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REVIEW ARTICLE

Put two and two together: A systematic review of combining computational thinking and project-based learning in STEM classrooms

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ABSTRACT

Burgeoning academic research has been devoted to the study of computational thinking (CT). Yet, it has not been widely practiced and applied in K-12 education. In the meantime, scholars and educators anticipate project-based learning (PBL) to help integrate CT into Science, Technology, Engineering, and Mathematics (STEM) classrooms because PBL is one of the most adaptive pedagogies to integrate multidisciplinary skills. For this reason, we systematically combed through the basics of project-based STEM classrooms at the K-12 level that incorporate CT. We found that a high-quality and interdisciplinary CT curriculum is very demanding for teachers' versatile expertise (input side), yet such curriculums are not always in high demand by K-12 schools, which often anticipate narrowly defined teaching/learning objectives (output side). This ultimately creates a perceived "educational deficit" that may explain the absence of CT at the K-12 educational level.

Key words: computational thinking, project-based learning, STEM + CT, K-12

INTRODUCTION

People compute, or think computationally to solve problems, whereas problem-solving is one of the ultimate goals in Science, Technology, Engineering, and Mathematics (STEM) education—cultivating the next generation of problem solvers (Wing & Computational, 2006; Wing, 2008; Wang et al., 2021; Weintrop et al., 2015). The central role of problem-solving highlights its unique position and function in applying computational thinking (CT) to STEM education (Jocius et al., 2021; Swaid, 2015). Indeed, recent literature in CT has observed a trend from separating CT as a distinct skillset to integrating it with interdisciplinary ideas (Li et al., 2020), partially thanks to the catalysis of problem-solving-oriented pedagogies (*e.g.*, project-based learning [PBL]) (Wang et al., 2021; Edmunds et al., 2017; Ching et al., 2019; Hsieh et al., 2022).

Yet, this catalytic process is not without challenges (Hurt et al., 2023; Lye & Koh, 2014). Teachers lack professional support in developing high-quality CT courses and subsequently supply CT curriculums that are misaligned with K-12 classroom objectives and demands (Kafai & Proctor, 2021). As a result, we often hear the call for an organic integration of CT into STEM education but do not see real-life practices that often. In this study, we examined the relevant studies that have been published in the Web of Science from January 2016 to April 2023 and synthesized two research directions, CT-STEM and PBL-STEM, to systematically investigate the current implementation of CT in PBL-STEM curricula in K-12 education. In addition, we also focus on the challenges that teachers encounter in the process on the other. Collecting information from current studies to analyze differences in teachers' demand and curricula's demand provides policymakers and schools with recommendations for improvement and then supports the

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diversification of project-based STEM and the professional development of teachers.

BACKGROUND OF THE RESEARCH

CT

The concept of CT was first referenced by Papert and Harel (1991) as "procedural thinking", later Wing and Computational (2006) adopted the term "computational thinking" in his article, which has been widely used by scholars. Wing and Computational (2006) defined CT as an approach to thinking and analysis, which incorporates problem-solving, designing systems, and understanding human behavior. He considers that CT is a basic skill for everyone, not just for those people who work with computers. As the theory has developed, the definition of CT has become more refined. Currently, CT is an important method for analyzing and problem-solving, and this process of cognition and thinking generally includes elements of reformulation, recursion, abstraction, decomposition, and testing (or debugging) (Shute et al., 2017). Of these, abstraction is the essence of CT (Wing, 2008). It is a process of finding relationships among information, in which the detail of information needs to be distinguished, retained, and removed.

It is worth noting that CT originated from computer science (Wing & Computational, 2006; Shute et al., 2017), but the integration is not limited to computers (programming) or robotics. Unplugged activities are also capable of implementing CT in subjects other than computer science, such as biology, chemistry, and mathematics (Swaid, 2015). In other words, CT is everywhere (Wing & Computational, 2006; Wing, 2008). Therefore, this review will also focus on those subject areas outside of computer science and explore the situation of unplugged tools in CT courses.

Project-based STEM

STEM is an acronym for Science, Technology, Engineering and Mathematics, proposed by the National Science Foundation (NSF) in the 1990s. STEM was proposed to solve complex scientific and technological problems in the real world (Purzer et al., 2014; Kelley & Knowles, 2016; Hobbs et al., 2018), design high-quality products, develop learners' ability to respond to the challenges of future societies, and enhance the nation's economy to maintain its prosperity and competitiveness (Smith & Karr-Kidwell, 2000; McDonald, 2016; Sari et al., 2018; Pawilen et al., 2019). There are many different interdisciplinary integration approaches worldwide, and the most common ones include problem-based learning, PBL, inquiry-based learning, as well as design and make. After decades of research and practice, scholars and educators have reached a consensus that PBL is the most appropriate pedagogy for STEM education since other pedagogies can also be supported in the PBL framework (Lou et al., 2017; Souza et al., 2019; Yang et al., 2020).

