

Article

STEM Professional Development Activities and Their Impact on Teacher Knowledge and Instructional Practices

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Abstract: The science, technology, engineering, and mathematics (STEM) field is a crucial global driver for the development of various aspects of modern society, such as the economy, technology, education, and skills of the 21st-century workforce. All countries strive to produce STEM talent to meet future economic markets. Sustained professional development (PD) can support reform in STEM. Teachers need professional training to improve their knowledge, understanding, and teaching practices, which affect the development of their students' meaningful learning. As a result, a systematic study was carried out to identify STEM PD activities and their influence on teachers' knowledge and instructional methods. The peer-reviewed publications were published between 2017 and 2021, and Scopus, Web of Science, and EBSCOhost databases were used to find them. A comprehensive review of these empirical articles produced a total of 15 subthemes under activities and impact themes. The results exhibited that the dominant activities of STEM PD included engineering activities that indirectly had an extremely high impact on teachers' knowledge and teaching practices related to engineering design, the problem-solving process as it relates to the engineering design process, and experiences of scientists and engineers. Finally, several recommendations for STEM PD sustainability and future research reference are presented.

Keywords: professional development; science; technology; engineering; and mathematics; teacher knowledge; STEM teachers; instructional practices



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1. Introduction

Teachers face significant challenges when implementing science, technology, engineering, and mathematics (STEM) education in the classroom, including steep learning curves and the unpleasant process of obtaining skills, knowledge, and confidence in guiding pupils through numerous tasks [1–4]. One of the four goals of STEM education is to train the best STEM experts globally [5,6]. Generally, STEM education as a teaching approach can utilize the multidisciplinary nature of the STEM disciplines or integrate learning topics into the engineering design process while encouraging open inquiry to solve real-world problems [7]. Defining STEM education is one of the challenges of providing professional training that includes STEM courses. “STEM education refers to teaching and learning in the fields of science, technology, engineering, and mathematics”, according to the United States Department of Education's report on STEM Education Federal Strategies, which includes “educational activities across all grade levels in both formal and informal settings” [8]. Based on the 2014 STEM Task Force Report in the United States, STEM education encompasses real-world, problem-based learning that integrates STEM disciplines through active learning [9,10]. Interdisciplinary STEM education is a pedagogical approach where students connect different STEM fields [11]. As a consequence, STEM education includes methods for examining teaching and learning across two or more STEM disciplines, as

well as between a STEM subject and one or more other school subjects [12]. In addition to improving their knowledge of a wide variety of academic areas, pedagogical skills across disciplines, and access to relevant resources, STEM instructors must possess specific personal and professional characteristics [13]. Researchers argue this can be accomplished through proficient learning opportunities, particularly STEM professional development (PD), that advances a profound comprehension of various topics and highly effective instructional practices [14,15].

The quality of its teachers has a major influence on a school's educational quality. The teacher contributes to a broad variety of cognitive, metacognitive, and motivational-affective learning outcomes by selecting and executing curricular content and providing adequate learning and socio-emotional support to pupils. According to educational academics, teachers' professional knowledge lies at the core of their competency. This professional knowledge includes both general educational concepts and practices as well as information specific to the subject topic taught [16].

The content domain is a critical component of teacher knowledge, since it primarily pertains to an understanding of the subject matter and its organizational structure [17]. Teachers' comprehension of the subject matter extends beyond factual knowledge to include a sense of the topic's significant structures [18]. Teachers who have extensive and strong knowledge are able to plan various strategies in their teaching. Teachers use instructional strategies to assist students in becoming more self-sufficient and tactical learners. When students handpick the best ones and employ them to accomplish assignments, these methods become effective learning strategies. Students might be stimulated by instructional tactics that help them focus and combine knowledge in order to grasp and retain it [19].

Schools, workplaces, and PD programs all have the ability to limit knowledge transmission and teaching approaches. These elements are vital for teachers' learning, but they may also stifle the transfer of new information and instructional approaches to the classroom. A PD program that includes opportunities to enhance knowledge and practice should include support for the transfer of information or techniques [20]. Thus, a review of research on STEM PD may offer insight into and influence future educational research.

2. Literature Review

Teacher PD can take on many different forms. Many researchers regard PD as a series of training events that occurs when teachers work in schools after they graduate from teacher education institutions [21]. This is recognized as the cornerstone of all kinds of educational reform [22]. Effective PDs are vital in equipping teachers with the necessary knowledge and skills to improve the quality of their instruction and enhance student learning [23,24]. A typical PD program in the separate STEM disciplines aims to enhance teachers' knowledge and practice, which in turn can enhance students' knowledge [25]. Teacher learning is supported during a PD program through the integration of features that enable teachers to work collectively in an active setting that suits their classrooms' contexts and focuses on a disciplinary area [26,27]. The PD programs that adopt these design features have improved teacher instruction and student knowledge [28–31].

Extensive reform attempts in STEM education over the last few decades have necessitated the advancement of the corpus of research on STEM education PD. When new standards are approved and new national educational programs emerge, PD is often utilized as an agency to educate teachers and affect change in their practices. National and local educational goals and efforts now concentrate on including more children in STEM learning and activities in the hopes that they will continue in STEM courses and career pathways to satisfy STEM employment needs, thereby increasing societal STEM literacy [32]. Within their subject area, teachers must be sufficiently exposed to the expanding complexities of the STEM reform movement, as well as to become acquainted with developments in other relevant topics [33]. The vital importance of PD in providing opportunities for teachers to continually grow professionally is based on empirical research

that shows students who have teachers who participate in lifelong learning or PD reach higher levels than students who do not have such teachers [34].

However, the traditional teacher PD does not result in sustained improvement of teacher practice and student learning [35]. The single discipline model of PD programs is being challenged by standards and global goals in the STEM fields. For example, in K-12 schools, the Next Generation Science Standards (NGSS) and the Common Core Standards for Mathematics build a relationship between mathematics and science. These standards require people's STEM literacy to be increased in order for them to be equipped to participate in today's technologically and scientifically evolved global civilization [36]. As a result, teachers must broaden their expertise by illustrating connections across STEM subjects and supporting students in applying STEM abilities in their everyday lives [37]. STEM PD programs are essential for teachers who want to adopt an integrated STEM curriculum. Learning about numerous disciplines and how they link to each other is undoubtedly more complex than learning the content of a single discipline PD program [20].

