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Design Principles for Effective Teacher Professional Development in Integrated STEM Education: A Systematic Review

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ABSTRACT: In recent years, there has been increasing emphasis on integrated STEM education, reflecting the fact that the four STEM disciplines (i.e., science, technology, engineering, and mathematics) are often integrated in real-world applications. However, most K-12 teachers are trained within their own subject discipline and may not be capable of implementing an integrated approach to STEM education. There is therefore a need to develop teacher professional development (TPD) programs that can provide high-quality learning opportunities and support for teachers. The overarching goal of this research synthesis is to develop a set of design principles for effective TPD for integrated STEM education. To this end, this paper reviews 48 empirical studies and identifies the elements of effective TPD and potential challenges to implementing integrated STEM education. Content knowledge, pedagogical content knowledge, and sample STEM instructional materials are the three most frequently reported elements of effective TPD programs. However, even with TPD, teachers encounter various obstacles to the implementation of integrated STEM education, including pedagogical challenges (e.g., teachers' limited STEM knowledge) and structural challenges (e.g., teachers' lack of preparation time and resources). Based on the findings of this review, a set of design principles (e.g., allocate TPD time for teachers' micro-teaching) is proposed. This review contributes to the design and implementation of TPD programs by leveraging studies of the effective elements of TPD and addressing the potential challenges to integrated STEM education.

Keywords: STEM education, STEM integration, Professional development, Teacher education, Literature review

1. Introduction

In today's information-based and highly technological society, STEM (science, technology, engineering, and mathematics) education is becoming increasingly important (Hauze & French, 2017; Li et al., 2020; Thibaut et al., 2018). Although STEM is four separate subject disciplines in K-12 educational contexts, real-life applications of STEM are naturally integrated (Honey et al., 2014). For example, engineers often need an in-depth understanding of various science disciplines, mathematics, and technology to support their engineering designs and applications (Breiner et al., 2012). Therefore, recent reform initiatives advocate for integrated STEM education in which K-12 students learn to solve problems by drawing on the knowledge and skills of multiple STEM disciplines (see Committee on STEM Education, 2018; Honey et al., 2014; NGSS Lead States, 2013 for a review).

However, most K-12 teachers in STEM subjects are trained within their own subject discipline, and they may not be capable of implementing an integrated and holistic approach to STEM education (Cavlazoglu & Stuessy, 2017; Margot & Kettler, 2019; Rich et al., 2018). Teacher professional development (TPD) is thus a critical strategy for helping in-service teachers to teach STEM subjects using integrated approaches (Brand, 2020; Chai et al., 2019; Williams et al., 2019b). Researchers (e.g., Brenneman et al., 2019; Dyehouse et al., 2019; Goodnough, 2018) have explored the elements of effective TPD for integrated STEM education. However, some of the recommendations made by these studies may not be generalizable, because they are limited to the researchers' TPD interventions in a single context. Therefore, the goal of this research synthesis is to develop a generalizable set of design principles for TPD programs that support integrated STEM education. In addition to effective elements, understanding how TPD facilitators design their programs and teacher challenges can inform the development of the design principles (Lesseig et al., 2016). The following research questions (RQ1 to RQ3) are thus formulated:

- RQ1: How do TPD facilitators design TPD programs for integrated STEM education?
- RQ2: What are the key elements of TPD programs for integrated STEM education?
- RQ3: What are the major challenges perceived or encountered by teachers who have taken the TPD training programs in their implementation of integrated STEM education?

2. Conceptual background

The conceptual background of this review is threefold. First, the theoretical foundation of integrated STEM education is described. Second, previous reviews of TPD for STEM education and their findings (e.g., effective elements and challenges) are highlighted. Third, the model of effective TPD developed by Darling-Hammond et al. (2017) is adopted as a lens for analyzing the empirical studies in this review.

2.1. Integrated STEM education

Integrated STEM education mirrors the real-world work of engineers and scientists (STEM Task Force Report, 2014). Students can experience the interconnected nature of these subject disciplines. English (2016) and Vasquez et al. (2013) defined a spectrum of STEM integration from non-integrated to fully integrated.

- Disciplinary: Concepts and skills are learned separately in each discipline.
- Multidisciplinary: Concepts and skills are still learned separately in each discipline but linked by a common theme.
- Interdisciplinary: Closely linked concepts and skills are learned in two or more disciplines with the aim of deepening student learning.
- Transdisciplinary: Knowledge and skills learned in two or more disciplines are applied to real-world problems and projects, and thus shape the learning experience.
- Progression along this continuum indicates greater levels of STEM integration (English, 2016; Vasquez et al., 2013).

The commitment to the interdisciplinary and transdisciplinary STEM integration is increasing in the education sector (English, 2016). In the United States, for example, NGSS Lead States (2013) established the Next Generation Science Standards (NGSS), which promote more in-depth connections among the STEM disciplines. The NGSS has further emphasized the integration of engineering design and practices into K-12 STEM subjects (see NGSS Lead States, 2013 for a review). According to Kelley et al. (2020), "Engineering design provides an ideal platform for situated learning because it provides a context situated in a problem that is authentic and bound by science and engineering practices" (p. 3). They proposed a conceptual framework for STEM learning (Kelley & Knowles, 2016). In their framework, the connections between science inquiry, technology literacy, mathematical thinking, and engineering design are established by engaging with a community of practice. Various STEM partners, such as practicing scientists, engineers, and technologists, can help teachers and students focus on learning in real-life STEM contexts. However, Kelley and Knowles (2016) cautioned that using a community of practice approach to integrated STEM education can be challenging because it is difficult for teachers to network with STEM professionals. They therefore suggested that a sustainable community of practice (e.g., STEM teachers, researchers, and industry partners) be established through TPD programs.

2.2. Previous reviews of TPD for STEM education

Although there have been quite a few reviews (e.g., Ibáñez & Delgado-Kloos, 2018; Martín-Páez et al., 2019; Thibaut et al., 2018) of STEM education (not necessarily integrated education), a scarcity of reviews has been published on TPD for STEM education. Margot and Kettler (2019) reviewed 25 articles on teachers' perceptions of STEM integration and education. They summarized the barriers reported by teachers, such as curriculum challenges (e.g., difficult to integrate STEM curriculum into existing curricula), structural challenges (e.g., no platforms for teachers from different subject disciplines to collaborate), and concerns about students. Teachers generally believed that well organized and effective TPD could improve their effort to implement integrated STEM education (Margot & Kettler, 2019). In their meta-analysis of 95 TPD programs in STEM disciplines, Lynch et al. (2019) found significantly positive effects of TPD on student achievement (mean pooled effect size = +0.21 *SD*) across studies. They further identified the following characteristics of TPD programs as being associated with improved student achievement (p. 284):

- focusing on improving teachers' content/pedagogical content knowledge;
- focusing on how to use of new curriculum materials; and
- providing summer workshops to begin the TPD learning process, followed by meetings to troubleshoot and discuss teaching practice.