There is no single, unified definition of PBL, three of them are widely accepted by scholars and educators. Tal et al. (2006) provide one of the most comprehensive and earliest definitions of PBL, they described PBL as a process in which students participate in authentic inquiry through an authentic driving problem, engage in collaborative work, communicate, and find solutions, and finally create an artifact to show their understandings. Holm (2011) defines PBL as a student-centered instruction with which real-world problems or authentic challenges are answered over an extended period by planning, investigating, making products, and presenting. Buck Institute for Education (PBLWorks), a head organization that promotes and implements PBL, considers PBL to be "a teaching method by means of which students gain knowledge and skills through working for an extended period to investigate and respond to an authentic, engaging, and complex question, problem, or challenge". Overall, PBL is a student-centered and interdisciplinary pedagogical approach that encourages students solve a real-world problem over a long period (Souza et al., 2019; Capraro & Slough, 2013; Han et al., 2015; Chiu, 2020).

The pedagogy of PBL fits well with the interdisciplinary nature of STEM education, which creates opportunities for students to face and solve complex real-world problems (Capraro & Slough, 2013; Larson et al., 2018). In the process, they use multiple subjects' knowledge (Han et al., 2014), resort to the power of the team, and conduct in-depth investigations under self-guidance, which would develop their high-order skills (Larson et al., 2018; Barak & Dori, 2009; Thuan, 2018).

To clarify the scope of this research, the following is the definition of project-based STEM in this review: STEM education comes in different forms: some schools offer STEM as a compulsory subject, some set it as after-school clubs and summer schools, and some teachers use the concept of STEM in single-subject classrooms. This paper, therefore, defines STEM as a formal or informal classroom where teachers use interdisciplinary knowledge to design lessons and where students can practice their ability to integrate knowledge from different disciplines. PBL refers to students working in groups to solve a real-life problem, with the project lasting for a certain period.

Theoretical framework

Angeli and Giannakos's five-step research plan for CT education was employed as the theoretical framework of this paper (Angeli & Giannakos, 2020). This framework identified research directions for the five areas of challenges in CT education, as shown in Figure 1.

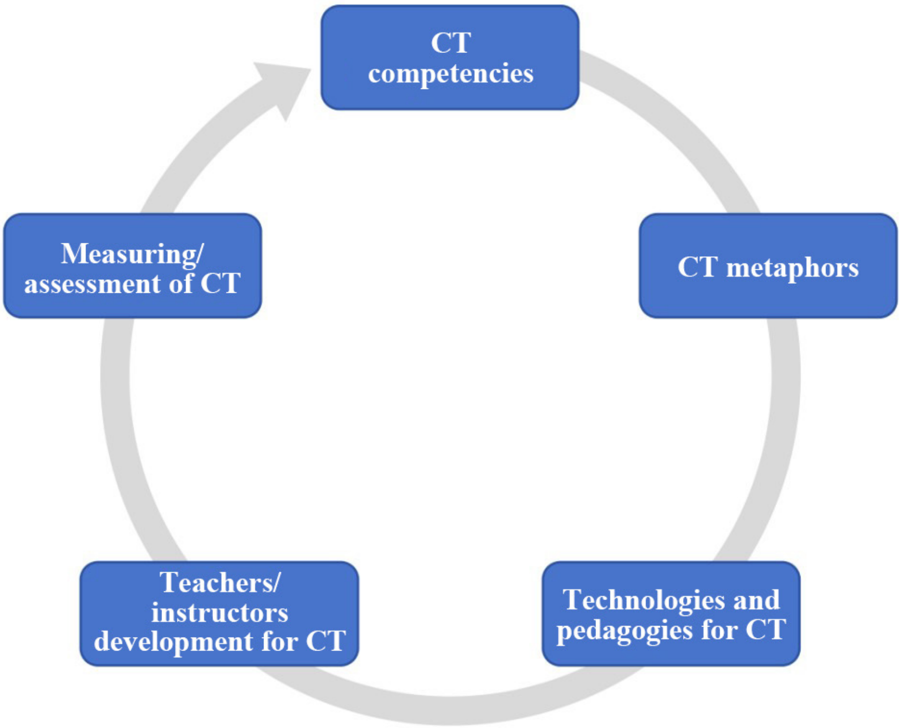

Figure 1. A five-step research plan for CT education. CT, computational thinking.

The first step is to define CT competencies for different grade-level students, considering how CT skills (*e.g.*, abstraction, problem decomposition, and data structures) match up with different abilities, grade levels, subjects, genders, and education levels. The second step is to effectively teach CT concepts to students and teachers leveraging metaphors. For example, Manches et al. (2020) and Pérez-Marín et al. (2020) found that utilizing learner-centered metaphors enhanced students' understanding and learning of CT concepts. Third, the use of pedagogical strategies and technologies in teaching CT. Several studies have pointed out the importance of leveraging appropriate instructional strategies and tools to support students' learning while engaging in CT activities (Papavlasopoulou et al., 2019; Angeli & Valanides, 2020). For instance, the increasing availability of student-friendly programming (*e.g.*, Scratch, Kodu, and BlueJay), hardware materials (*e.g.*, 3 dimensions [3D] printers and robots), and other initiatives can be used as a tool to promote CT education (Angeli & Giannakos, 2020). Fourth, teachers' development for CT. To further promote CT education, in-service and pre-service teachers need to be provided with professional development support so that they can be systematically prepared in how to design, teach, and assess CT, as well as how to use technology. The fifth step is the assessment of CT competencies and skills. The way of assessment provides a comprehensive picture of students' mastery of CT skills, which is an area of research that is still in its infancy.

The five-step research plan for CT education is presented in a cyclical format because it is expected that through in-depth research and practice, progress in each area would reinforce each other and continue to evolve over time.

