Halawa *et al.*
International Journal of STEM Education (2024) 11:43
https://doi.org/10.1186/s40594-024-00503-5

International Journal of STEM Education

REVIEW

Open Access

Exploring instructional design in K-12 STEM education: a systematic literature review

Suarman Halawa[1], Tzu-Chiang Lin[2,3] and Ying-Shao Hsu[4*]

Abstract

This study aimed to analyze articles published in the Web of Science database from 2012 to 2021 to examine the educational goals and instructional designs for STEM education. We selected articles based on the following criteria: (a) empirical research; (b) incorporating instructional design and strategies into STEM teaching; (c) including intervention; (d) focusing on K-12 education and on assessment of learning outcomes; and (e) excluding higher education and STEAM education. Based on the criteria, 229 articles were selected for coding educational goals and instructional designs for STEM education. The aspects of STEM educational goals were coded including engagement and career choice, STEM literacy, and twenty-first century competencies. The categories of instructional designs for STEM education were examined including design-based learning, inquiry-based learning, project-based learning, and problem-based learning. The results showed that engagement and career choices and STEM literacy were mainly emphasized in STEM education. Design-based learning was adopted more than inquiry-based, project-based, or problem-based learning, and this instructional design was mainly used to achieve STEM literacy. It is suggested that studies on twenty-first century competencies may require more research efforts in future STEM education research.

Keywords STEM education, Engagement and career choice, STEM literacy

Introduction

Emphasizing STEM (science, technology, engineering, and mathematics) has been the main focus of policy makers in many countries (English, 2016; National Academy of Engineering & National Research Council, 2014; National Research Council, 2012, 2013) to meet economic challenges (Kelley & Knowles, 2016). Educational systems are accordingly prioritizing STEM to prepare students' capability for the workplace to face the sophisticated technologies and competitive economy (Kayan-Fadlelmula et al., 2022). Hence, students are expected to be interested in STEM so that they will engage in and pursue careers in STEM-related fields (Lie et al., 2019; Struyf et al., 2019). Besides, we need a new generation that has the abilities to develop proficient knowledge, to apply such knowledge to solve problems, and to face existing and upcoming issues of the twenty-first century (Bybee, 2010).

Although STEM education has been proved to benefit students, there is a lack of understanding of instructional design for STEM education, despite the fact that such understanding is critical to research and to classroom practices. Limited understanding of relevant instructional design may lead to problems in implementing STEM education in the classroom. There is hence a need to examine educational goals, specific designs, and features of the instructional designs consistently and specifically documented in the STEM education literature. Therefore, this current study conducted systematic analysis of the literature to understand the educational

*Correspondence:
Ying-Shao Hsu
yshsu@ntnu.edu.tw
[1] Research Center for Education, National Research and Innovation Agency, Jakarta, Indonesia
[2] Center for Teacher Education, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan
[3] Center for the Liberal Arts, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan
[4] Graduate Institute of Science Education, National Taiwan Normal University, Taipei, Taiwan

goals and instructional designs for STEM education. Based on the analysis, we present a thorough picture of how researchers have developed instructional designs for STEM education.

Despite the fact that many researchers have promoted STEM education, the definition of STEM education has not reached a consensus in the literature, and there is a certain degree of disagreement in the scientific community. Lamb et al. (2015) defined STEM as a broad area encompassing many disciplines and epistemological practices. Other researchers, such as Breiner et al. (2012), defined STEM as applying transdisciplinary knowledge and skills in solving real-world problems. A similar definition established by Shaughnessy (2013) regarding STEM education is problem solving based on science and mathematics concepts that incorporate engineering strategies and technology. Another study defined STEM education as teaching approaches based on technology and engineering design that integrate the concepts and practices of science and mathematics (Sanders & Wells, 2006). In this study, we clarify STEM education as an approach that utilizes integrations of knowledge and skills from science, technology, engineering, and/or mathematics to solve real-world problems that help students to succeed in school learning, future careers, and/or society.

The definition of STEM as an integrated approach involving science, technology, engineering, and mathematics raises several pertinent questions about its composition and expectations. First, the requirement for all four disciplines to be present in order to qualify an educational program or project as “STEM” is debatable. Conceptually, integrating any two or more fields helps foster the interdisciplinary learning that is the hallmark of STEM education. This flexibility allows educators to tailor their programs to match the available resources and specific learning outcomes without necessarily incorporating all four disciplines in every instance. Regarding the classification of “science” within STEM, it is more a conglomerate of disciplines—such as biology, chemistry, physics, and earth sciences—than a single field. This diversity within science enriches STEM education, providing a broader knowledge base and problem-solving skills. Each scientific discipline brings a unique perspective and set of tools to the interdisciplinary mix, enhancing the complexity and richness of STEM learning experiences.