According to Darling-Hammond et al. (2017), however, these characteristics are only few elements (i.e., content focus, use of models and modeling, and sustained duration) of effective TPD. How can we design an overall approach to TPD programs for integrated STEM education? As Margot and Kettler (2019) stated, there is a need to develop a mechanism for TPD that can provide high-quality learning opportunities for teachers.

2.3. Effective teacher professional development

In a frequently cited research synthesis, Darling-Hammond et al. (2017) identified seven design elements of effective TPD: (a) content focus; (b) use of models and modeling; (c) active learning; (d) collaboration; (e) coaching and expert support; (f) feedback and reflection; and (g) sustained duration (Table 1). The TPD program of Roth et al. (2011) was one of their reviewed studies. It began with a three-week summer program focusing on science content (i.e., content focus). The teacher participants engaged in video analysis of teaching practices (i.e., use of models and modeling). They then used what they had learned to plan and deliver their own lessons (i.e., active learning). In follow-up sessions throughout the school year (i.e., sustained duration), they met in small groups facilitated by a program leader to discuss their teaching practice (i.e., coaching and expert support). The groups would collaboratively analyze their teaching practice and student work (i.e., collaboration). The collaborative analysis and subsequent revisions were scaffolded by TPD facilitators (i.e., feedback and reflection). Roth et al. (2011) found that their TPD program significantly improved teachers' content knowledge and their ability to analyze their teaching practice. Most importantly, the participants were more able to facilitate students' science learning. The framework developed by Darling-Hammond et al. (2017) has been used in TPD across contexts. Table 1 shows some new examples from integrated STEM education. Their framework provided an analytical lens for this review.

Table 1. Design elements of effective TPD identified by Darling-Hammond et al. (2017)

Design elements	Description	Examples
Content focus	TPD activities focus on the content that teachers teach in their classroom and context.	Brenneman et al. (2019) built teachers' content knowledge by covering the topics in mathematics (e.g., counting) and science (e.g., animal adaptations).
Use of models and modeling	Teacher participants are provided with instructional models (e.g., demonstration lessons and sample materials) as a vision of practice.	Brenneman et al. (2019) provided model lesson guides with suggestions for modification to fit teachers' school context, such as their available resources and student ability.
Active learning	Teacher participants are directly engaged in the practices which are connected to their classrooms and students.	Williams et al. (2019b) engaged their teacher participants as students in various integrated STEM activities, such as performing design-, build-, and test-based engineering activities.
Collaboration	Teacher collaboration is facilitated at the teacher, department, school, and/or district levels.	Singer et al. (2016) encouraged interactions between teacher participants and community members to share information/designs, negotiate meaning, and build consensus.
Coaching and expert support	Coaching and expert scaffolding support teacher participants' implementation of new curricula, tools, and instructional approaches.	The district coaches of Brenneman et al. (2019) supported their teacher participants in lesson planning, such as adopting integrated STEM activities into their existing curriculum and teaching schedule.
Feedback and reflection	Teacher participants are provided with time to think about, received input on, and make changes to their practice.	Singer et al. (2016) used lesson videos to support teacher reflection on teaching practice. Feedback was provided focusing on both positive exemplars and aspects worthy of improvement.
Sustained duration	Teacher participants are offered multiple opportunities to engage in learning.	The TPD program of Herro et al. (2019) included a year-long field placement, during which the TPD facilitators observed teachers' lessons and offered suggestions for improvement.

3. Method

The methodology of experiential (qualitative) reviews was employed. According to Munn et al. (2018), this systematic review methodology can explore why interventions are or are not effective using qualitative evidence as well as quantitative data of the reviewed studies.

3.1. Search strategies

The process of selecting relevant studies followed the preferred reporting of items for systematic reviews and meta-analyses (PRISMA) statement (Moher et al., 2009). Following Margot and Kettler (2019), four electronic databases were searched: (1) Academic Search Ultimate; (2) ERIC; (3) PsychINFO; and (4) Web of Science. The search string with Boolean operators was as follows: ("professional development" OR "professional learning" OR "teacher education" OR "teacher training") AND STEM AND integrat*. The asterisk was used as a wildcard to include most of the common expressions of integrated STEM education (e.g., STEM integration). The last search was run on July 15, 2020.

3.2. Inclusion and exclusion criteria

Empirical studies published between January 2015 and June 2020 (five and a half years) were reviewed. To be included in this review, the studies had to report on TPD intervention(s) in integrated STEM education and include a description of their TPD programs. The articles without these details were excluded. No constraints were imposed on subject disciplines, but the TPD content had to be in STEM fields, such as life sciences or engineering design (Guzey et al., 2019). Moreover, the authors had to mention the approaches they used to bring "together at least two STEM disciplines through the integration of both content topics and disciplinary practices" (Brown & Bogiages, 2019, p. 116). Thus, studies of single-discipline TPD programs were excluded. As PreK-12 education was the scope of this review, the participants of the TPD programs had to include PreK-12 in-service teachers. Thus, programs restricted to other participants (e.g., pre-service teachers) were excluded. Finally, no constraints were imposed on the language of instruction or the location of the studies. However, the manuscripts had to be written in English and published in peer-reviewed journals because peer review is a useful criterion for including methodologically sound studies (Korpershoek et al., 2016).

3.3. Data extraction and analysis

The following data were extracted from each article: author(s), year of publication, participants, location, subject disciplines, and duration of TPD programs (RQ1); effective TPD elements (RQ2); and challenges that teacher participants perceived or encountered in their implementation of integrated STEM education (RQ3). To answer RQ2 and RQ3, all of the findings/results, discussions, and conclusions of the reviewed studies were coded. In other words, the count of effective TPD elements and challenges was based upon the actual empirical evidence reported in each article (Akçayır & Akçayır, 2017; Akçayır & Akçayır, 2018).