Research questions

CT, as an important problem-solving mindset, has become one of the top educational research topics, and began to show its potential in the K-12 PBL-STEM classrooms (Gong et al., 2023). In this context, understanding the implementation status of CT in K-12 schools, and examining the obstacles encountered in this process is important for the applying CT in K-12 classrooms to leverage its positive and potential impact.

This article aimed to figure out how current PBL-STEM curricula integrate CT, what tools are used to assess and integrate CT, and what challenges are encountered in the integration of CT and PBL-STEM, the following research questions (RQ) were asked. RQ1: In the context of project-based STEM, what are the subject areas, educational levels, and integration objectives when it comes to integrating CT into the classroom? RQ2: What tools or technologies are used in project-based STEM classrooms to promote the integration of CT? RQ3: What assessment content and tools are included when CT is integrated into project-based STEM classrooms? RQ4: What challenges have project-based STEM teachers encountered when integrating CT into their classrooms?

METHODOLOGY

Conceptual framework

This review adapted York Centre for Review and Dissemination systematic reviews and meta-analysis approach (Davis et al., 2014) to guide the comprehensive literature review and elicit research findings. Based on this approach, a visual image of the research steps was developed as shown in Figure 2.

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement was used in the study selection phase (Moher et al., 2009). The screened articles were then coded to extract data that could answer the research questions. In the assessment phase, the quality of the screened articles and extracted data was evaluated. After the relationship was identified, the data was synthesized to answer the research questions, and the results of the analysis were eventually reported.

Search strategy

Based on the research topic, the search strategy was set using key words that included "project-based learning", "STEM education" and "computational thinking" in searching the Web of Science database. The initial search without adding filtering criteria provided 118 articles. However, 62 conference papers were excluded from the initial search results. As a result, 56 documents including journal papers, review papers, online publications, and reprints were screened, which were published from January 2016 to April 2023.

Selection criteria

The selection criteria are shown in Table 1. The PRISMA statement used in the study selection consists of 27 items and a four-phase process (Moher et al., 2009). Figure 3 shows the study selection flow chart of this systematic review. PRISMA ensures consistency and accountability of this paper and serves as a tool to refine the 56 articles screened (Moher et al., 2009), rather than a method used to measure the quality of this systematic review. Based on the research topic and questions, specific criteria were developed to help select relevant articles for this paper.

Data extraction and analysis

Based on the selection criteria, a reading of the titles and abstracts of 56 articles resulted in the rejection of 2 duplicates and 29 papers that were not relevant to the research topic, as shown in Figure 3. After a careful reading of the full content, 12 articles were finally retained for an in-depth systematic review.

Quality assessment

To ensure the quality of the scholarly literature included and its relevance to the research questions, in the later stages of the screening process we assessed the participants, course contexts and teaching contents of the 25 articles in depth. Ultimately, 13 papers were excluded, and the remaining 12 articles were explicitly related to the integration of CT in PBL-STEM classrooms.

Furthermore, the articles in this paper were sourced from Web of Science, which is regarded as one of the highest quality and leading citation databases worldwide (Chadegani et al., 2013). The authority of this database helped this study to draw important conclusions, although the full picture of the research topic cannot be mapped.

RESULTS

Subject areas

In the context of CT-project-based STEM classrooms, the 12 papers in this review spanned across different science subjects with four in STEM or Science, Technology, Engineering, Arts, and Mathematics (STEAM), two in Computer Science, two in Physics, one in Climate Science, one in Ecosystem Science, one in Elementary Science, one in Health or Physical education and Art, as shown in Table 2.

As can be seen, there was a higher proportion of studies in multidisciplinary courses than that in single-disciplinary ones. In other words, the fact that more teachers chose to incorporate CT in integrated courses rather than single subjects may indicate a higher demand for CT in interdisciplinary courses. Multidisciplinary courses usually require both teachers and students to be equipped with a high level of interdisciplinary competence, while CT is one of the most effective methods to solve complex problems. Therefore, it is not hard to understand that more teachers are now opting to integrate CT into their interdisciplinary classrooms.

Integration objectives

After in-depth reading and coding, five types of research objectives were found from these 12 studies, two of which had two research purposes while the rest had only one. The specific research objectives are shown in Table 3.

Teachers have different purposes for integrating CT into their classrooms, which can be broadly classified into five categories. The first and main purpose is to develop students' CT skills. For instance, Tengler et al. (2021) proposed a method of combining educational robotics with storytelling to improve students' CT skills, using the Tell, Draw, and Code approach. The results showed an increase in CT skills after the intervention. Similarly, Yin et al. (2022) proposed to enhance and evaluate students'

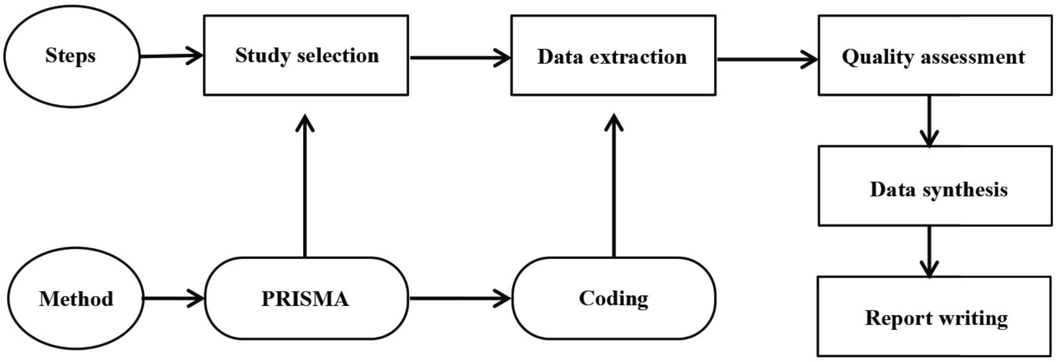

Figure 2. Process adapted from York Centre for reviews and dissemination. PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses.