Furthermore, previous studies have identified several challenges to the implementation of STEM education in the classroom including poor motivation of students, weak connection with individual learners, little support from the school system, poor content without integration across disciplines, lack of quality assessments, poor facilities, and lack of hands-on experience (Ejiwale, 2013; Hsu & Fang, 2019; Margot & Kettler, 2019). To help teachers face challenges in the advancement of STEM education, Hsu and Fang (2019) proposed a 5-step STEM curriculum designs framework and provided examples of how to apply it to a lesson plan to help teachers design their instruction. This previous study also suggested that researchers conduct more investigations related to instructional design to enrich our understanding of various aspects of STEM education. Teachers of STEM require more opportunities to construct their perspective and a vision of STEM education as well as to conduct appropriate instructional designs. Moreover, from review articles published from 2000 to 2016, Margot and Kettler (2019) found that in multiple studies concerning similar challenges and supports, teachers believed that the availability of a quality curriculum would enhance the success of STEM education. Teachers need to provide and use an appropriate instructional design for STEM education and understand the educational goals. Therefore, we see the need to conduct research related to STEM education, especially exploring the instructional design because identifying and using a quality instructional design could increase the effectivess of STEM education.

According to the previous literature review, educational goals for instructional design were highlighted in STEM education. First, engagement and career choice need to be emphasized in STEM learning to improve students’ interest and self-efficacy (Vongkulluksn et al., 2018). Students need to engage in STEM education to raise their interest and engagement in STEM and to increase and develop a STEM-capable workforce (Honey et al., 2014; Hsu & Fang, 2019; Schütte & Köller, 2015). Engaging students in STEM education could improve their attitudes (Vossen et al., 2018) and their interest in STEM fields, and encourage them to pursue STEM careers (Means et al., 2017).

Second, STEM literacy needs to be promoted in K-12 schools (Falloon et al., 2020; Jackson et al., 2021) to develop students’ ability to encounter global challenges (Bybee, 2010). Students need to have the ability to apply concepts from science, technology, engineering, and mathematics, and skills to solve problems related to social, personal, and global issues in society (Bybee, 2010; Jackson et al., 2021). Besides, improving students’ STEM literacy is needed for their decision-making, participation in civic and cultural affairs, and economic productivity (National Academy of Engineering & National Research Council, 2014; National Research Council, 2011).

Last, regarding the twenty-first century competencies, students are anticipated to have abilities of creativity and innovation, problem solving, critical thinking, collaboration and communication (Boon, 2019) as citizens, workers, and leaders in the twenty-first century (Bryan et al., 2015; National Academy of Engineering & National Research Council, 2014; Stehle & Peters-Burton, 2019). These abilities are critical for students to adapt and thrive in a changing world (National Research Council, 2013). Also, students need to have the abilities to adapt to the twenty-first century in order to succeed in the new workforce (Bybee, 2013).

Considering the achievement of students' engagement, motivation, STEM literacy, as well as twenty-first century competencies, many countries have significantly enlarged the funding for research and education relevant to STEM (Sanders, 2009). One of the strands of the existing research is to help teachers know how to implement STEM education in schools (Aranda, 2020; Barak & Assal, 2018; English, 2017). Researchers have proposed instructional designs for STEM education including design-based learning (Kelley & Knowles, 2016; Yata et al., 2020), inquiry-based learning (Bybee, 2010), project-based learning (Capraro et al., 2013), and problem-based learning (Carpraro & Slough, 2013).

Design-based learning focuses on technological and engineering design. This instructional design engages students in learning about engineering design practices (Fan et al., 2021; Guzey et al., 2016; Hernandez et al., 2014) through the steps of designing, building, and testing (Yata et al., 2020). Design-based learning promotes problem solving, design, building, testing, and communication skills (Johnson et al., 2015) and improves students' interest in STEM activities (Vongkulluksn et al., 2018). Also, design-based learning improves students' engineering abilities and twenty-first century competencies (Wu et al., 2019) and attitudes (Vossen et al., 2018), and engages them in understanding core disciplinary ideas (Guzey et al., 2016).

Inquiry-based learning focuses on engaging students in hands-on activities to investigate scientific phenomena (Lederman & Lederman, 2012) and to construct their new knowledge (Bybee, 2010; Halawa et al., 2020). Students are encouraged to plan and design their experiments, analyze and interpret data, argue, and communicate their findings (Halawa et al., 2023; National Research Council, 2012, 2013). Inquiry-based learning is also deemed to improve students' knowledge, interest, engagement (Sinatra et al., 2017) and creativity (Smyrnaiou et al., 2020). Besides, researchers have noticed the importance of inquiry-based learning for improving students' attitudes toward science-related careers (Kim, 2016). Although inquiry-based learning mainly focuses on science education to engage students in authentic learning (Halawa et al., 2024), it has been known to share common goals and characteristics with mathematics, technology, and engineering (Grangeat et al., 2021; Lin et al., 2020). Common elements in STEM education are engaging students in asking questions and testing their ideas in a systematic and interactive way (Grangeat et al., 2021).