To analyze the data, Miles and Huberman (1994) suggested "creating a provisional 'start list' of codes" (p. 58). Coffey and Atkinson (1996) explained that this is a useful way to begin coding. The framework of Darling-Hammond et al. (2017), shown in Table 1, provided a basis for a thematic analysis of effective TPD elements. To recall, Margot and Kettler (2019) identified challenges to STEM integration and education across 25 articles. Their categories were thus used to develop the initial framework for coding teacher challenges: (a) pedagogical challenges; (b) curriculum challenges; (c) assessment challenges; (d) structural challenges; and (e) student-related challenges. To enhance the consistency of coding, several exemplary quotes (Tables 2 and 3) that could clearly illustrate each constructed theme were identified. Multiple reviews of the data were done to ensure the understanding of each theme (Creswell, 2012). It is important to note that although these frameworks were used a priori, this review did not forcefully impose any of the coding categories onto the data set. New categories (e.g., socio-emotional challenges) were allowed to emerge inductively during the coding process.

To establish coding reliability, 25% of the articles were randomly selected and double coded by a second member of the research team. The percent agreement method was used to calculate a consensus estimate of interrater reliability using the formula given by Stemler (2004). Interrater reliability was greater than 80%. In the event of disagreements, the author and the team member re-examined the articles in question together to come to a consensus.

4. Findings

4.1. Study selection and characteristics of the reviewed studies

As of July 15, 2020, the search string described above had identified 361 journal articles published between January 2015 and June 2020. Some of the articles were removed due to duplication across databases. After analyzing the titles and abstracts of the search outcomes, quite a few articles were excluded because they were not relevant to this review (i.e., TPD in integrated STEM education). Ultimately, 81 full-text articles were assessed for eligibility. Some of them did not meet the criteria outlined above (e.g., no empirical data were provided; no details of their TPD programs were reported). Nevertheless, some of the excluded articles were used for background reference. The final sample included 48 articles. Among them, the following researchers reported on their TPD programs in multiple articles:

- Guzey and her colleagues (i.e., Guzey et al., 2016, 2019; Johnston et al., 2019; Lie et al., 2019);
- Herro and her colleagues (i.e., Herro & Quigley, 2017; Herro et al., 2018, 2019; Quigley & Herro, 2016);
- Kelley and his colleagues (i.e., Kelley et al., 2020; Knowles et al., 2018);
- Rich and his colleagues (i.e., Rich et al., 2017, 2018);
- Ríordáin and her colleagues (i.e., Johnston et al., 2020; Ríordáin et al., 2016); and
- Singer and his colleagues (i.e., Singer et al., 2016; Williams et al., 2019a, 2019b).

Therefore, a total of 37 unique TPD programs (the unit of analysis) for integrated STEM education were analyzed. Figure 1 outlines the process of article selection.

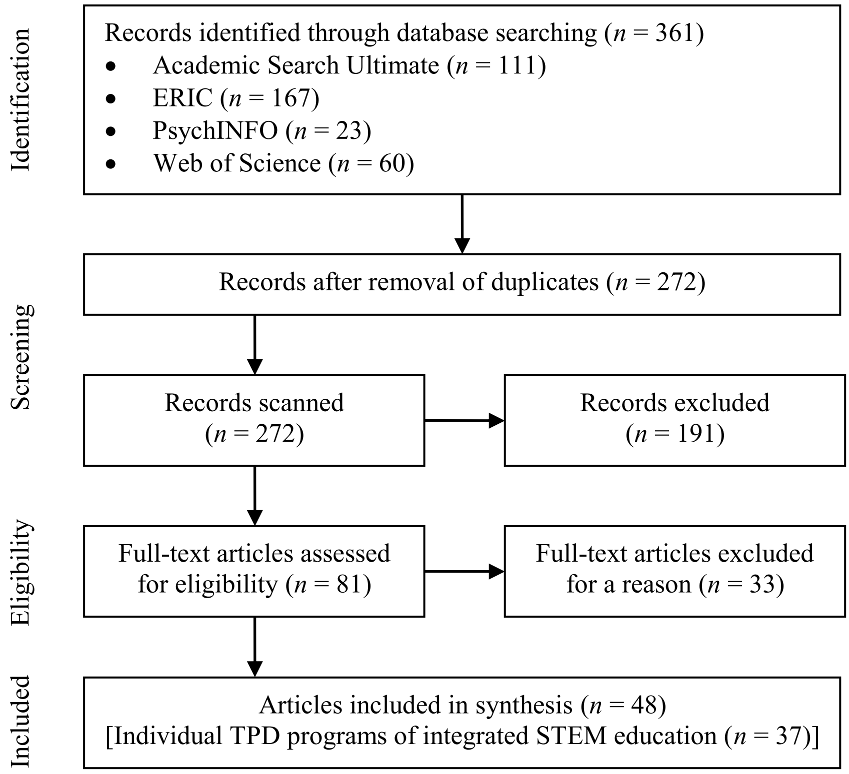

Figure 1. PRISMA flow diagram of article selection

Thirty-one of the 37 TPD programs (83.8%) were conducted in the United States; the others were from Canada (n = 2), Australia (n = 1), Ireland (n = 1), Israel (n = 1), and Saudi Arabia (n = 1). It is worth noting that the number of teacher participants in the TPD programs were not always provided. Besides, researchers might not recruit all teacher participants as their research participants. The available information indicated that the number of teacher research participants (M = 23.3; SD = 17.7) varied across the 48 reviewed studies, ranging from one (e.g., Johnston et al., 2019; Meyer, 2017) to 75 (DeCoito & Myszkal, 2018). Five studies also involved student research participants (M = 716.8; SD = 621.2), ranging from 58 (Kermani & Aldemir, 2015) to 1695 (McHugh et al., 2018). Figure 2 shows that more than half (n = 19) of the 37 TPD programs involved secondary school teachers only (e.g., Aldahmash et al., 2019). Some TPD programs recruited teachers from different school levels, such as elementary and middle schools (e.g., Mathis et al., 2017). In contrast, relatively few TPD programs involved early childhood educators (e.g., Marksbury, 2017).