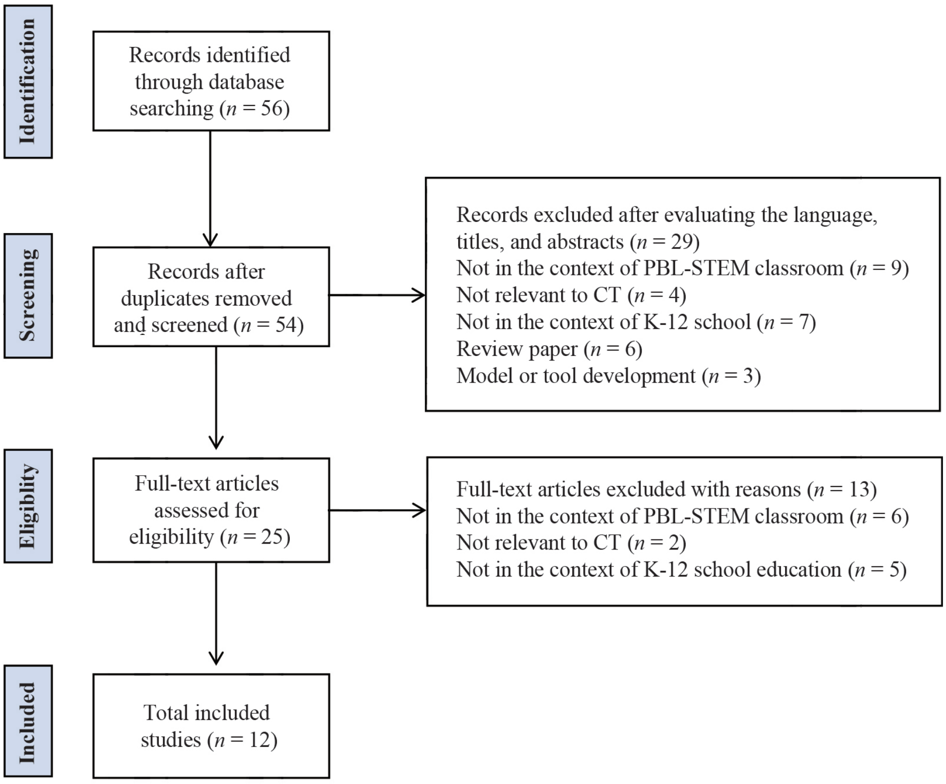

Figure 3. PRISMA flow chart. CT, computational thinking; PBL, project-based learning; STEM, Science, Technology, Engineering, and Mathematics.

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Types of studies	Empirical papers published in peer reviewed: articles, online publications, reprints, journal papers	Conference proceedings, review papers, book chapters
Language	Published in English	Published in other languages
Research topic	The integration of CT in project-based classrooms under the setting of STEM education	Studies that do not include CT application in project-based classrooms under the setting of STEM education
CT integration	CT is applied in a K-12 school educational setting	CT is applied in educational setting outside of K-12 schools

CT, computational thinking.

basic CT skills by developing real-world applications employing Arduino, a microcontroller commonly used for maker activities. Pre- and post-test results suggest that the Arduino or similar devices can be used to improve students' CT skills.

Secondly, integrating CT into K-12 classroom had a positive impact on students' learning of the subject knowledge. Three papers intended to monitor the enhancement of students' subject-specific knowledge (Bernstein et al., 2022; Hutchins et al., 2019; Tucker-

Table 2. Summary of the included studies

Authors	Year	Country	Grade level	Projects setting	Methodology
Bernstein et al.	2022	America	Middle school	General education: "Creative Robotics" project	Qualitative
Bernstein et al.	2022	America	Middle school	Biology and Engineering: "Biorobots" project—bionic search and rescue robots, earthquake excavation robots, refining the internal structure of robots	Qualitative
Ching et al.	2019	America	Elementary	After school STEM activity: "Life on Mars" project—design a robot to search life on mars	Mixed
Dickes et al.	2019	America	Elementary	Ecosystems science: "EcoMOD Curriculum"	Qualitative
Hutchins et al.	2020	America	High school	Physics: "Amazon Jungle Drug Transport" project	Mixed
Kopcha et al.	2017	America	Elementary	STEM: "Danger Zone" project—design robots to help scientists collect 3 samples from an active volcano	Qualitative
Leonard et al.	2016	America	Middle school	After school STEM club: design a robotic roadmap and develop a digital game	Mixed
Ozturk et al.	2018	America	Elementary	STEAM: "Cosmic Colonies" project	Qualitative
Pierson and Clark	2018	America	Elementary	Elementary science: computational models about tides	Mixed
Tengler et al.	2020	Austria	Elementary	Regular course: visualize the fairy tale "Little Red Riding Hood" with a robot	Quantitative
Tucker-Raymond et al.	2019	America	Middle school	Climate science: "Climate Change" project	Qualitative
Yin et al.	2022	America	High school	Physics: maker space of summer academy project—complete four LED-lights projects.	Quantitative

STEM, Science, Technology, Engineering, and Mathematics; STEAM, Science, Technology, Engineering, Arts, and Mathematics; LED, light-emitting diode.