In the last century, teacher PD programs have received attention in the United States, the United Kingdom, France, Russia, Finland, China, and Australia, and each country has created a national strategic plan for the STEM fields. For example, in the United Kingdom, the National STEM Learning Centre was established to serve as a center that provides ongoing training specifically for STEM educators. At the same time, Finland and the United States have implemented the LUMA Centre and the Federal STEM Education Strategic Plan, respectively, to improve student enrollment in STEM fields and subsequently encourage students to select STEM-related careers [21]. Furthermore, in Malaysia, high numbers of teachers need STEM-related training. According to Science Outlook 2017, of the 16,115 Malaysian secondary school STEM teachers surveyed, 47% had never attended STEM-related training and were never exposed to STEM-oriented teaching materials. Professional training is vital for teachers to ensure that effective STEM education can be implemented [38].

In the past five years, a variety of unique STEM initiatives have evolved in Chile, Peru, Colombia, and Mexico, each with its own focus and objectives, but all emphasizing the necessity of encouraging science-integrated and practice-based learning experiences in the school curriculum. Even if STEM as a concept is still developing at the policy level, there are several factors that, when combined with other policies and public initiatives, reinforce the need for this integrated approach. The importance of women's engagement in science, a critical citizenship, a prepared workforce for changing markets, and educational opportunities for everyone are often debated in government publications. In-service and pre-service teacher training, as well as opportunities for PD for teachers, are all included in these programs, as are efforts that are directly focused on working with students [39].

Although there is a vast body of literature on STEM teacher PD at present, the effort to systematically review empirical studies, identify a pattern, and develop potential themes on the associated activities and their impact remain limited. Previous studies have not fully addressed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) review processes, which includes identification, screening, and eligibility. In fact, the traditional literature reviews of the empirical studies on STEM teacher PD have several issues related to transparency and bias. Some researchers have conducted systematic reviews on the challenges and obstacles of STEM PD implementation [6] and meta-analytic studies to evaluate the effect of STEM PD on student achievement [40,41]. Also, there is a review focusing on design and teacher knowledge and practices that presented STEM PD in terms of collaboration, coherence, the siloing of activities, and integration, but did not discuss the activities for each STEM PD or their impact on instructional practices and knowledge [20].

3. Methods

In this study, we examined and synthesized selected articles that were relevant to STEM PD activities and their impact on teacher knowledge and instructional practices. The

effort to synthesize these studies based on their inclusion of any activities and analysis of the impact of STEM PD on teacher knowledge and instructional practices is still scarce. We, as researchers, believe that understanding the effects of STEM PD on teacher knowledge and teaching practices is crucial to ensuring the activities' effectiveness in sustaining teacher and student learning. Thus, in conducting the review, the main research questions that framed the study were as follows:

- (a) What are the activities conducted for STEM PD?
- (b) What are the impacts of STEM PD on teacher knowledge and instructional practices?

Through this systematic literature review, the PRISMA checklist is utilized to guide researchers with the related and necessary information that will enable them to conduct a rigorous review and examine the quality of the outcome [42]. In addition, PRISMA emphasizes that studies report and utilize randomized trials, which can be fundamental in reporting systematic reviews for other types of research with benefits to various fields [42]. The methodology enables systematic searching using a step-by-step procedure that provides useful guidance for attaining the required articles. Additionally, the PRISMA procedures provide researchers with a clear comprehensive process, easy observation of the connection between information and its sources via systematic review recording, and a straightforward evaluation of reported systematic reviews [43].

The data collection was conducted using three primary databases, namely Scopus, Web of Science (WoS), and EBSCOhost. The important parts of this systematic review were (a) eligibility and exclusion criteria, (b) identification review, (c) screening, (d) eligibility, and (e) data abstraction and analysis, according to PRISMA principles [44]. Scopus is Elsevier's database of abstracts and citations for peer-reviewed literature, which includes 34,346 journals from 11,678 publishers from all over the globe. WoS is a powerful database maintained by Clarivate Analytics that comprises 12,000 high-impact journals and 160,000 conference proceedings. There are over other 256 disciplines in science, social science, the humanities, the arts, and cross-disciplinary topics that it supports. The impact assessments, availability of open-access journals, and whether the database covers numerous academic fields are also criteria in the selection process. Scopus and WoS complement one another in terms of journal coverage [45]. According to [46], the search process by researchers should include more databases to increase the probability of finding relevant articles. Thus, this study also used the EBSCOhost database to search for articles related to STEM PD.

The systematic review process for the selection of relevant articles in this study comprised three main stages, as illustrated in Figure 1. The first stage was to identify keywords, followed by finding relevant and similar terms from a thesaurus, dictionary, encyclopedia, and previous research. After selecting all relevant terms, search strings for the Scopus, WoS, and EBSCOhost databases were created in September 2021 (Table 1). Database searching of similar keywords was also conducted on EBSCOhost.

All of the selected articles were screened by the first researcher by choosing the criteria for article selection, which was performed automatically using the sorting function in the databases. The selection criteria were based on the research questions [47]. In the second step, 270 papers were screened using the researchers' inclusion and exclusion criteria. The type of literature was the first criteria. Because indexed journals (research papers) constitute the primary source of empirical data, the researchers decided to focus their efforts on them. This study did not include systematic reviews, reviews, meta-analyses, meta-syntheses, books, book series, book chapters, or conference proceedings. According to [48], researchers should determine the time period to be reviewed. Therefore, the timeline between 2017 and 2021 was selected as one of the inclusion criteria. Only articles published in English were included in this review so that confusion due to translation could be avoided. At this step, the process rejected 210 items because the inclusion criteria did not match, in addition to 11 duplicate articles. In the final step, the remaining 49 articles were assessed for eligibility (Table 2).