Project-based learning and problem-based learning, both instructional designs, engage students in experiential and authentic learning with open-ended and real-world problems (English, 2017). Yet, project-based learning tends to be of longer duration and occurs over an extended period of time (Wilson, 2021), while problem-based learning is usually embedded in multiple problems (Carpraro & Slough, 2013). STEM project-based learning focuses on engaging students in an ill-defined task within a well-defined outcome situated with a contextually rich task, requiring them to solve certain problems (Capraro et al., 2013). Project-based learning and problem-based learning are both used to develop students' problem solving, creativity, collaboration skills (Barak & Assal, 2018), and attitude (Preininger, 2017).

According to previous studies, researchers have adopted STEM instructional designs to achieve certain educational goals. For instance, in the aspects of engagement and career choice, Sullivan and Bers (2019) used design-based learning to improve students' interest in engineering and students' performance in elementary school. Kang et al. (2021) adopted inquiry-based learning for secondary school by embedding careers education to foster the students' interest in science. Vallera and Bodzin (2020) adopted project-based learning at primary school in the northeastern United States to improve students' STEM literacy and attitude. Preininger (2017) used problem-based learning to influence students' attitudes toward mathematics and careers involving mathematics. In the aspect of STEM literacy, King and English (2016) adopted design-based learning to enable students to apply STEM concepts to the model of the construction of an optical instrument. Han et al. (2015) adopted STEM project-based learning to improve the performance of low-performing students in mathematics. Lastly, regarding the twenty-first century competencies, English et al. (2017) adopted design-based learning to improve students' capabilities of handling the complexity of the task (English et al., 2017).

In conclusion, studies have grown to explore educational goals related to instructional designs for STEM education. However, consistent and systematic reviews related to instructional designs in K-12 STEM education are comparatively scarce. Although there are some reviews of the STEM education literature (Andrews et al., 2022; Gladstone & Cimpian, 2021; Kaya-Fadlelmula et al., 2022; López et al., 2022; Margot & Kettler, 2019; Martín-Páez et al., 2019; Nguyen et al., 2021), it is noteworthy that previous studies only explored undergraduate instruction in STEM education (Andrews et al., 2022; Henderson et al., 2011; Nguyen et al., 2021). Therefore, to fill the research gap, this current study conducted a systematic analysis of literature to understand the educational goals and instructional designs for K-12 STEM education from articles published between 2012 and 2021. The research questions of this study were formulated as follows:

1. What STEM education goals were more focused on in the reviewed articles? What was the trend of educational goals in the reviewed articles?
2. What instructional designs were more focused on in the reviewed articles? What was the trend of the instructional design in the review articles?
3. What instructional designs were more focused on to achieve certain educational goals in the reviewed articles?
4. What features of instructional designs were more focused on in the reviewed articles?

Methods

Data collection

To identify the target literature for further analysis, this study conducted several rounds of searching the Web of Science (WOS) database for articles (Gough et al., 2012; Møller & Myles, 2016). A systematic literature review using the PRISMA guidelines was used for article selection (Møller & Myles, 2016). First, we searched for articles using the keyword "STEM Education" along with "learning", "teaching", "curriculum", and "professional development", to refine the search results. The search identified a total of 1,531 articles published in the Web of Science from 2012 to 2021 (Fig. 1). We initially excluded duplicated articles; the search retrieved a total of 1,513 articles. We then screened the titles, abstract, and keywords