Table 3. Articles distribution of integration objectives

Research objectives	The number of articles
Subject learning	3
CT skills learning	7
Integration status	1
STEM attitude and self-efficacy	2
Teacher professional development	1

CT, computational thinking; Science, Technology, Engineering, and Mathematics.

Raymond et al., 2019). For example, Hutchins et al. (2019) employed a computational modeling approach to support the learning of high school physics by combining CT and STEM. Another two integrated CT to support students in ecological knowledge, scientific practice, engineering, and climate science learning (Bernstein et al., 2022; Tucker-Raymond et al., 2019).

Thirdly, one of the purposes of combining CT with STEM classes is to impact students' STEM attitudes and self-efficacy. Ching et al. (2019) investigated the effects of a project-based STEM-integrated robotics program on primary school students' attitudes towards STEM and perceptions of after-school learning. The results showed a significant improvement in students' attitudes towards math at the end of the robotics course. The findings of Leonard et al. (2016) showed a significant increase in self-efficacy for playing video games in a combined robot-and-game context, compared to a game-only environment. However, middle school students' attitudes towards STEM did not change significantly in their study. This result may imply that PBL-STEM classrooms that incorporate CT may exist to have a more significant impact on the STEM attitudes of students in the lower grades.

The fourth purpose is to evaluate the integration of CT into project-based STEM classrooms. Only one research has involved this dimension. The researchers focused on investigating teachers' motivations for integrating CT into their classrooms and how they use robots to support disciplinary goals (Bernstein et al., 2020). One of the key findings showed that teachers' teaching design lagged behind the pedagogical objectives.

Lastly, research tried to investigate teachers' professional development. In this study, PBL was found to be highly feasible for integrating CS across disciplines, although teachers encountered time and resource constraints in the process (Ozturk et al., 2018).

Education level

The educational level in these classrooms ranged from elementary to high school levels. Of the 12 studies ultimately included, six were in elementary schools, four in middle schools, two in high schools. Specific educational levels and research topics are shown in Table 2. Most studies focused on the elementary level of K-12 education in terms of CT integration into project-based STEM classrooms. The results in Table 2 also show that there are no relevant studies in preschool education and the number of studies decreases from the elementary to high school levels. This result may be related to (1) the fact that comprehensive courses such as STEM or STEAM, science, and general education are offered at the primary school level; and (2) a tendency of middle school students towards "pipeline leakage" in STEM interest (Archer et al., 2010; Archer et al., 2012). That is, a decrease in the instructional demand (output) of the project-based STEM curriculum happened when step in the upper K-12 grades level.

Tools

Of the twelve studies, six used robots, three used computer modeling, one used a breadboard with electronic circuits and LEDs, one did not mention the use of tools, and one only used scratch programming. Generally, classes using robots also used programming software, as the robot's drive needs to be controlled by the programming language. In addition, although unplugged activities were mentioned in some of the articles, they were generally used in the classroom with plugged-in activities and did not appear to be used alone.

The results of the overview demonstrate the types of tools used to integrate CT into the project-based STEM classroom, as seen in Table 4.

Robots are the most frequently used tool when integrating CT in PBL-STEM classes, accounting for 6 of the 12 studies. In addition, the use of robots often requires the incorporation of programming software, a teaching tool that can be used to exercise logical thinking. The advantages of the robot's versatility and timely feedback may explain the high frequency of use in the research or classroom.

Another note-worthy result about the plugged tool is the form of programming. Most STEM activities used block-based programming, which did not require students and teachers to master complex programming languages, but instead, write blocks with simple functions. By dragging and combining these blocks, lines of logic can be distilled out of complex programming languages. This type of block-based programming requires less specialization and solves the problem of students and teachers not having a professional programming background, which is probably why they were so widely used.

From the results in Table 4, the use of unplugged tools can also be seen. They are of less types and utilized frequency than plugged tools, but they have a potential of wider application, especially as a better option for schools and districts that do not have sufficient education resources. The reasons are as follows. First, unplugged tools are less expensive and require less expertise, which is conductive to breaking down technical barriers. Second, unplugged tools also have a positive impact on teaching effectiveness. For instance, both storyboard (Bernstein et al., 2020) and casual map (Dickes et al., 2019) use in the classroom helped to improve students' CT skills and subject learning.

Overall, the incorporation of CT in project-based STEM classrooms is still dominated by emerging plugged tools. From this perspective, if teachers without relevant background want to integrate CT into their classrooms, they will have a higher demand for technology training (input) than in other project-based STEM classrooms.

Assessment

The different purposes of CT integration into project-based STEM classrooms resulted in different assessment approaches and contents in different studies. We grouped the assessment contents of the 12 articles screened into three categories: cognitive domain (thinking, knowledge), psychomotor domain (doing, skills), and affective domain (feeling, attitudes), as shown in Table 5.