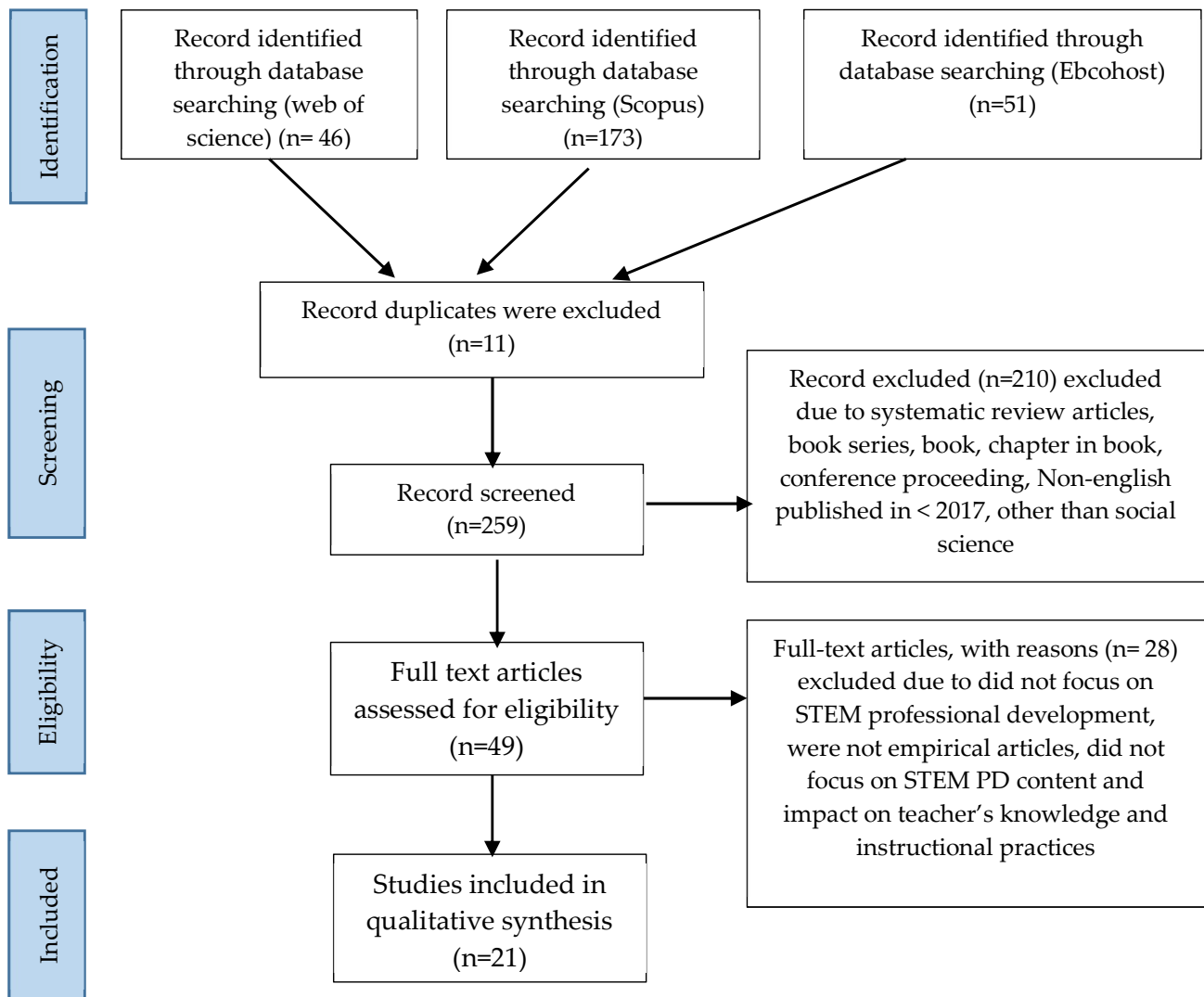


Figure 1. PRISMA flow diagram [44].

Table 1. The search string.

Database Search String	
WoS	TS = (“STEM professional development” OR “teacher professional development”) AND (“syllabus” OR “programme” OR “activity” OR “activities” OR “content” OR “programing” OR “program” OR “programs” OR “programmed” OR “format”) AND (“teacher” OR “science teacher” OR “mathematics teacher” OR “STEM teacher”) AND (“challenge” OR “challenging” OR “challenges” OR “obstacles”) AND (“impact” OR “impacts” OR “effect” OR “effective” OR “effectiveness”))
Scopus	TITLE-ABS-KEY (“STEM professional development” OR “teacher professional development”) AND (“syllabus” OR “programme” OR “activity” OR “activities” OR “content” OR “programing” OR “program” OR “programs” OR “programmed” OR “format”) AND (“teacher” OR “science teacher” OR “mathematics”))
EBSCOhost	STEM professional development AND STEM teachers AND (impact or effect or influence or outcome or result or consequence)

Table 2. The inclusion and exclusion criteria.

Criteria	Eligibility	Exclusion
Literature type	Journal (research type)	Journals (systematic review), book series, book, chapter in book, conference proceeding
Language	English	Non-English
Timeline	Between 2017 and 2021	<2017
Subject area	Social Science, STEM education, Teacher professional development	Other than Social Science, STEM education, Teacher professional development

The researchers manually assessed the remaining articles at the eligibility stage to verify that they met the inclusion criteria to meet the goals of this study. The process was completed by screening the title, abstract, and main contents of the articles. After reviewing the required material, 28 articles were eliminated because they were not empirical or did not concentrate on STEM PD activities or their impact on teachers' knowledge or instructional practices. To select acceptable themes and subthemes, data were taken from the 21 articles that were kept. Themes connected to STEM PD were discovered via qualitative content analysis. Following that, the researchers organized subthemes around the typology's key themes. The results of prior investigations were identified using thematic analysis, which included grouping subthemes according to similarities or significance and classifying them [49].

For quality assessment, all 21 articles were read and coded by the first researcher with the other co-researchers. The papers were randomly coded, and the results were compared to see whether there were any irregularities in the coding process. When discrepancies were discovered, the researchers addressed them, and all of the articles in question were coded and updated to assure uniformity. Consensus agreement among the researchers was also achieved by turning to the opinions of a co-researcher, a STEM specialist, to perform quality evaluation, which is an important step [48].