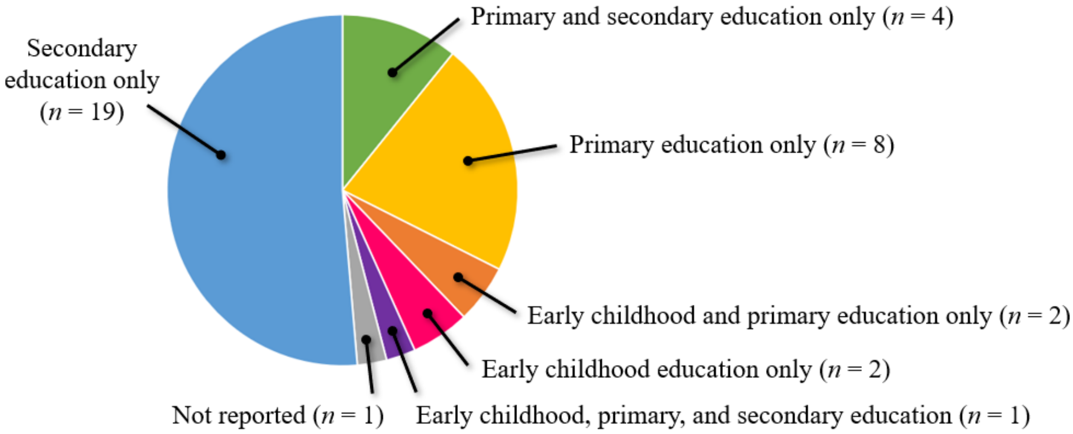

Figure 2. Teaching contexts of the teacher participants (Remarks: Early childhood education includes preschools and kindergartens; primary education includes elementary and primary schools; secondary education includes middle, high, and secondary schools)

4.2. Design of TPD programs for integrated STEM education (RQ1)

Reports on 20 TPD programs explicitly mentioned that the main TPD activities were conducted during the summer (e.g., Ring et al., 2017). However, most of the reviewed studies did not report the exact training hours and days. The available information indicated that in 22 TPD programs the main TPD activities lasted within two weeks (e.g., Constantine et al., 2017), and about 60% of the TPD programs (n = 22) provided ongoing support throughout a semester or academic year (e.g., Baker & Galanti, 2017; McFadden & Roehrig, 2017).

Figure 3 summarizes the findings on TPD content. Seven TPD programs (18.9%) integrated knowledge from all four STEM subjects. For example, Du et al. (2019) focused on "scientific inquiry, engineering and technological design, and mathematical analysis" (p. 107). Fifteen TPD programs (40.5%) integrated knowledge from three STEM subjects, such as "engineering, mathematics, and biology in a biomedical engineering theme" (Al Salami et al., 2017, p. 69). Eleven of the 37 TPD programs (29.7%) focused on two of the four STEM subjects. For example, the TPD program of Murcia and Pepper (2018) aimed to develop teachers' scientific and technological literacy skills. Other TPD programs emphasized pedagogical approaches to integrated STEM education, such as project-based learning (e.g., Herro & Quigley, 2017), or simply stated that they had covered STEM knowledge.

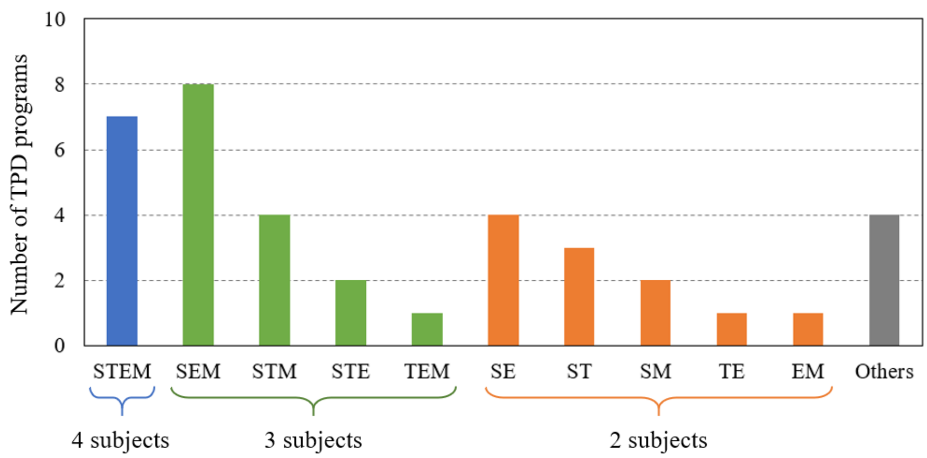

Figure 3. Subject integration in the 37 TPD programs

Figure 4 summarizes the major instructional activities, apart from facilitator presentations, of the 37 TPD programs. Facilitators from 25 TPD programs explicitly mentioned the use of small-group activities (e.g., Ortiz et al., 2015). Nearly two thirds of the TPD programs (n = 24) engaged teacher participants in model activities/lessons that they could use in their classrooms. For example, the teacher participants of McFadden and Roehrig (2017) "experienced STEM-integrated curriculum as learners" (p. 5). In about 60% of the TPD programs (n = 22), teacher participants designed and developed their own instructional materials. In other words, they "were tasked with developing activities for their classrooms" (Brand, 2020, p. 5). In addition, facilitators from 22 TPD programs arranged ongoing meetings with teacher participants. In-school coaching (Smith et al., 2018), virtual meetings (Wang et al., 2020), and attending teachers' planning meetings (Goodnough, 2018) were some of the formats used. A few notable TPD programs (*n* = 6) used micro-teaching, during which teacher participants piloted their integrated STEM lessons with a small group of summer camp students (e.g., Lie et al., 2019) or graduate students (e.g., Brand, 2020). They could thus revise their teaching plan and instructional materials based on the feedback and reflection on micro-teaching. As shown in Figure 4, other instructional activities of the TPD programs included reflection (*n* = 15), expert sharing (*n* = 9), and STEM site visits (*n* = 4).