In Table 5, the assessment of the cognitive domain focused on both subject knowledge and cognitive load. The analysis of students' subject knowledge was mainly based on their classroom paper records and learning performance, while the assessment of cognitive load was based on questionnaires.

In the psychomotor domain, most studies refer to the evaluation of CT capability. The analysis of CT capability was based on the measurement results using theoretical instruments. Two instruments, the Bebras test and the Beginners Computational Thinking test (BCTt), were adopted frequently to evaluate CT capability, with both instruments appearing twice (four of the eight articles

Table 4. Use of integration tools

Plugged		Unplugged	
Types	**Tools**	**Types**	**Tools**
Robot	NUWA robots LEGO (MINDSTORMS or EV3) Hummingbird robotics kit Ozobot robots Breadboard with electronic circuits	Storyboard with sketch	Show timeline Abstract animal structure
Block-based programming	NUWA LEGO EV3 programming Scratch MakeCode AgentCubes	Casual map	Causal reasoning Birds eye view maps Graphs of change over time
Non-block-based programming	Arduno ViMap programming	Paper-based programming	Ozobot's paper-based version of programming
Digital game	AgentCubes	Students' design notebooks and sandbox	-
3D immersive environment	Unity game engine	Literary texts	Summarize data

3D, 3 dimensions.

Table 5. Assessment content and tools

Domains	Content	Ways of assessment
Cognitive domain	Subject knowledge	Worksheet, software, reading, comments form, learning performance
	Cognitive load	Questionnaire
Psychomotor domain	Discursive practices	Asking questions, critique, peer review
	Technical operation	Level of fluency and independence when implementing the unit, bots (inclusion of key technologies such as motors, sensors, and lights)
	CT capability	Bebras instrument, PFL, BCTt, User guides or reports of students, interview
Affective domain	STEM attitude	Likert scale, use Upper Elementary STEM Survey questionnaires
	Self-efficacy	SETS scale
	Teachers and students' reflection	Interview, video recording

CT, computational thinking; PFL, preparation for future learning; BCTt, Beginners Computational Thinking test; SETS, Self-Efficacy in Technology and Science.

on developing CT skills are related to these two tools). For the discursive practices and technical operation, they were not described at great length in the 12 studies, possibly because the purposes of these researches were not relevant to them.

In terms of the affective domain, the studies focused on three dimensions: STEM attitude, self-efficacy, and teacher or student reflection. Among them, teacher or student reflection is valuable for assessing CT integration because it reflects the problems that currently exist. For example, teachers who used to believe that they could not waste time and be test-oriented began to identify with PBL and reflect on their previous adherence after seeing the effectiveness of PBL in the classroom (Dickes et al., 2019). But only one of the 12 articles is relevant to this. Thus, there is less research on CT integration status (1 out of 12 studies) compared to research on cultivating CT skills (7 out of 12 studies). The integration status of CT in the classroom might be included in future research orientations.

In summary, most CT-integrated project-based STEM courses hope to positively impact students' learning of CT skills and subject knowledge. The assessment content again mirrored the limited teaching objectives of such courses.

Challenges

After an in-depth analysis of the 12 articles, we found that, in the process of integrating CT technology into the project-based STEM classroom, the challenges encountered by teachers come from three levels: the teachers themselves, their students, and the school levels, as shown in Table 6.

The first type of challenge is at the teacher level, such as lack of experience in technology, difficulty in balancing subject knowledge with technical knowledge, technological diversity, and reluctance to undertake these courses due to exam pressure. Most of the teacher-level pressure comes from the technology field. For schools and the education sector, if they wish to integrate CT into the classroom in the future, they may need to consider adapting the content of teachers' professional training by adding training in the use of emerging technologies such as robotics and programming. It would also be possible to make the training more diverse by adding hands-on practice in addition to the traditional oral and written training.

The results in Table 6 show that teachers also encountered some challenges at the student level, such as ineffective teamwork, lack of alignment between teaching objectives and reality, and students' weak abstract thinking. These challenges are not only related to the teachers' teaching objectives but also to their classroom management skills. In this regard, scaffolding and pedagogical assistance may be needed for less experienced teachers to help them adjust their teaching objectives, teaching methods, and content.

The third type of challenge encountered by teachers is at the school level. Time constraints (3 out of 12 articles) may be a more prominent issue compared to technology accessibility, equipment reliability, and choice of resource type. For project-based STEM classrooms that integrate with CT, if most integration tools chosen are time-consuming robotics + programming (6 out of 12 articles), coupled with the limited time available in school classrooms (typically 40 or 45 minutes a lesson), the problem of lack of time can easily arise.

It is also worth noting that all three articles that suggested time constraints were set in the context of elementary education, and two of them explicitly pointed to the use of integration tools for robotics and programming in the classrooms. This type of integration tool is more complex for elementary school children, which is perhaps why teachers feel they do not have enough time. In this regard, teachers could choose a more gradual approach, such as starting with unplugged tools and then gradually integrating block-based programming, and then robotics and programming. In future research, it might be possible to compare the effectiveness of several integration tools at the elementary level to find the best way to integrate them.