On the basis of thematic analysis, the procedures of establishing relevant topics and subthemes were carried out. The data collection phase was the initial step in the theme creation process. The researchers carefully examined the selected publications in this step to obtain statements or data that addressed the study topics. Following that, in the second step, the authors used a coding approach to establish meaningful categories based on the data's nature. In other words, the second step converts unusable data into useful data by discovering themes, concepts, or ideas that may be utilized to produce additionally connected and related data [50,51]. Finally, the approach yielded two major themes. Then, in each of the established themes, the process was resumed, with any connected themes, concepts, or ideas being developed as subthemes inside that developed subject. As a result of this extra phase, the researchers identified a total of 16 subthemes. Within the scope of this review, the first author cooperated with the other co-researchers to generate themes based on the results, and a record was maintained throughout the data analysis process to capture any analyses, thoughts, riddles, or other ideas relevant to the data interpretation. The researchers also compared their data to see if there were any differences in the theme generation process, and if there were any, the researchers discussed them with one another. Finally, the produced themes and subthemes were adjusted to ensure that they were all consistent. Expert evaluations were conducted by a total of two experts, one in the field of systematic literature review and the other in the field of STEM, in order to ensure that the themes and subthemes were valid. By ensuring domain validity, the expert review process ensured the clarity, relevance, and appropriateness of each subtheme within its respective theme. Adjustments were made based on the researchers' judgment and the advice and comments of the experts. The study team and the researchers agreed on the themes and subthemes after considering the second viewpoint of the experts and revising the coding.

4. Results

Through the above-mentioned systematic revision process, the results in this section were organized to answer the first and second research questions according to the number of articles by year and the research method used. The search and analysis were guided by the research questions. Of the 21 research studies, two of them were published in 2021, five in 2020, seven in 2019, two in 2018, and five in 2017. The researchers determined that nine studies used a qualitative method, three applied a quantitative approach, and nine employed mixed methods, as shown in Table 3.

Table 3. The themes and subthemes of STEM PD.

Authors	Activities										Impacts					
	EG	CT	IBL	PBL	PO	MD	ID	IS	TC	SE	DS	CU	PCK	IQ	CT	ID
Dyehouse et al. (2018)	✓					✓		✓		✓	✓					
Biddy et al. (2021)		✓									✓					
Nesmith and Cooper (2019)	✓												✓			
Ong et al. (2020)			✓											✓		
Havice et al. (2018)	✓			✓	✓						✓					
Rich et al. (2017)	✓												✓	✓		
Li et al. (2019)		✓													✓	
Aldahmash et al. (2019)								✓		✓						
Alsalamy et al. (2017)	✓															✓
Baker and Galanti (2017)				✓				✓		✓						
Du et al. (2019)					✓			✓		✓						
Shernoff et al. (2017)	✓				✓							✓		✓		
Lasica et al. (2020)							✓		✓			✓		✓		✓
Humble et al. (2020)		✓													✓	
Christian et al. (2021)	✓												✓			
Maass and Engeln (2019)			✓											✓		
Williams et al. (2019)	✓		✓										✓			
Estapa & Tank (2017)	✓									✓			✓			
Kelley et al. (2020)	✓		✓							✓						
Mangiante and Gabriele-Black (2020)	✓										✓		✓			
Johnston et al. (2019)	✓									✓	✓		✓			

EG = Engineering based. CT = Computational thinking. IBL = Inquiry-based learning. PBL = Problem-based learning. PO = Project-based learning. MD = Modelling. ID = Interdisciplinary subjects. IS = Integrated STEM. SE = Self-efficacy. DS = Designing ability. CU = Conceptual understanding. PCK = Pedagogical content knowledge related to engineering fields. IQ = Inquiry skills. CT = Computational thinking. ID = Interdisciplinary teaching approach. TC = Technology based.

4.1. Activity of STEM PD

Based on the thematic analysis, the activities conducted during STEM PD consisted of nine subthemes: Engineering-Based, computational thinking (CT), inquiry-based learning, problem-based learning, project-based learning, modeling, interdisciplinary subjects, integrated STEM, and technology-based activities.

4.1.1. Engineering-Based

Twelve studies focused on activities that were based on engineering tasks or the engineering design process [52–63]. One STEM PD program’s activity involved exposure to the work of scientists, namely investigating, building models, and studying natural phenomena, as stated in [56]. The content included engineering-based activities that provide an authentic experience in engineering and research, allowing for teacher classroom application. Similarly, ref. [53] stated that teachers gained experience in engineering principles through investigating and studying natural phenomena. The modules for the activities discuss the core ideas of the discipline, crosscutting concepts, science and engineering practices through theory-based instruction and discussions, hands-on assignments, and

collaborative assessment design. It is important to note is that the activities involved problem identification, the application of design thinking through a scientific approach, and the determination of limitations and criteria for technological solutions. The engineering-based activities also emphasized the engineering design process, which involves numerous phases when designing a solution, as stated in [52,62]. These studies described the engineering design process as a five-step process to design prototypes and solve problems, namely: ask, imagine, plan, create, and improve. The five-step description of the engineering design process was also mentioned in a project by [55], namely the project curriculum module, focusing on designing and building a hemodialysis system. The activities revealed the role of applied science, mathematics, and technology in authentic engineering problems.

In a study by [60], the STEM PD activities provided scientific inquiry instruction on the pedagogies of engineering design, including engineers' notebook instruction; meanwhile, ref. [61] utilized an engineering curriculum via Engineering is Elementary units consisting of the mechanical engineering unit, catching the wind-geotechnical engineering unit, and landscape evaluation. Both studies, [61] included engineering problem-solving introductory activities so participants could experience the nature of engineering and technology before beginning the respective unit. In addition, refs. [58,63] noted the importance of an interdisciplinary teaching technique incorporating an engineering design-based learning approach with mathematics, science, technology, and engineering education. Ref. [54] utilized the difficulties of hands-on engineering design (with a focus on new engineering practices), modelling activities, and a discussion of major developments in NGSS and problem-based learning to emphasize design-based engineering. Interestingly, engineering talk activities that integrate engineering with science and mathematics content were also included in a study by [59] and enhanced STEM teachers' knowledge of interdisciplinary subjects.

4.1.2. Computational Thinking

The researchers identified three different CT-based activities included in STEM teacher PD as described by [64–66]. Specifically, ref. [66] utilized activities to create lesson plans by integrating CT that involved modeling using Starlogo Nova and a game-based approach using Scratch. Both are agent-based games and simulation programming environments, as stated in [64]. According to [64], one iteration of the CT-Integration Cycle includes teacher learning, planning, implementation, and reflection on a codesigned unit. The teachers' capacity to engage deeply with CT practices grew throughout their participation in the PD, and they thoughtfully facilitated a CT-integrated unit with their students.