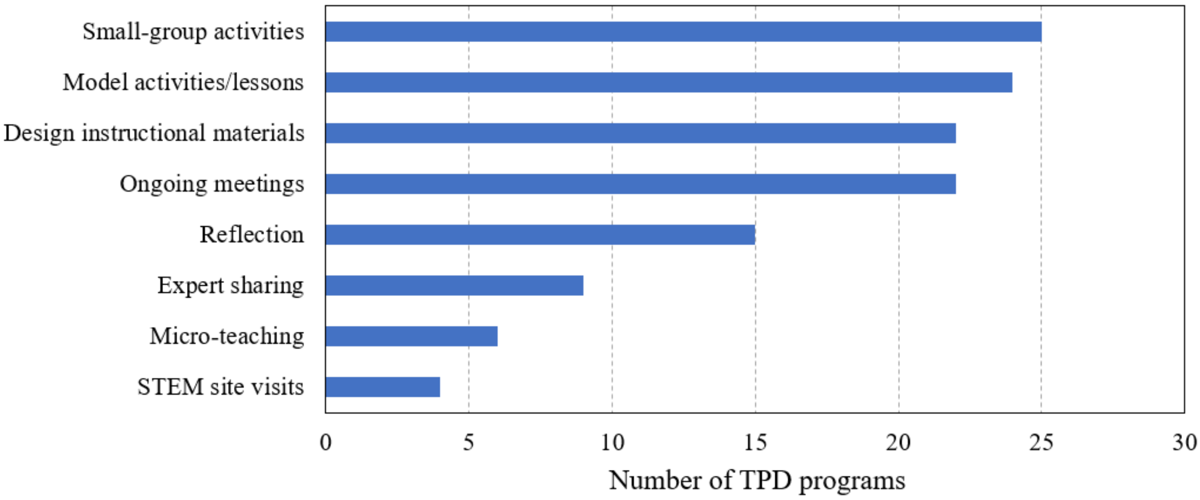

Figure 4. Major instructional activities in the 37 TPD programs (Remark: Totals are greater than 37 because most TPD programs provided multiple instructional activities)

4.3. Elements of effective TPD for integrated STEM education (RQ2)

This review identified a number of elements that contributed to the effectiveness of the TPD programs. These elements were organized using the framework developed by Darling-Hammond et al. (2017) and are summarized in Table 2. First, content focus was the most frequently mentioned element. Following Singer et al. (2016), this theme was further classified into two sub-themes, content knowledge (*n* = 16) and pedagogical content knowledge (*n* = 15). The researchers found that building teachers' content knowledge and pedagogical content knowledge improved their implementation of integrated STEM education. Second, nearly 40% of the TPD programs (*n* = 14) provided evidence to support the use of models and modeling. More specifically, teacher participants stated that sample STEM instructional materials, such as lesson plans (Rich et al., 2018) and hands-on activities (Brenneman et al., 2019), provided ideas and/or became resources for their teaching practice. Third, seven TPD programs found that engaging teacher participants in sample STEM activities/lessons, such as laboratory experience (Wang et al., 2020) and problem-solving activities (Herro & Quigley, 2017), enhanced their understanding of integrated STEM education.

Collaboration was another frequently mentioned element of effective TPD programs, which was divided into in-school interdisciplinary collaboration (*n* = 7) and beyond school collaboration (*n* = 6). Taking in-school interdisciplinary collaboration as an example, Wang et al. (2020) found that interdisciplinary collaboration involving teachers from different subject areas facilitated the implementation of integrated STEM education in both classroom and extracurricular activity settings. Furthermore, coaching and expert support for teachers' knowledge of STEM practice (*n* = 8) and instructional strategies for teaching STEM (*n* = 3) were essential. According to Herro and Quigley (2017), "the majority of [teacher] participants talked about the value of connecting to experts (via Google Hangout) to assist in teaching content, explaining that they were a bridge to understanding 'problem-based learning in action in their classroom'" (p. 428). Some researchers also provided evidence for the benefits of feedback (*n* = 7) and teacher reflection (*n* = 4). One district coach working with Brenneman et al. (2019) said that "the feedback we shared was constructive as they [teacher participants] often applied the suggestions given" (p. 23). Furthermore, their teacher participants recognized the value of reflection. Finally, seven of the TPD programs found that sustained duration was valuable. In Meyer's (2017) 2-year TPD program, the teacher participants set their own goal in the second year of learning. As a result, they were better able to integrate science and engineering in their teaching.

Table 2. Elements of effective TPD in integrated STEM education across the 37 TPD programs

Themes and sub-themes	Count	Representative citations
Content focus		
• Content knowledge	16	"I felt like the task today really pushed my math content knowledge and allowed me to pull more information to create new understandings" (Teacher participant, quoted in Brown & Bogiages, 2019, p. 122).
• Pedagogical content knowledge	15	"[Teacher participants] attempted, liked, or used inquiry-based approaches in their practice … the majority of teachers reported that the STEM-OP [STEM outreach program] workshops influenced their teaching and provided them with new teaching ideas" (DeCoito & Myszkal, 2018, p. 497).
Use of models and modeling		
• Sample STEM instructional materials	14	"Hands-on activities are helpful to me as we share and gather info to bring back to our classrooms" (Teacher participant, quoted in Brenneman et al., 2019, p. 23).
• Active learning		
• Engaging in sample STEM activities/lessons	7	"Going through the process as a student [using the technology] helped me to better understand what I need to do as teacher in my classroom" (Teacher participant, quoted in Herro & Quigley, 2017, p. 430).
Collaboration		
• In-school interdisciplinary collaboration	7	"Ray [one teacher participant] believed that the interdisciplinary approach allowed teachers to use their strengths to teach a more complex idea to students. … Ray was amazed to see Josh and Melvin [two teacher participants in the same school] using analytical skills to solve problems with their hydroponics systems" (Wang et al., 2020, p. 8).
• Beyond school collaboration	6	"[Teacher] participants also noted that collaboration, oftentimes enabled by technology, allowed them an opportunity to connect with experts in the field in content areas outside of their specialty" (Herro & Quigley, 2017, p. 429).
Coaching and expert support		
• Knowledge of STEM practice	8	"TRAILS teachers experienced a blend of science and technology practices during professional development and learned how these practices are used in industry and scientific research from guest speakers. These experiences may have impacted teachers' increase in self-efficacy in teaching STEM" (Kelley et al., 2020, p. 10).
• Instructional strategies for teaching STEM	3	"[T]he coaches' helpfulness—pedagogical instructional assistance, materials instructional assistance, and role as reflective practitioners and encouragers—was evident in how prepared the coaches were to transfer content knowledge to the teachers" (Parker et al., 2015, p. 297).
Feedback and reflection		
• Feedback	7	"[Teacher participants] demonstrated that the feedback we shared was constructive as they often applied the suggestions given" (District coach, quoted in Brenneman et al., 2019, p. 23).
• Reflection	4	"The findings indicated that the teachers' continuous reflections on their practice and the framework initially presented to them, led to an understanding of the value of activities integrating inquiry and engineering design for their students" (Brand, 2020, p. 7).
Sustained duration		
• Sustained TPD	7	"The long-term, sustained professional development model resulted in consistent results in a variety of classroom settings. Student outcomes were measured and indicated improvements in science mastery and positive attitudes" (McHugh et al., 2018, p. 820).