Table 6. Challenges for teachers

Level	Code	Content
Teacher level	Teachers' resistance	When conflict with exam, teacher change to more direct teaching approach (Ozturk et al., 2018)
	Balance problem	Hard to determine the percentage of programming and subject knowledge (Hutchins et al., 2019)
	Dynamic changes of technology	The diversity of tool types in integrated courses requires teachers to re-learn how to use and facilitate the use of different kinds of software (Leonard et al., 2016; Bernstein et al., 2020)
	Lack of professional development	Awareness that the curriculum lags technology, but lack of experience in translating general knowledge of the process into steps that lead to an intertwined curriculum unit (Bernstein et al., 2020)
Student level	Ineffective teamwork	Over-reliance of the group on one member (Ching et al., 2019)
	Alignment problem	Students' attention is on game play rather than subject knowledge (Tucker-Raymond et al., 2019)
	Abstract or transfer problem	Students struggle to transfer from subjects knowledge to integrating tools (Hutchins et al., 2019; Bernstein et al., 2020)
	Persistence of interest	Prolonged non-change of learning platforms leads to loss of interest and is more pronounced in girls (Leonard et al., 2016)
School level	Technic popularity	Schools are making slow progress in using technology to improve student outcomes (Leonard et al., 2016)
	Time limitation	There are many course tasks and not enough time to complete them (*e.g.*, programming is very time-consuming) (Ching et al., 2019; Ozturk et al., 2018; Kopcha et al., 2017)
	Unreliable infrastructure	Unstable networks and insufficient equipment (Ching et al., 2019; Ozturk et al., 2018)
	Resource selection	The breadth of the curriculum makes it difficult for design teams to determine which resources to select to support students in problem solving (Bernstein et al., 2022)

DISCUSSION

In answering the four research questions, we found that multidisciplinary courses at elementary level showed greater demand for incorporating CT in PBL-STEM lessons, compared to single subjects (RQ1). The main purpose of such classes was to develop CT skills and to facilitate students' learning of subject knowledge (RQ1). Notably, we found that the need for CT integration into project-based STEM classrooms may show a "pipeline leakage" from elementary to high school (RQ1). In addition, in the project-based STEM courses, there are limited tools that teachers apply to the assessment of their students (RQ2 and RQ3). In order to further explore how these situations relate to teachers, the challenges encountered by teachers were analyzed. These challenges were found to be closely related to teachers' professionalism, students' thinking development, and the constraints of schools (RQ4). Overall, the relationship between teachers' demand and curricula's demand is unbalanced, and there was a pressing need for training on the teachers' end. This uneven relationship may partially explain the underutilization of CT in K-12 education (Hurt et al., 2023; Lye & Koh, 2014).

The results of this review show that there is limited research on integrating CT into PBL-STEM classrooms at the kindergarten level. This may be explained by the fact that the main integration approach is robotics + programming in current, which requires a high level of abstract thinking of students. Interestingly, CT-PBL-STEM courses mainly applied at primary level and show a tendency of decrease when stepping in higher education level. Whereas children begin to develop abstract thinking after about 12 years old according to the cognitive development theory (Caldeira & Carvalho, 2021), *i.e.*, at the secondary school level. In other words, the CT integration classroom is gradually sinking into the younger age groups, which appears to be a contradiction between it and the patterns of children's cognitive development. Besides, it has been found that over-reliance of group members on one single member occurs at the primary level (Ching et al., 2019), and there are also middle school teachers who have expressed challenges such as students' easily distracted attention and limited transfer ability (Hutchins et al., 2019; Tucker-Raymond et al., 2019; Bernstein et al., 2020). Therefore, the CT-integrated classroom that is sinking to the elementary school cannot be a rigid application, and teachers or schools need to think about what adaptations should be made.

For integration tools, the findings show that the most used vehicle is plugged instrument, with robotics + programming being the most popular. However, programming requires a high level of skill on the part of both students and teachers, and unless specialized training is given, the pedagogical effect is very limited. As mentioned earlier, for students, the formation of abstract thinking is limited by physiological development. As for teachers, some of them lack relevant professional background, but the professional training that schools can provide is very limited. However, it is worth noting that teachers are experimenting with unplugged tools, although they still need to be used in conjunction with plugged-in tools. Examples include sketch drawing and graphs of change over time (Bernstein et al., 2022; Dickes et al., 2019). Compared to plugged-in tools (currently the most commonly used course carriers), unplugged tools are less technically demanding for students and teachers, and are rarely limited by space or equipment, and therefore have a wider prospect of application. Although further research is needed to support whether the use of unplugged tools on their own can lead to the same pedagogical results as plugged-in tools, it may be one of the adaptive directions for CT-integrated classrooms to sink to the younger age groups, and an opportunity to break down disciplinary barriers.

As with the use of tools, the content of the assessment also has limitations. Most of the studies assessed students' subject knowledge and mastery of CT capability in CT-PBL-STEM classrooms, and there is strong consistency between this result and the purpose of integration. In addition, we identified STEM attitude as another potential dimension of assessment. This is because the analyses showed a trend of a "leaky drain" in the demand for CT-integrated classrooms from elementary to high schools. For one thing, this may be related to the increasing pressure for higher education (midterm and high school exams); for another, research has shown that students' interest in STEM decreases as they enter high school (Archer et al., 2010; Archer et al., 2012). This consistency allows us to see the campus version of under-representation in STEM fields. From the review results, the intervention of Ching et al. (2019) on STEM attitudes of upper elementary students was significantly positive, but middle school students' attitudes towards STEM careers remained the same in the study of Leonard et al. (2016). Besides, there is a lack of research data to support whether CT-integrated classrooms can positively impact STEM attitude of high school students.