Meanwhile, the study by [65] included three exercises, textual programming, block programming, and unplugged programming (programming without the use of a computer), all of which have been proven to have substantial effects in terms of teacher knowledge. This empirical study provided teachers and other stakeholders with practical applications for integrating programming in K-12 education. In addition, all of the studies gave helpful information about teachers' experiences with different programming tools.

4.1.3. Inquiry Based Learning

There were three types of STEM teacher PD activities focusing on inquiry-based learning [15,60,67]. For example, ref. [15] listed activities using a STEM-based 5E inquiry learning model involving engagement, exploration, explanation, elaboration, and evaluation using the context of an electric circuit. Interestingly, ref. [15] argued that the activities also involved participants in the process of predicting whether the torchlight bulb would switch on or not for each circuit, testing if their predictions were correct, and understanding the electric circuit-based on experiments they conducted. Additional materials were provided, and participants were required to complete the construction of the torchlight using knowledge gained during the activities. These investigative and exploratory activities encouraged participants to be part of the ongoing process of scientific inquiry, as outlined by [60]. STEM teacher PD involves scientific inquiry consisting of prompt investigations designed to utilize prior scientific knowledge, acquire new knowledge, and find ways

to solve new problems with the application of knowledge [60]. Furthermore, teachers in fields related to science and engineering technology were taught fundamental entomology concepts, such as food webs, aquatic habitats, adaptations, and evolution. The activities involved the development of fishing lure prototypes to imitate an identified aquatic insect as fish bait (bluegill or bass). Specifically, the teachers drew their selected insects using computer aided design (CAD) software, used the drawings to design split molds for soft plastic lures, and tested the designs using standard fishing poles. These inquiry-based activities provided meaningful learning experiences for teachers in building their knowledge and skills in STEM [15].

4.1.4. Problem-Based Learning

Refs. [58,68] described two critical activities in STEM teacher PD based on problem-based learning. According to [58], problem-based activities are implemented through an interdisciplinary STEM teaching approach that provides an exemplary model for students to engage in lifelong learning that will impact the larger community. Participants learned how to incorporate problem-based learning that assists students working in groups to develop cross-curriculum skills. The program emphasizes the development of an integrated STEM curriculum in the context of real-world situations. The need for focusing on real-world issues was also addressed in the research [68]. Model-eliciting activities (MEAs) were identified as a medium for STEM integration in the research. MEAs demand that participants conceive, develop, and construct mathematical models for problem solving repeatedly. In addition, teachers can also be exposed to MEAs through activities that require problem solving and a multidisciplinary approach.

4.1.5. Project-Based Learning

The researchers identified three project-based learning activities in STEM PD programs as described by [54,58,69]. The activity highlighted by [54] involved developing and implementing an integrated STEM curriculum unit using a project-based learning approach. The teachers worked collaboratively using project-based learning as the primary focus, along with scientific inquiry, technological design, engineering, and mathematical analysis throughout the activity. The focus on developing curriculum units is similar to the content focus stated in [54]. In this study, teachers developed an NGSS-aligned unit based on project-based learning [54]. Two challenges involving hands-on engineering design (with an emphasis on new engineering practices), an overview of critical shifts in NGSS and project-based learning, a gap analysis to identify disadvantages in existing curricula, a modelling exercise, and the collaborative development of an original NGSS-aligned instructional unit, complete with a concept map and rubric evaluation, were among the highlights of the summer institute. Ref. [58] shared with teachers how to teach integrated STEM through project-based learning and the appropriate tools to implement it in classrooms to enhance student learning.

4.1.6. Modeling

Some modeling activities were focused on in a study by [56]. Scientists use a variety of behaviors when exploring and building models and theories about the natural world, and engineers use a variety of engineering techniques when designing and constructing models and systems. MEAs involve problems that require individuals to apply science and mathematics concepts and practices while using a model-development process. Teacher participants collaborated with training staff and NASA engineers to devise a novel MEA and corresponding 3D model. Subsequently, the participants developed 3D models central to the overall situation explained in the MEAs. The experiences they gained during the modeling activities boosted their learning trajectory.

4.1.7. Interdisciplinary Subjects

Several PDs focused mainly on a single subject, such as mathematics [26,67] or science [70,71]. Only two studies discussed STEM activities that focused on interdisciplinary subjects, based on the analysis. According to [60], using augmented reality (AR) technology, teachers were able to make their topic more interdisciplinary by incorporating instructional information from other fields. A STEM approach proposed by a teacher included teaching the Pythagorean Theorem (mathematics) throughout the course, describing the forces caused by a ladder and a balcony (physics), and guiding students through the process of drawing these forces using a mathematics software program (Geogebra). Many teachers agreed that school management should encourage teachers to engage in PD programs on topics like innovation and new technologies in education. Teachers were stimulated to use AR technology in interdisciplinary ways rather than focusing on their specific disciplines, which is a new component of this study.

4.1.8. Integrated STEM

The analysis showed that there were four types of STEM activities based on integrated STEM, as reported by [68,69,72]. For example, ref. [72] provided activities that focused on theoretical and practical aspects of integrating and implementing STEM lessons in the classroom. Discussions on ideas connected to scientific inquiry, teaching for conceptual comprehension, scientific discourse, contradicting phenomena in science and mathematics instruction, and how instructors monitor science and mathematics courses were among the activities highlighted. Observation and argumentation throughout the activities provided teachers with an authentic learning task framework [56]. The authentic learning task framework included 40+ h of face-to-face training, curriculum development tasks, exposure to real-world engineering problems, discussion with on-site scientists and engineers, and collaboration within peer curriculum development teams. Similarly, ref. [69] found that teacher participants were interested in developing a STEM curriculum. Teachers cooperated to create and implement a new integrated STEM curriculum unit in collaborative grade-level teams focused on problem-based learning and project-based learning as well as scientific inquiry, engineering and technical design, and mathematical analysis. On the other hand, participants in [68] were exposed to an open-ended task that stimulated their thinking through integrated STEM MEAs. These activities included realistic challenges, open-ended exercises, higher-order thinking, metacognitive coaching, self-assessment, self-directed learning, group collaboration, and interdisciplinarity.