4.4. Teacher challenges to integrated STEM education (RQ3)

Teachers who received the training in TPD programs reported challenges to the implementation of integrated STEM education. Using the framework of Margot and Kettler (2019), the major challenges were organized into five main themes. As shown in Table 3, some of these themes were further categorized into sub-themes. First, pedagogical challenges were frequently reported. Researchers discovered that even after participating in TPD programs, some teachers lacked the necessary knowledge of STEM (n = 20) and level of comfort to implement integrated STEM education (n = 12). In fact, these two sub-themes could be interrelated. As Rich et al. (2017) argued, "Their lack of background in these [STEM materials] and related fields heavily influenced their lower self-efficacy for teaching computing and engineering" (p. 15). Another frequently mentioned theme was curriculum challenges, including time constraints (n = 16) and the discrepancy between STEM and curriculum requirements (n = 7). Herro et al. (2019) pointed out that "The challenge was not in meeting standards per se but instead in meeting standards by timelines" (p. 182). One related theme was assessment challenges. More specifically, the use of class activities was limited by the need to prepare for mandated exams (n = 7). One teacher lamented that "Testing for Educational Progress takes the fun out of what we do as teachers" (Wang et al., 2020, p. 10), although she had the goal of teaching STEM using an integrated approach.

Table 3. Challenges to integrated STEM education identified in the 37 TPD programs

Themes and sub-themes	Count	Representative citations
Pedagogical challenges		
• Teachers' limited STEM knowledge	20	"All three teachers had limited knowledge about technological electronic components such as resistors, diodes, transistors and their functions in an electric circuit" (Awad et al., 2019, p. 5).
• Teachers' discomfort	12	"One of the key disconnects evident in the activity system was the teachers' lack of comfort with teaching in STEM areas" (Goodnough, 2018, p. 2192).
Curriculum challenges		
• Time constraints	16	"[S]he [one teacher participant] was indeed aware of the importance of the mathematics component, but time constraints were hindering greater exploration of the concepts" (Johnston et al., 2020, p. 1409).
• Discrepancy between STEM and curriculum requirements	7	"Mr. Ferroni and Ms. Williams [two teacher participants] both highlighted the fact that the inclusion of angles at this particular time of the school year was not in alignment with the mathematics scope and sequence as set by the district" (Smith et al., 2018, p. 162).
Assessment challenges		
• Confined by mandated exams	7	"Despite the values Malcom [one teacher participant] perceived of STEM integration, he was required to use the standards and teach according to the state exams. This prevented him from using hands-on experiences in teaching STEM because he did not think they fit together" (Wang et al., 2020, p. 11).
Structural challenges		
• Teachers' lack of preparation time	10	"Adapting these new lessons to incorporate either engineering or computing did not just involve having to take time to create the lesson, but also take the time to learn the material for themselves" (Rich et al., 2018, p. 458).
• Teachers' lack of resources	10	"I think for me one of the challenges is going to be … coming up with hands-on things, because budgets are tight in the public school system" (Teacher participant, quoted in Fore et al., 2015, p. 108).
• Absence of school planning	6	"The teachers saw the benefits of integrating both subjects but felt that school structures and supports need to be flexible in terms of accommodating and achieving integration, particularly in relation to timetabling and subject planning" (Ríordáin et al., 2016, pp. 246-247).
Student-related challenges		
• Unable to understand STEM materials	12	"[H]e [one teacher participant] believed the topic was too complicated and too advanced for students at the freshman level and lower, which was the majority of his students" (Wang et al., 2020, p. 11).
• Negative attitudes toward STEM learning	5	"Students not convinced of curricular tie-in" (Teacher reflection, quoted in Al Salami et al., 2017, p. 79).

In the reviewed studies, three types of structural challenges to integrated STEM education were identified: lack of teachers' preparation time (n = 10); lack of resources (n = 10); and absence of school planning (n = 6). In particular, when TPD programs involved the use of specific equipment (e.g., 3D printers), the implementation of their STEM activities might not be feasible in some schools (see Dyehouse et al., 2019; Schelly et al., 2015 for a review). Finally, the studies identified a few challenges related to students. Some teachers reported that their students were unable to understand the STEM materials introduced in the TPD programs (n = 12). One teacher even asserted that "his students would find such problems to be profoundly troublesome" (Fore et al., 2015, p. 106). In addition to student ability, some students might have negative attitudes toward STEM learning (n = 5). For example, teachers might not have a broad buy-in from their students (Al Salami et al., 2017).

5. Discussion

This review analyzed 48 articles reporting on 37 TPD programs for integrated STEM education. Consistent with Lynch et al. (2019), the major themes in this literature were content focus, use of models and modeling, and sustained duration. In fact, content knowledge, pedagogical content knowledge (content focus), and sample STEM instructional materials (use of models and modeling) were the three most frequently reported elements of effective TPD programs (Table 2). Resonated with Margot and Kettler (2019), this review also identified various challenges to the implementation of integrated STEM education in schools. Some challenges (e.g., time constraints and teachers' lack of resources) appear to be generic for non-STEM contexts. TPD facilitators should therefore leverage the literature of teaching and teacher education when designing their TPD programs. In STEM contexts, however, one should pay particular attention to pedagogical and structural challenges – the two most frequently reported challenges (Table 3). Drawing on these findings and the framework of Darling-Hammond et al. (2017), this section develops a set of 10 design principles for effective TPD for integrated STEM education.