The challenges encountered by teachers were analyzed along three dimensions: teachers, students, and schools. The results show that these challenges reveal three different contradictions. Firstly, the high demand for technology in CT integrated classrooms becomes the biggest challenge for teachers, such as not having a relevant technological background (Bernstein et al., 2020; Kopcha et al., 2017), and not being able to learn fast enough to keep up with the iterative pace of technological updates (Leonard et al., 2016). In other words, there is a tension between teachers' own weak technological background and the current dominance of plugged activities. Secondly, schools' strict curriculum schedules limit lesson time and also lack adequate equipment support (Ching et al., 2019; Ozturk et al., 2018; Kopcha et al., 2017). From this perspective, there is a clear contradiction between the strict demand for the program and the shortage of resources in schools. Thirdly, even though some of the programs come in the form of after-school activities without the problem of time constraints, the problem of group members' over-dependence on one single competent group member still arises (Ching et al., 2019). As mentioned earlier, there is also a contradiction between the limitations of the abilities of students in the younger age groups and the technological requirements of the CT-integrated classroom.

Putting the results of these analyses together, we have found that the relationship between the challenges faced by teachers and the current status of teaching may explain the lack of CT at the K-12 education level. From the input side of the curriculum, emerging technologies are still the dominant teaching tools in CT-integrated classrooms, so most teachers have a relatively urgent need for technological training to ensure the quality of teaching. However, schools are unable to provide adequate support to address the problem of teachers' weak technological background. As a result, teachers may be resistant, and the quality of the course cannot be guaranteed. From the output side of the curriculum, limited time and examination-oriented (subject knowledge) make teaching and learning objectives restrictive, so elementary multidisciplinary programs with less academic pressure become the main implementation site. However, the most used CT integration programs are still the more technically demanding forms of robotics + programming as they descend into the lower age groups. Considering that the development of abstract thinking in students can be limited by physiological development, the effectiveness of the teaching may be greatly reduced. This shows that there is a large demand for the input side of the CT integration, but the output demand and effectiveness are limited. This discrepancy between supply and demand may be one of the reasons why CT is not widely used in K-12 education and becomes more apparent as students enter high school.

Future research

Based on the above discussions, the following future research directions are proposed. (1) Many researches have focused on the elementary level, which could move to the secondary level in the future. (2) Most researches have probed students' acquisition of CT capability in CT integration courses, the diversity of assessment could be further considered in future research, such as STEM attitudes, and self-efficacy. (3) Unplugged tools are not restricted by site or equipment and have the potential for widespread applications. However, further research is needed on whether unplugged activities can completely replace plugged ones and make positive impacts on K-12 students in low educational resources areas. (4) Concerning the challenges encountered by teachers, lack of time (training and teaching time) and programming skills usually occur at the primary level. This could be addressed in two ways in the future. First, explore an integration tools or approaches that are more appropriate for elementary education, using simplistic unplugged tools (*e.g.*, punch cards) or block programming tools (*e.g.*, Scratch). Second, identify a level of education that is more suitable for an integrated tool such as robotics + programming. This needs more investigation and research in the future.

CONCLUSION

Most of the CT integration PBL-STEM courses were applied at the primary level and tend to decrease sharply as they enter secondary school. This "leaky" phenomenon show a contradiction to the pattern of children's cognitive development. Besides, many PBL-STEM classes and researches relied on computer and robot programming for CT integration. This limitation caused teachers to face technological barriers and solidified teaching scenarios. The emergence of unplugged tools in parts of these researches offered educators and schools the possibility to break this limitation. Thirdly, this review demonstrated the different positive impacts of integrating CT into PBL-STEM classrooms, but more than half addressed the cultivation of CT skills. This increases confidence for educators to plan and implement CT learning in the classroom but also implies that (1) educational research should tap into the multifaceted possibilities of CT, and (2) schools need to revisit the comprehensiveness of instructional assessment in such classrooms.

Additionally, there is a strong connection between the challenges faced by teachers and the teaching status in the CT-PBL-STEM curriculum. In terms of the teacher demand (input) dimension, their inexperience in the use of relevant technology and their unfamiliarity with the pedagogies resulting in poor classroom management and limited teaching effectiveness. This reflects the need for training on teachers' end, and the lack of support in the school, which puts a lot of pressure on teachers. From the dimension of instructional demand (output), the limited time and exam orientation make it easy to understand why most of the research and classroom teaching objectives and effectiveness are limited, such as improving subject learning and CT skills. This situation where the demand on the input side is greater than the output side can be understood as the problem of "educational deficit" in project-based STEM fields. Notably, this phenomenon becomes more pronounced as one enters the upper grades. For those K-12 schools that wish to integrate CT into the classroom, it is important not only to provide training for teachers, but also to reevaluate the justification for the instructional needs of CT-PBL-STEM, especially at the secondary level.

DECLARATION

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Author contributions

Chen JX: Writing—Original draft, Data Analysis, Methodology, Writing—Review and Editing. Hui JJ: Writing—Original draft. All authors have read and approve the final version.

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The authors have no conflicts of interest to declare.

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No additional data.

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