4.1.9. Technology-Based

Only one technology-based activity was identified, specifically in [73]. The PD program's activity involved the utilization of contemporary technology and related equipment (i.e., tablets, smartphones, cardboards), and teachers engaged in authentic and collaborative educational exercises. Furthermore, the activity included HP Reveal, Metaverse, ARTutor, Scratch, and Unity, as well as other tools and programs for developing ARLoS in STEM-related courses. The activity provided teachers with great exposure to authentic collaborative educational exercises. AR visualizations, open-ended explorations, cooperation, and reflection on one's own and others' ideas and experiences as well as the creation of a learning environment were some of the teaching techniques employed throughout the program. Participating teachers' grasp of STEM, AR-supported teaching, and interdisciplinarity enhanced as a result of this activity. Furthermore, the learning environment acted as a model for teachers to use in their classrooms regarding learning situations, curricula, and emerging technologies.

4.2. *The Impacts of the STEM PD on Teachers' Knowledge and Instructional Practices*

The impacts of STEM PD on teachers' knowledge and teaching practices contained seven subthemes: self-efficacy, designing ability, conceptual understanding, pedagogical

content knowledge related to engineering fields, inquiry skills, CT, and an interdisciplinary teaching approach.

4.2.1. Self-Efficacy

STEM PD should promote a deep understanding of the subject matter and focus on the best pedagogical practices of integrated STEM [54,55,57,58,68,69,72]. According to [61], the activities implemented through STEM PD impacted teachers' self-efficacy in STEM education. Therefore, the attitudes and interest of teachers in teaching can be enhanced via their involvement in integrated STEM PD using this approach [57]. Researchers found that teachers could guide their students confidently when the knowledge and skills in the STEM context they learned were transferred into action and they were able to solve problems they faced [60,69]. Specifically, ref. [60] mentioned that teachers reinforced their self-efficacy by implementing integrated STEM lessons in the classroom. These activities indirectly helped teachers connect ideas across disciplines, develop a method for unsiloing STEM content, and work towards a more integrated approach while supporting teachers' needs to develop pedagogy and content in STEM [57].

4.2.2. Designing Ability

Teachers also benefit from STEM PD by improving their designing ability through constructing explanations (for science) and designing solutions (for engineering). In two studies, [56,64], researchers discussed the impact of design skills on STEM teachers. According to [56], the teachers were faced with the challenge of developing MEAs and 3D design tasks. They made some modifications during the integrated curriculum, went through all the designs and tests, and ensured that the problem could be solved by arriving at a final model solution. According to [64], the teachers were not only exposed to collaborative design (codesign) and the problem-solving cycle, in which teachers cycle between preparing, teaching, and reflecting iteratively, but they were also exposed to how to design storylines, plan for and analyze lessons, and codesign, implement, and reflect on how science and CT can complement each other in the school curriculum and classroom instruction. As an essential component of developing both storylines and their associated lessons and classroom resources, the designing process incorporates teachers' ideas and expertise. As a result, the process ensures that the resulting units are both feasible and appropriate for teachers to implement within their local school contexts.

4.2.3. Conceptual Understanding

STEM PD can also affect teachers' conceptual understanding [54]. Most of the teachers who participated in STEM professional training obtained knowledge and understanding of the concepts of project-based learning and NGSS [54]. Buoyancy (including the difference between positive, negative, and neutral buoyancy), density, and force balancing concepts were all employed by the participants [54]. They also found the value of previous knowledge and cooperative teamwork (e.g., the concept of density). During the iterative trial-and-error design process, they faced both inventive and creative ideas as well as frustration. This suggests that instructors may reinforce conceptual understanding, although the findings are similar to those supported by educational psychology research, which is commonly described as research on learning, teaching, and related cognitive, emotional, and behavioral elements.

4.2.4. Pedagogical Content Knowledge Related to Engineering Fields

STEM PD activities in engineering areas, such as engineering tasks, engineering practices, and engineering design, have had a substantial influence on teachers' pedagogical subject understanding, self-efficacy and confidence level, engineering work, and engineering practices. All of the engineering efficacy components are equally important in assisting teachers to become confident in their own views about their skills to favorably influence students' engineering learning [53,55,57,59,61–63]. According to [59], the participants used

“engineering speak” to explain how to apply the great engineering concepts taught in the NGSS. They also went beyond the NGSS principles and practices to present engineering and to demonstrate how engineers solve issues to their pupils by including additional engineering practices such as ethical thinking and teamwork. Engineering discussion activities were also utilized by teachers to connect science, mathematics, and technology. This approach indirectly encouraged students to utilize their communication skills, including writing in a notebook and engaging in team interactions through balancing multiple ideas for their design solution. All of the activities were able to increase teachers’ knowledge of engineering design pedagogies as well as to provide them with experience, confidence, and self-efficacy in teaching new (engineering) content to their students [53,55,62,63]. Teachers’ professional abilities in identifying and reacting to students’ engineering design thinking, making sense of students’ ideas, and engaging in engineering-design decision-making improved as a result of engineering practices [48]. Through engineering design activities, teachers also identified STEM content connections that could be implemented within an engineering design activity. Engineering practices also indirectly assisted teachers in implementing an integrated approach [44]. In the long run, STEM PD can enable teachers to increase student interest and aptitude for STEM-related careers, particularly within the engineering field.

4.2.5. Inquiry Skills

In studies conducted by [15,54], researchers explained the effect of the inquiry teaching method. According to [15], among the benefits gained were lessons that included expanded, enhanced, and sustained inquiry in a series of discovery-based activities. Teachers also used an inquiry-based learning approach and increased the exploratory nature of the activities. Through STEM PD, teachers strengthened their knowledge of concepts of STEM education, teaching to understand the concept of scientific discourse, scientific inquiry, and discrepant phenomena in science and mathematics education. In addition, teachers also enriched the pedagogical skills of STEM-based inquiry learning and managed the classroom well with collaborative learning. According to [54], the activities also helped to keep teachers interested in a series of discovery-based activities that looked at their motivating questions. Teachers were also shown how lesson plans may improve by devoting more time to inquiry in the framework of more comprehensive research inspired by a genuine, real-world topic. Furthermore, the PD programs aided in the transition from teacher-centered to student-centered or inquiry-based teaching.

