEAM Implementation. *Education Sciences*, *15*(10), 1300. https://doi.org/10.3390/educsci15101300

Tan, L., & Wei, B. (2025). How science teachers deal with STEM education: An explorative study from the lens of curriculum ideology. *Science Education*, *109*(1), 82–105. https://doi.org/10.1002/sce.21904

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-de Pauw, J., Dehaene, W., Deprez, J., De Cock, M., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Van De Velde, D., Van Petegem, P., & Depaepe, F. (2018). Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education. *European Journal of STEM Education*, *3*(1) Article 02. https://doi.org/10.20897/ejsteme/85525

Wang, H.-H., Charoenmuang, M., Knobloch, N. A., & Tormoehlen, R. L. (2020). Defining interdisciplinary collaboration based on high school teachers’ beliefs and practices of STEM integration using a complex designed system. *International Journal of STEM Education*, *7*(1), 3. https://doi.org/10.1186/s40594-019-0201-4

Wu, Y., Cheng, J., & Koszalka, T. A. (2020). Transdisciplinary Approach in Middle School: A Case Study of Co-teaching Practices in STEAM Teams. *International Journal of Education in Mathematics, Science and Technology*, *9*(1), 138–162. https://doi.org/10.46328/ijemst.1017