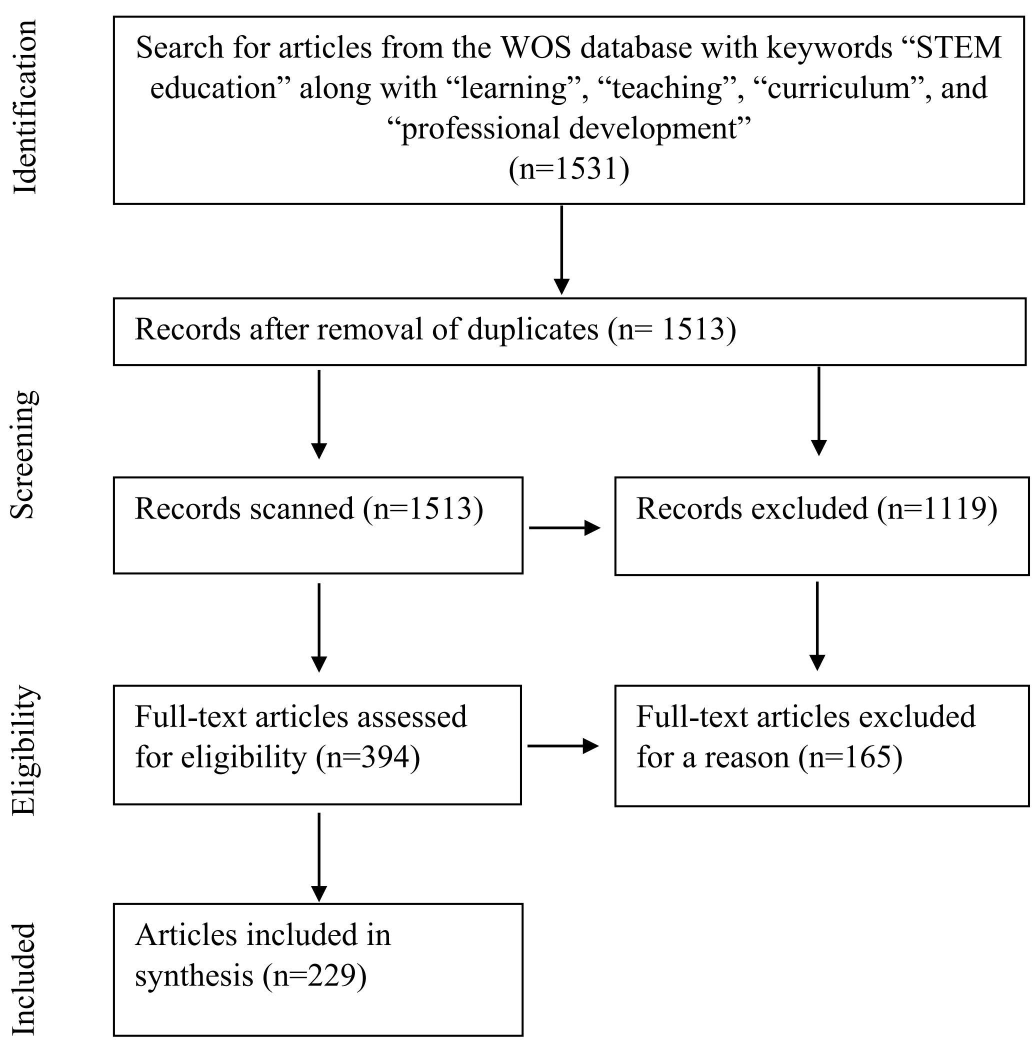

Fig. 1 PRISMA flow diagram of articles selection

of the articles based on the following criteria: (a) empirical research; (b) incorporating instructional design and strategies into STEM teaching; (c) including intervention; (d) focusing on K-12 education and on assessment of learning outcomes; and (e) excluding higher education and STEAM education. During this screening, we discussed which articles met the criteria through roundtable discussions, and determined the preliminary target candidates composed of 394 articles. A full-text examination was then conducted. In this round of examination, we removed the articles without clear information about the educational goals and instructional designs related to STEM education. Finally, a corpus of literature comprising 229 articles was formed for further analysis.

Data analysis

According to the research questions, for this study, we developed a coding framework to conduct content analysis and to categorize the target literature. We first selected paradigmatic references of STEM education and instructional design from high quality publications. These articles provided sets of core concepts and terms to shape the provisional coding categories. We then constantly reviewed the paradigmatic references and discussed them to improve the coding scheme. The final analytic framework with coding categories was developed as follows. The first category, STEM educational goals, includes engagement and career choice (Honey et al., 2014; Hsu & Fang, 2019), STEM literacy (Falloon et al., 2020; Jackson et al., 2021), and twenty-first century competencies (Boon, 2019) (see Appendix 1). The second category, instructional design, includes design-based learning (Yata et al., 2020), inquiry-based learning (Bybee, 2010; Halawa et al., 2020), project-based learning (Capraro & Slough, 2013), and problem-based learning (Priemer et al., 2020). From the review articles, we found that 6E-oriented STEM (engage, explore, explain, engineer, enrich, and evaluate) and game-based learning were used for STEM education. These two instructional designs were added to our coding scheme. Articles that did not specify the instructional design were coded as "others". We then analyzed the outcomes to see whether instructional design successfully improved STEM educational goals. We analyzed design-based, inquiry-based, and project-based learning to achieve engagement and career choice, STEM literacy, and a combination of engagement and career choice and STEM literacy because the selected articles mainly concentrated on them. We categorized the outcomes as positively improved, partially improved, and none (Amador et al., 2021). Instructional design that successfully increased STEM educational goals was categorized as positively improved. Instructional design that only increased a part of STEM educational goals was categorized as partially improved. If the instructional design did not increase STEM educational goals, we categorized it as none.