4.2.6. Computational Thinking

Throughout the STEM PD activities described by [65,66], teachers found that connecting programming to other tasks was simple, which is linked to the expectation of pupils getting help in developing other abilities such as problem solving, creativity, cooperation, reasoning, and CT. These researchers believed these STEM PDs equipped teachers with the content and pedagogical knowledge related to CT integration that helped them learn computational skills. Ref. [66] argued that teachers with no experience in computer science were also exposed to concrete examples of CT from day-to-day life and considered blending CT with different subjects. Indirectly, the process exposed teachers to student-centered learning strategies such as multidisciplinary approaches. STEM PD also helped teachers connect programming to other school-based activities, such as logic and problem solving [65].

4.2.7. Interdisciplinary Teaching Approach

In studies conducted by [52,73], researchers explained the effect of the interdisciplinary teaching method. Based on the study by [52], the interdisciplinary unit was taught to students by teachers in their classrooms. The teacher delivered 12–15 weeks of interdisciplinary teaching on a design problem unit covering a variety of STEM subjects. The activities also exposed teachers to interdisciplinary STEM “ideology”, encouraging various teaching strategies and teamwork. According to [52], teachers collaborated with other

colleagues to produce interdisciplinary learning plans. Meanwhile, ref. [73] reported that teachers were introduced to incorporating AR technology in their classrooms, either in conjunction with other teachers (interdisciplinary approach) or as part of their STEM-related topics. Some teachers further suggested that with AR technology, they might make their topic more multidisciplinary by incorporating instructional information from other fields. Both studies affirmed that teachers were exposed to applying interdisciplinary approaches instead of focusing on a single subject. These activities prepared teachers to shift to interdisciplinary teaching by developing essential knowledge, skills, and attitudes toward a STEM-integrated curriculum. Teachers' PD is seen as a critical component in assisting them in making these kinds of changes. Researchers should explain their findings and how they might be interpreted considering previous research and the working hypothesis. The findings and their consequences should be stated in the broadest sense possible. Future research directions might also be included.

Along the same lines, ref. [69] pointed out the impact of a three-year-long sustained STEM PD that included the design of the lesson, lesson implementation, mathematics/science content, and classroom culture. Ref. [69] discovered that teachers who participated in STEM PD improved their STEM teaching skills and adopted a more student-centered approach that encouraged student discourse and exhibited concern for students' access, equity, and diversity issues. They were also able to add real-world connections to their integrated STEM curriculum courses, which led to a better teaching environment.

5. Discussion

A summary of the findings of this study would be that integrated STEM teacher PD possesses some unique challenges from those generally presented by single-discipline programs [14,20]. The use of a cohesive conceptual framework to structure PD experiences may enhance teacher experiences and increase the possibility that the PD will impact teacher professional practices [74]. A comprehensive review sourced from three databases resulted in 21 STEM PD-related articles across different countries. Results demonstrated the diversity of STEM PD activities affecting teachers' knowledge and instructional practices. The scope of this study led to nine subthemes for STEM PD activities and seven subthemes for effects or implications on teachers' knowledge and instructional practices. Activities of STEM teacher PD that are coherent and appropriate can enhance teachers' knowledge, experience, and professional practices. Teachers should improve STEM content knowledge impacting various variables that would influence their practices. Teachers may need PD that attends to STEM knowledge at multiple stages in their careers [75]. Interestingly, STEM PD that includes engineering-based activities can enhance teachers' understanding of integrated STEM implementation [52–63].

Integrated STEM education should incorporate engineering design of relevant technologies and compelling goals in order to foster problem-solving ability, creativity, and higher-order thinking capabilities. This can also involve engineering thinking, technological advancement, and technology reverse engineering [76]. Through the implementation of the engineering design process, STEM becomes a pedagogical architecture that enables engineering design to drive learning across the four STEM disciplines. This is one possible paradigm for assisting students in integrating material and practices from all STEM disciplines [77]. Engineering components are highlighted in the process, and the design of the solutions is compared to the solution. Teachers' exposure to engineering tasks, activities, and engineering design processes can indirectly encourage students to be active in their learning by developing engineering habits, namely system thinking, optimism, creativity, communication, collaboration, and attention to ethical considerations [78]. In addition, experienced STEM teachers would help students successfully integrate the four STEM disciplines [77,79,80]. Although integration of STEM activities is considered difficult and teachers need a strong understanding of the integrated content, teachers can increase their disciplinary knowledge within STEM through activities implemented in PD programs. Engineering-based activities also provide teachers with experience using

engineering practices as a stimulator for integrated STEM [59,69]. Ref. [68] added that STEM integration indirectly made teachers engage in iterative engineering and design as well as scientific reasoning to create and recreate shelters that fulfil client constraints. Using these activities, teachers learned about open-ended, client-driven, real-world mathematics and the engineering design process, according to [56], which is what they did.

Repetitive activities and practices can represent the engineering design process at each design stage, such as solution planning, implementation, testing, and evaluation [81]. This practice, in turn, can provide a real-world context for the teaching of mathematics and science through the engineering design process [82]. Some researchers also have perceived engineering as an essential tool for integrating science, technology, and mathematics [83]. Engineering-based activities can expose teachers to critical parts of the engineering design process: engineering thinking (thinking like an engineer), creativity, innovation, communication, and systems thinking. Teachers can wisely guide students to manage risk, learn from failure, develop and use technology, and consider previous experiences. The engineering design process combined with thinking like an engineer allows students to become reflective independent thinkers who can combine ideas to solve problems [79,84–86].

STEM PD content that focuses on inquiry-based learning can provide teachers with experience with scientific inquiry, which refers to the thinking practices used by scientists to answer questions about natural phenomena. Scientists use various approaches to study the natural world, making suggestions based on the evidence obtained from research studies and observations. Notably, inquiry-based activities allow teachers to guide students to build knowledge and understanding of scientific ideas performed by scientists in a real-world context [87]. The application of inquiry processes, 21st-century skills, critical thinking, creativity and innovation, problem solving, and a strong focus on disciplinary knowledge allows for an improvement in the understanding of concepts and processes in integrated STEM education [88,89]. Disclosure of inquiry-based activities in STEM PD provides an opportunity for teachers to support the development of a deeper understanding of STEM by engaging in hands-on, inquiry-based activities.