5.1. Content focus

5.1.1. Principle 1: Develop a connected foundation of content knowledge and pedagogical content knowledge across disciplines for STEM integration

The inclusion of content knowledge and pedagogical content knowledge is vitally important to TPD programs (Table 2). However, this review indicated that even after training, quite a few teachers lack the necessary knowledge (Table 3). For example, Smith et al. (2018) found that "the teachers did not understand the 'big' picture with regards to either the science or mathematics contents" (p. 164). Without understanding the interconnected nature of STEM disciplines, teachers are not able to achieve greater levels of STEM integration (English, 2016; Vasquez et al., 2013). Therefore, TPD facilitators should (1) develop a connected foundation of content knowledge and pedagogical content knowledge across disciplines for STEM integration, and (2) engage teacher participants in integrating the STEM concepts. Cavlazoglu and Stuessy (2017) used concept maps to facilitate this process. They first identified a list of essential earthquake engineering and related STEM concepts through a discussion with experts in the field. The overall structure and connections among the concepts were then represented using a concept map. In addition to the acquisition of TPD content, Cavlazoglu and Stuessy (2017) emphasized the need to provide teacher participants with concept mapping experience during their TPD program. They asked their teacher participants to develop their own concept maps and establish connections among earthquake engineering and STEM concepts. In this way, they could see how the STEM concepts were integrated.

5.2. Use of models and modeling

5.2.1. Principle 2: Provide exemplars of instructional materials and deliver model activities/lessons

TPD facilitators can provide teacher participants with exemplars of instructional materials (Table 2). These materials can provide ideas or frameworks for their design and implementation of integrated STEM activities (Estapa & Tank, 2017; Guzey et al., 2016). Teachers in some TPD even adopted the materials as their teaching resources. In Rich et al. (2018), for example, "These resources included (but were not limited to): mobile applications, online modules, printed lesson plans, interactive robots, and other resources that they [teachers] could take into their classroom" (p. 453). With these resources, the challenge of teachers' lack of preparation time for STEM activities (Table 3) can be remedied. TPD facilitators should further introduce the design and use of new instructional materials (Lynch et al., 2019). By doing so, Estapa and Tank (2017) found that most teacher participants were able to develop quality lesson plans through reference to their sample activities. As Sias et al. (2017) observed, however, some teachers did not practice what they had learned in their TPD program because they had no personal experience with these educational innovations (Table 3). Therefore, TPD facilitators can demonstrate how to deliver their STEM activities/lessons. Teacher participants in different TPD programs (e.g., Herro & Quigley, 2017; Rich et al., 2017) confirmed that going through the learning process as students increased their understanding and self-efficacy in using those STEM activities/lessons in their classrooms (Table 2).

5.3. Active learning

5.3.1. Principle 3: Allocate TPD time for teachers to develop their own instructional materials

Ríordáin et al. (2016) observed that some teachers did not take ownership of the STEM materials developed by TPD facilitators. The teachers thought that the materials were not suitable for their students and school context (e.g., teaching schedule and lecture hour). In fact, students' difficulty in learning STEM subjects is one of the major challenges to integrated STEM education (Table 3). Viewed from another perspective, this may be the result of teachers failing to provide suitable learning tasks for facilitating their STEM learning. Therefore, TPD facilitators should allocate time for teacher participants to create their own instructional materials. As Fore et al. (2015) stated, teachers understand their students' capabilities as well as the realities of their classrooms. These understandings can inform the development of their own instructional materials. They can tailor the materials for their students and share them with their colleagues. During the development process, TPD facilitators can provide additional supporting recourses as well as feedback for improvement (McFadden & Roehrig, 2017).

5.3.2. Principle 4: Allocate TPD time for teachers' micro-teaching

Consistent with the finding of Margot and Kettler (2019), teachers' lack of comfort was one of the challenges to integrated STEM education identified in this review (Table 3). Rich et al. (2018) found that providing their teacher participants with instructional resources and learning opportunities was insufficient for making them feel comfortable in teaching integrated STEM. Moreover, although the teachers were able to design quality instructional materials for STEM integration, they did not always use the materials and enact their lessons satisfactorily (Estapa & Tank, 2017). To bridge the gap between planning and implementing lessons, TPD facilitators can allocate time for teachers' micro-teaching. For example, the teacher participants in Brand's (2020) program piloted their lessons with a group of graduate student volunteers. At the end of each pilot lesson, the teachers and audience evaluated the quality of teaching using an established rubric (i.e., Science Teaching Inquiry Rubric). They could thus have a more focused discussion on the lesson design and teaching performance. Based on the feedback and reflection on their micro-teaching, the teacher participants could make necessary revisions to their lesson plans and instructional materials before implementing them in their own classrooms. Most importantly, they gained experience delivering integrated STEM activities, which increased their familiarity with the new instructional materials and their self-efficacy (Parker et al., 2015; Rich et al., 2017).

5.4. Collaboration

5.4.1. Principle 5: Facilitate teachers' in-school interdisciplinary collaboration for integrated STEM education

This review confirmed the importance of in-school interdisciplinary collaboration for integrated STEM education (Table 2). Teachers from different subject disciplines can use their strengths and expertise to design instructional materials for students (Johnston et al., 2020). To facilitate such collaboration, TPD facilitators can recruit a team of teachers from the same school (Dyehouse et al., 2019). For example, Kelley et al. (2020) encouraged the participation of two teachers from a school. They could collaborate on lesson plans and implementation according to their school context. Goodnough (2018) further supported a team of teachers in each participating school. Her teams designed and implemented their integrated STEM activities using a collaborative action research approach. The teacher participants thus had the opportunity to share ideas and discuss their practice. This kind of collaboration enables teachers to determine feasible and sustainable ways of implementing integrated STEM education in schools (Dyehouse et al., 2019; Goodnough, 2018).

5.4.2. Principle 6: Familiarize school leaders with the strategies for supporting integrated STEM education

Fore et al. (2015) pointed out that the involvement of school leaders has often been overlooked in integrated STEM education. If school leaders lack a background in STEM, they may not provide relevant support and resources for teaching STEM. In fact, the structural challenges identified in this review (Table 3) must be resolved at the school level (Ríordáin et al., 2016). First, some teachers discussed the difficulty of finding meeting times that suited colleagues from different departments (Quigley & Herro, 2016; Wang et al., 2020). In addition, quite a few teachers did not have sufficient preparation time and resources to design and implement integrated STEM activities (Fore et al., 2015; Ríordáin et al., 2016). To reduce or avoid these problems, school leaders can schedule meetings for interdisciplinary collaboration and allocate additional resources (e.g., budget and manpower) to support the development of new instructional materials. In future TPD programs, an orientation session for the leaders of participating schools can be offered to increase their familiarity with integrated STEM education (Al Salami et al., 2017) and to help them establish a detailed implementation plan (Rich et al., 2017).