We then extended our coding scheme to identify the features of design-based, inquiry-based, and project-based learning. We focused on these three instructional designs because the selected articles mainly adopted them. Yata et al. (2020) proposed designing, building, and testing as the features of design-based learning. Other features of instructional designs including questioning or identifying problems, experimenting, analyzing, explaining, collaborating, communicating, and reflecting were proposed as features of inquiry-based learning (Bybee, 2010; Halawa et al., 2020) and project-based learning (Capraro et al., 2013). From the review articles, we found that redesigning was one of the features of instructional design and so added it to the coding scheme. These features of instructional designs were adopted for our coding scheme including questioning or identifying problems, designing, building, testing, experimenting, analyzing, collaborating, reflecting, communicating, and redesigning (Appendix 2). We then calculated the number of articles that adopted these features of instructional designs. We further summarized the features of instructional designs that were frequently used in the selected articles.

In order to make sure the coding process was reliable, we conducted a trial coding by randomly selecting 40 articles and individually categorizing the articles into the aforementioned categories: (a) STEM education goal, and (b) instructional design. Interrater reliability was calculated using a percent agreement metric reaching an acceptable level of 0.85 (McHugh, 2012). The discrepancies between authors were negotiated and solved through discussions. The NVivo 11 software was utilized to complete coding works on the remaining articles. We then calculated and reported descriptive statistics of the coded data as the analytic results.

Results

Engagement and career choice as the main focused STEM educational goals

Table 1 shows that more articles focused on engagement and career choice (64 articles) and STEM literacy (61 articles) than twenty-first century competencies (16 articles). The articles also mainly focused on a combination of engagement and career choice and STEM literacy (47 articles) and a combination of engagement and career choice and twenty-first century competencies (18 articles). Nine articles were found that focused on the three learning goals of engagement and career choice, STEM literacy, and twenty-first century competencies.

Table 1 Frequency of the reviewed articles focused on STEM educational goals

Educational goals	2012–2013	2014–2015	2016–2017	2018–2019	2020–2021	Total
Engagement and career choice (EC)	1 (0.4%)	2 (0.9%)	9 (3.9%)	12 (5.2%)	40 (17.5%)	64 (27.9%)
STEM literacy (SL)	2 (0.9%)	2 (0.9%)	10 (4.4%)	11 (4.8%)	36 (15.7%)	61 (26.6%)
EC & SL	4 (1.7%)	8 (3.5%)	4 (1.7%)	11 (4.8%)	20 (8.7%)	47 (20.5%)
EC & 21st C		2 (0.9%)	2 (0.9%)	4 (1.7%)	10 (4.4%)	18 (7.9%)
21st⁻century competencies (21stC)			1 (0.4%)	1 (0.4%)	14 (6.1%)	16 (7.0%)
SL & 21st C	1 (0.4%)		1 (0.4%)	1 (0.4%)	7 (3.1%)	10 (4.4%)
EC, SL & 21st C			4 (1.7%)	1 (0.4%)	4 (1.7%)	9 (3.9%)
NGSS					3 (1.3%)	3 (1.3%)
EC & NGSS				1 (0.4%)		1 (0.4%)
Total	8 (3.5%)	14 (6.1%)	31 (13.5%)	42 (18.3%)	134 (58.5%)	229 (100%)

STEM educational goals

EC: engagement and career choice; SL: STEM literacy; 21st C: Twenty-first century competencies; NGSS: next generation science standard

Table 1 shows the numbers of articles regarding educational goals for STEM education for each 2 years in the review papers. The number of articles per 2 years increased from 2012 to 2021. The trend analysis indicated that engagement and career choice and STEM literacy increased greatly from 2014 to 2021. The numbers of articles focused on the combination of two educational goals (STEM literacy and twenty-first competencies) and three learning goals (engagement and career choice, STEM literacy, and twenty-first competencies) from 2016 to 2021 are also presented.

Design-based and inquiry-based learning as the main instructional designs for STEM

Table 2 reveals the numbers of articles that used instructional design for STEM education. The instructional designs of design-based, inquiry-based, project-based, and problem-based learning were mainly used and continued to be used over the study period. The trend analysis indicated a big jump in design-based, inquiry-based, and project-based learning from 2018 to 2021.

Table 2 also shows the instructional designs and educational goals for STEM from review papers. Most articles adopted design-based (80 articles), inquiry-based (46 articles), project-based (42 articles), and problem-based (27 articles) learning.