Nevertheless, changing classroom behavior procedures is easier to achieve than improving content knowledge or inquiry oriented instruction techniques. Thus, STEM PD that focuses on inquiry-based activities [75] can indirectly provide opportunities for teachers to design problem-based instruction, which in turn guides students to solve STEM-related problems. The inquiry approach is also one of the teaching approaches that can cultivate high-level thinking skills and is suitable for STEM subjects, especially science and mathematics. In relation, when teachers emphasize thinking skills, students are capable of thinking and communicating scientifically, which is essential to having students who are competitively competent at the international level [90]. STEM PD that features project- and problem-based activities can provide essential skills that place an individual in a meaningful learning situation emphasizing solutions to problems drawn from actual cases [91]. The meaningful learning process can bridge the theory and the real world and boost the individual's conception of STEM integration. Moreover, it can encourage subject integration and application [92,93]. The evidence suggests that, when implemented qualitatively, inquiry-oriented instruction has a meaningful effect on student learning. The challenge lies in designing sustainable PD that fosters this type of instruction effectively [94].

An integrated STEM approach is necessary to address global and local challenges and support success in careers in the 21st century and those anticipated in the future [76]. Thus, STEM teacher PD needs to provide an appropriate training framework to ensure that competent and knowledgeable teachers can guide students to understand the basics in each STEM discipline. Our daily challenges are multidisciplinary, and most require the integration of multiple STEM concepts as a problem-solving method. Teachers must expose students to project-based and problem-based learning problems in order to implement meaningful learning, and integrated STEM education should embrace standards-based mathematics and science objectives in learning activities [76]. Since the beginning of the 21st century, the importance of problem-based learning and project-based learning in

STEM has received greater attention. A good PD program may help teachers develop the pedagogical abilities they need to implement STEM project-based learning. Understanding how to execute successful STEM project-based learning has a significant impact on teachers' teaching approaches as well as students' overall learning experience. In-service teachers should be informed about successful pedagogical techniques for implementing project-based learning activities, as well as mentored in the design and execution of STEM project-based learning classes, preferably via persistent PD [95,96]. The STEM project design process has a favorable impact on 21st-century teachers' skills and abilities, integrated STEM teaching objectives, and STEM attitude. As a result, teachers may be taught a variety of skills and abilities, increasing their willingness and positive attitudes about incorporating STEM into their professional life [97]. For example, engaging in engineering activities supports teachers in problem solving, project design, and design solutions, including engineering thinking, technological progress, and reverse engineering of technologies [76].

On the other hand, the modeling activities emphasized in STEM PD can foster an integrated and authentic STEM education and STEM literacy [98]. According to [56], the PD framework for implementing modeling activities, such as MEAs and developing 3D models, that related to current aerospace research enabled participants to produce an additional 19 aerospace themed MEAs. These activities indirectly exposed participants to real-world engineering problems, discussion with on-site scientists and engineers, and collaboration within peer curriculum development teams [56].

6. Conclusions

The aim of this study was to systematically review STEM PD activities and their impact on knowledge and instructional practices. The results of the study offer several imperative contributions to the body of knowledge and practice. From the review, STEM PD activities that are engineering-based, inquiry-based, problem-based, project-based, or technology-based or include modeling or integrated STEM affect teachers' knowledge and practices. Through such activities, teachers can profoundly enhance their understanding of the concept of integrated STEM and improve their understanding of each STEM discipline. Teachers can also improve their teaching practices by employing various teaching methods, such as problem-based learning, project-based learning, design, and interdisciplinary teaching approaches. These findings also place responsibility with multiple stakeholders, such as teachers, administrators, higher education institutions, and the community, with regard to formulating appropriate PD activities that improve teacher professionalism in the education field, especially STEM. STEM PD developers and organizers need to consider content that can increase teacher knowledge and provide ample time for teachers to adapt the content presented. The findings also suggest that STEM PD be analyzed for its long-term impacts on students and the community. Continuous reflection and evaluation are needed during and after a PD program to ensure that such knowledge can be expanded into the classroom and benefit other colleagues [37]. A continuous evaluation of a PD program offers data to the designers and instructors, allowing them to make necessary changes.

Though research on integrated STEM PD is limited, STEM PD needs to implement integrated STEM-oriented activities to ensure that teachers can make conceptual connections within and across STEM disciplines. Thus, an effective teacher PD in the STEM disciplines is able to focus on the development of teachers' subject-matter content and pedagogical knowledge, address the needs of teachers in their classroom context, and provide sustained iterative opportunities, as learning over time is strongly needed. For example, mathematics has historically been taught in a silo. Teachers might only view the integration of mathematics in STEM education as a supporting role, such as when students compute, create data displays, or use measurement tools [99]. STEM PD content also requires a focus on interdisciplinary activities and integration with various STEM disciplines, such as technology, computing, and programming. The lack of content knowledge across STEM fields and teachers' limited design, technology, and engineering knowledge may also cause barriers to implementing STEM education [14]. Thus, STEM PD content, format, and activities

should focus on integrated STEM as an approach to teaching and learning so that students and teachers know when and how to apply knowledge and practices from various STEM disciplines. It is hoped that such knowledge application will allow students to develop a deeper understanding of STEM concepts and processes and their interrelatedness [100].

STEM PD program developers need to collaborate with various parties, especially stakeholders (industry, community), ensuring teachers and curriculum builders can interact with experts in the STEM fields, such as engineers and scientists in research settings [56]. The content of STEM PD should reflect real-world concepts and provide teacher participants with a genuine STEM experience or situation to demonstrate open-ended problem-solving skills in a real-world context [56]. The resources and duration of each program must be appropriate to the content to be conveyed. Participants require time to understand the knowledge learned and opportunities to apply and explore. This process is crucial to ensure that they master the knowledge learned and allocate ample time for collaborative efforts among all program participants, especially near the beginning of the program [15,66,72]. It is recommended that PD content have at least one or more authentic features [56]. Content knowledge usually needs to incorporate conceptual and exploratory STEM disciplines in STEM education. When teachers understand the way students learn, then teachers can modify the teaching environment to support student learning in a better direction [37]. STEM PD also needs to be extended to schools for continuous implementation to allow teachers and school administrators to collaborate on a larger scale and produce appropriate PD models suitable to be widely implemented in schools and communities. This also provides stakeholders with opportunities to develop a shared passion to prepare students with meaningful ways to solve real-world challenges [52,58,72].

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