5.4.3. Principle 7: Connect teachers to a community of practice that supports integrated STEM education

Kelley and Knowles (2016) emphasized the vital role of a community of practice in integrated STEM education. However, this review found that not all TPD programs connected their teacher participants to a community of practice (Figure 4). STEM teachers from different schools, industry partners, and college faculty can offer insights into a school's teaching practices (Table 2). In particular, STEM professionals can share not only their practice and current job challenges (Dyehouse et al., 2019) but also their career pathways (Knowles et al., 2018). Such sharing allows teacher participants to provide students with authentic learning experiences based on recent STEM practice (Knowles et al., 2018). Herro and Quigley (2017) found that the majority of teacher participants confirmed the value of connecting with experts when developing teaching content and instructional approaches such as problem-based learning. With these connections, teachers can invite STEM professionals to their classrooms as guest speakers, which broadens students' understanding of STEM practice and careers (Knowles et al., 2018).

5.5. Coaching and expert support

5.5.1. Principle 8: Understand the context and needs of teachers and provide relevant support

This review suggested that coaching and expert support in both subject knowledge and instructional strategies for teaching STEM contributed to the effectiveness of TPD programs (Table 2). There are some strategies to ensure the relevance and effectiveness of the support. For example, Williams et al. (2019b) met with district personnel and teacher participants at the design and development phase of their program. In this way, the TPD facilitators and teacher participants could "develop a common vision and design, including the establishment of goals, strategies, needs assessment, targets, and contextual factors" (p. 180). In addition, some STEM professionals and experts may not have the knowledge of the education field and the experience of working with teachers. As the teacher participants in the study by Parker et al. (2015) said, some STEM coaches seemed unapproachable. In future practice, TPD facilitators can brief their coaches on the best coaching practice before the start of their TPD programs (Brenneman et al., 2019). Estapa and Tank (2017) even took a few days to train their engineering fellows in how to support teachers' instructional practice. Using lesson videos and instructional materials, the fellows were familiarized with school contexts and existing curriculums. This kind of preparation can enhance the relevance and effectiveness of coaching and expert support.

5.6. Feedback and reflection

5.6.1. Principle 9: Facilitate teacher reflection on their understanding of STEM integration and teaching practice

Bandura's (1994) theory on improving self-efficacy emphasizes the role of continuous input and feedback throughout the three stages of learning new knowledge, putting the knowledge into practice, and reviewing the outcome of practices (Kelley et al., 2020). As integrated STEM education is new to some teachers (Table 3), Ring et al. (2017) allowed time for teacher participants to reflect on their own concepts both individually and with peers after learning new materials. They found that the reflective and collaborative nature of these TPD activities enabled the teachers to gain a deeper understanding of STEM integration. Furthermore, feedback from coaches or TPD facilitators can guide teacher reflection and inform their instructional improvement (Table 2). Brenneman et al. (2019) adopted a reflective coaching model in their TPD program. During each reflective coaching cycle, a district coach and a member of the research team first observed and videotaped a lesson of a teacher participant. Then, their conversation started with the teacher's self-evaluation of his/her teaching practice, followed by the coach's suggestions based on specific evidence from the lesson. Most of their teacher participants highly valued the reflective coaching sessions and improved their teaching practice.

5.7. Sustained duration

5.7.1. Principle 10: Use summer programs to begin the TPD learning process and provide ongoing support across several years

More than half of the TPD programs in this review were offered in the summer, a time when teachers were relatively less occupied by their teaching load. Echoing Lynch et al. (2019), the findings of this review suggested that ongoing support from TPD facilitators benefited teachers' implementation of integrated STEM education (Table 2). Lie et al. (2019) allowed their teacher participants to enroll in their TPD program repeatedly. They found that the number of years of teacher participation was positively associated with student attitudes toward engineering. Observing one of their teacher participants over a three-year period, Johnston et al. (2019) found that the teacher progressively increased his mastery of integrating science, mathematics, and engineering through engineering talk. The researchers explained that teachers' consecutive participation in the TPD program and ongoing support developed their confidence and increased their ability to teach STEM. However, it is worth noting that TPD facilitators' drop-ins (e.g., school visits) can "create a lot of work" (Al Salami et al., 2017, p. 79) for teachers. In addition to face-to-face formats, TPD facilitators can consider using approaches that have greater flexibility and sustainability, such as virtual meetings (Wang et al., 2020) and online asynchronous coaching (Brenneman et al., 2019).

6. Conclusion and limitations

This review was motivated by the need to develop TPD for integrated STEM education that provides high-quality learning opportunities and support for teachers. A systematic review of 48 empirical studies was conducted to identify the effective elements of TPD for integrated STEM education and the potential challenges to teaching integrated STEM in schools. The importance of content knowledge, pedagogical content knowledge, and sample STEM instructional materials was frequently stressed across studies. However, pedagogical challenges (e.g., teachers' limited STEM knowledge) and structure challenges (e.g., teachers' lack of preparation time and resources) hindered the implementation of integrated STEM education in schools. Based on these findings, this review proposed a set of 10 design principles for TPD programs for integrated STEM education. The principles were established by leveraging the elements of TPD identified as effective in this review, and addressing the potential challenges to teaching STEM. For example, Principle 4 suggests allocating TPD time for teachers' micro-teaching which allows teachers to customize their STEM materials and receive feedback on teaching performance. Although this set of design principles provides a potential agenda for TPD programs, further studies should be conducted to examine the efficacy of each principle. Based on their empirical findings, TPD facilitators can identify the principles that are most relevant to their programs.

Before the design principles are applied, several limitations of this review must be acknowledged. First, this review only considered the topics discussed in the published articles. Therefore, the absence of some types of TPD activities and/or findings does not necessarily imply the absence of these attributes. It only indicates that these topics were not explicitly explored in the published articles. Second, most of the TPD programs in this review were conducted in the United States. Besides, the scope of this review was limited to PreK-12 education. One should therefore consider whether the design principles are context specific. Further research is required to modify or extend them before applying them to other educational contexts, such as Asian counties. Finally, the findings of this review suggest that existing curriculum and assessment requirements still limit the implementation of integrated STEM education in schools. However, these challenges cannot be resolved at a TPD level. These findings thus have implications for policymakers, suggesting the need of significant and long-term reform to the current disciplinary curriculum and assessment practices.

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