Design-based learning mainly used to achieve STEM literacy

The findings shown in Table 3 identified that STEM instructional designs were used differently to achieve engagement and career choice, STEM literacy, and the combination of engagement and career choice and STEM literacy. We found that design-based learning was mainly adopted to achieve STEM literacy (28 articles), while inquiry-based learning was mainly used to achieve engagement and career choice (14 articles) and the combination of engagement and career choice and

Table 2 Frequency of the reviewed articles focused on STEM instructional designs

Instructional design	2012–2013	2014–2015	2016–2017	2018–2019	2020–2021	Total
Design-based	1 (0.4%)	4 (1.7%)	9 (3.9%)	16 (7.0%)	50 (21.8%)	80 (34.9%)
Inquiry-based	2 (0.9%)	4 (1.7%)	6 (2.6%)	6 (2.6%)	28 (12.2%)	46 (20.1%)
Project-based	4 (1.7%)	4 (1.7%)	7 (3.1%)	7 (3.1%)	20 (8.7%)	42 (18.3%)
Problem-based	1 (0.4%)	1 (0.4%)	5 (2.2%)	10 (4.4%)	10 (4.4%)	27 (11.8%)
Game-based			1 (0.4%)	1 (0.4%)	3 (1.3%)	5 (2.2%)
6E-oriented STEM					2 (0.9%)	2 (0.9%)
Inquiry and design-based					1 (0.4%)	1 (0.4%)
Inquiry and problem-based					1 (0.4%)	1 (0.4%)
Design and problem-based					1 (0.4%)	1 (0.4%)
Problem and 6E-oriented-based					1 (0.4%)	1 (0.4%)
Others		1 (0.4%)	3 (1.3%)	2 (0.9%)	17 (7.4%)	23 (10.0%)
Total	8 (3.5%)	14 (6.1%)	31 (13.5%)	42 (18.3%)	134 (58.5%)	229 (100%)

Table 3 Frequency of the reviewed articles focused on instructional design to achieve STEM educational goals

Educational goals	Design-based	Inquiry-based	Project-based	Problem-based	Game-based	6E-oriented STEM	Inquiry and design-based	Inquiry and problem-based	Design and problem-based	Problem and 6E-oriented	Others	Total
Engagement and career choice (EC)	11 (4.8%)	14 (6.1%)	15 (6.6%)	6 (2.6%)	2 (0.9%)		1 (0.4%)				15 (6.6%)	64 (27.9%)
STEM literacy (SL)	28 (12.2%)	9 (3.9%)	9 (3.9%)	7 (3.1%)	1 (0.4%)	2 (0.9%)			1 (0.4%)		4 (1.7%)	61 (26.6%)
EC & SL	15 (6.6%)	14 (6.1%)	9 (3.9%)	6 (2.6%)	1 (0.4%)					1 (0.4%)	1 (0.4%)	47 (20.5%)
EC & 21st C	5 (2.2%)	3 (1.3%)	6 (2.6%)	4 (1.7%)								18 (7.9%)
21st competencies (21stC)	7 (3.1%)	2 (0.9%)	1 (0.4%)	4 (1.7%)	1 (0.4%)						1 (0.4%)	16 (7.0%)
SL & 21st C	7 (3.1%)	3 (1.3%)										10 (4.4%)
EC, SL & 21st C	3 (1.3%)	1 (0.4%)	2 (0.9%)					1 (0.4%)			2 (0.9%)	9 (3.9%)
NGSS	3 (1.3%)											3 (1.3%)
EC & NGSS	1 (0.4%)											1 (0.4%)
Total	80 (34.9%)	46 (20.1%)	42 (18.3%)	27 (11.8%)	5 (2.2%)	2 (0.9%)	1 (0.4%)	1 (0.4%)	1 (0.4%)	1 (0.4%)	23 (10.0%)	229 (100%)

STEM educational goals

EC: engagement and career choice; SL: STEM literacy; 21st C: Twenty-first century competencies; NGSS: next generation science standard

STEM literacy (14 articles). Also, more articles (15 articles) adopted project-based learning to achieve engagement and career choice. Furthermore, more design-based learning (7 articles) and problem-based learning (4 articles) than inquiry-based learning (2 articles) and project-based learning (1) articles were adopted to achieve twenty-first century competencies.

As we identified that a major portion of the articles adopted design-based learning, inquiry-based learning, and project-based learning focused on engagement and career choice, STEM literacy, and a combination of engagement and career choice and STEM literacy (see Table 3), we focused further analysis on the outcomes of STEM educational goals in the articles. The total number of selected articles was 124, of which 54 adopted design-based learning, 37 adopted inquiry-based learning, and 33 adopted project-based learning (Table 4).

We categorized the outcomes of STEM education goals into three categories (positively improved, partially improved, and none) (Amador et al., 2021). Table 4 shows that the majority of selected articles adopted design-based, inquiry-based, and project-based learning, improving STEM educational goals positively. Most selected articles found that design-based learning positively improved engagement and career choice (10 articles), STEM literacy (26 articles), and a combination of engagement and career choice and STEM literacy (15 articles). Also, most of the selected articles indicated that inquiry learning has a positive impact on engagement and career choice (14 articles), STEM literacy (7 articles), and a combination of engagement and career choice and STEM literacy (13 articles). Project-based learning has demonstrated a beneficial impact on various outcomes, as reported across the selected literature. Specifically, 12 articles documented the enhancement of engagement and career decisions, nine indicated the advancement of STEM literacy, and six discussed a combined effect on engagement, career choice, and STEM literacy.

Table 4 Frequency of the reviewed articles adopted instructional design to achieve STEM educational goals

STEM educational goals	Instructional designs			Sum
	Design-based (54)	Inquiry-based (37)	Project-based (33)	
Engagement and career choice (EC)				
Positively improved	10	14	12	36
Partially improved	–	–	2	2
None	1	–	1	2
STEM literacy (SL)				
Positively improved	26	7	9	42
Partially improved	2	1	–	3
None	–	1	–	1
EC & SL				
Positively improved	15	13	6	34
Partially improved	–	1	3	4
None	–	–	–	–

Frequently used features of STEM instructional designs

To identify the frequently used features of STEM instructional design, we further explored the activities in the selected articles. As previous results show that the major part of articles adopted design-based learning, inquiry-based learning, and project-based learning, we further analyzed the frequently used features of these STEM instructional designs that focused on engagement and career choice, STEM literacy, and combination of engagement and career choice and STEM literacy (see Table 3). We selected 54 articles that adopted design-based learning, 37 adopted inquiry-based learning, and 33 adopted project-based learning (Table 5).

Frequently used features of design-based learning

Based on the findings, a large portion of the selected articles adopted design-based learning for STEM education (54 articles). Table 5 shows the features that were adopted to implement instructional design for design-based learning. More than half of the selected articles adopted designing, building, testing, collaborating, experimenting, and reflecting. Building (88.9%), designing (87.0%), and testing (70.4%) were used to engage students in engineering (Yata et al., 2020). Besides, engaging students in these activities required students to use their knowledge and skills (Kelley & Knowles, 2016). For example, Aranda et al. (2020) and Lie et al. (2019) implemented design-based learning by asking students to design a process to

Table 5 Frequency of the reviewed articles focused on features of each instructional design

Features	Design-based learning (54)	Inquiry-based learning (37)	Project-based learning (33)
Building	48 (88.9%)	9 (24.3%)	10 (30.3%)
Designing	47 (87.0%)	8 (21.6%)	9 (27.3%)
Testing	38 (70.4%)	5 (13.5%)	13 (39.4%)
Collaborating	35 (64.8%)	31 (83.8%)	16 (48.5%)
Experimenting	29 (53.7%)	34 (91.9%)	16 (48.5%)
Reflecting	28 (51.9%)	23 (62.2%)	17 (51.5%)
Redesigning	27 (50.0%)	–	–
Analyzing	19 (35.2%)	16 (43.2%)	11 (33.3%)
Communicating	19 (35.2%)	19 (51.4%)	–
Identifying problem	18 (33.3%)	1 (2.7%)	16 (48.5%)

both prevent and test for cross-pollination of non-GMO from GMO fields. In these selected articles, the curriculums were focused on helping students with designing, building, and testing.

Collaborating, which engages students in working with their classmates in the process of design-based learning, was also mainly emphasized in the selected articles (64.8%). For instance, English and King (2019) asked students to work with their groups to discuss the possible design of the bridge. Researchers also emphasized experimenting (53.7%) to engage students in design-based learning. English (2019) engaged students in investigating their feet and shoes. Students collected, represented, analyzed data, and drew conclusions from their findings. Lie et al. (2019) helped students conduct an investigation to prevent cross-contamination of non-GMO from GMO corn fields. The last critical feature of design-based learning is reflecting (51.9%). In this activity, students engaged in assessing their solutions against a set of criteria and constraints, generating, and evaluating solutions (Cunningham et al., 2019). By engaging students in reflecting, students have an opportunity to improve their design and choose their best strategy (Aranda et al., 2020; Lie et al., 2019).

Frequently used features of inquiry-based learning

As shown in Table 5, the inquiry-based learning approach was frequently adopted by researchers for STEM education. The features of this approach applied to achieve specific STEM education goals (e.g., engagement and career choice, and STEM literacy) included experimenting (91.9%), collaborating (83.8%), reflecting (62.2%), and communicating (51.4%) (see Table 5). This finding indicated that the top three frequently used features of inquiry-based learning in STEM were experimenting, collaborating, and reflecting, which play an essential role when learners try out their ideas about a real-world problem related to STEM. For example, a four-phase inquiry (clarifying the situation, hands-on experiments, representing, analyzing the produced data, and reporting/whole-class discussions) for authentic modeling tasks guided students to develop their credibility of the tasks and to acquire STEM knowledge (Carreira & Baioa, 2018).

Frequently used features of project-based learning

As previously mentioned, project-based learning is one of the major approaches to support instructional design in the reviewed STEM education studies. The results shown in Table 5 further indicate the features that researchers tended to integrate into instructional design for project-based learning. More than half (51.5%) of the selected articles reported "reflecting" as a pivotal part of teaching that triggered students' project-based learning. Reflecting is deemed to depict learners' active perceptions and deliberation of what they encounter and what they are doing. This may contribute to their competence to retrieve appropriate information, to provide feedback, and to revise the project underlying their learning. For example, in Dasgupta et al.'s (2019) study, a design journal was utilized to help students' reflection on what they knew, what is necessary to know, as well as their learning outcomes. Vallera and Bodzin (2020) also addressed the critical design features of their curriculum to help students achieve information obtaining, evaluating, and communicating in the learning project based on real-world contexts.

Besides, researchers focused on project-based learning regarding STEM have a tendency to foster students' learning via "identifying problems" (48.5%). These studies can be differentiated into two types based on whether the researchers provided a driving question for the learning project. In Vallera and Bodzin's (2020) study, the instructional design arranged a clear-cut driving question to guide students' thinking about helping farmers to prepare products for sale in a farmers' market. This led students to extend their thinking and identify further problems while solving the driving question. As for Barak and Assal's (2018) study, their instructional design provided open-ended tasks and ill-defined problems. Such arrangements were deemed to afford students' learning through problem defining and learning objective setting.

It is also noteworthy to mention that the percentages of "experimenting" and "collaborating" in studies involved with project-based learning design were lower than those of studies with design-based learning or inquiry-based learning. However, researchers who were interested in STEM project-based learning would still to some extent agree with instructional design that may provide opportunities to students to access authentic scientific activities and social communications.

Discussion

This study focused on analyzing the STEM educational goals and instructional designs adopted in the 2012–2021 articles. The findings of this study present knowledge and understanding of the educational goals that need to be considered in STEM education, and how these goals could be achieved by adopting various STEM instructional designs.

Educational goals for STEM education

The majority of reviewed articles adopted instructional designs to achieve the goals of engagement, career choice and STEM literacy. In contrast, few articles focused on twenty-first century competencies. It is not surprising because many recent studies in nature emphasized economic viewpoints and workplace-readiness outcomes in the STEM education field (Cheng et al., 2021; Kelley & Knowles, 2016). The aspects of engagement and career choice were frequently considered in many previous studies on STEM education (Struyf et al., 2019; Vongkulluksn et al., 2018; Vossen et al., 2018). It indicated that engagement and career choice are important goals for STEM education (Honey et al., 2014; Hsu & Fang, 2019; Kelley & Knowles, 2016). Engaging and motivating students in STEM education are necessary to enhance their understanding of their future careers (Fleer, 2021) and to cultivate them to continue STEM learning (Maltese et al., 2014). Students who were motivated and interested in STEM education would pursue STEM careers (Maltese & Tai, 2011). Furthermore, the aspects of STEM literacy are also addressed in the reviewed articles. The aspects of STEM literacy (e.g., knowledge and capabilities) are deemed important for students' productive engagement with STEM studies, issues, and practices (Falloon et al., 2020). The focus of STEM literacy encourages students to apply their knowledge to life situations and solve problems (Bybee, 2010). The importance of STEM literacy has been highlighted in several national documents (e.g., Committee on STEM Education of the National Science & Technology Council, 2018; National Research Council, 2011; U.S. Department of Education, 2016). These findings provide insights into what teaching goals have been focused on in STEM education. For instance, engagement and career choice have been mainly focused on in STEM education because the STEM teaching was designed to connect to the students' real-world experiences or future professional situations (Strobel et al., 2013). The authentic and meaningful experience could engage and motivate students in the activity, and later they should pursue their future careers related to what they have learned.

However, there are few selected articles focused on twenty-first century competencies, although many previous studies considered the twenty-first century competencies as important goals for students. Some studies have advocated that students should be engaged in interdisciplinary sets of complex problems and encourage them to use critical thinking and develop their creativity and innovation as well as collaboration (Finegold & Notabartolo, 2010; Jang, 2016). Engaging students in STEM education focused on twenty-first century competencies could prepare them for the workplace and help them become successful in STEM-related fields (Jang, 2016). Future researchers should consider integrating twenty-first century competencies into STEM education to complement the existing focus on engagement, career choice, and STEM literacy, preparing students for a broader range of skills necessary for the modern workforce.

Instructional design for STEM education

Although the reviewed articles adopted various instructional designs for STEM education, the articles mostly adopted design-based rather than inquiry-based, project-based, or problem-based learning. The findings are in accordance with the existing literature on STEM education. Notably, these results corroborate the conclusions drawn from a comprehensive systematic review conducted by Mclure et al. (2022). Design-based learning was adopted to achieve the goals of STEM literacy, engagement and career choice, and this instructional design tended to be used more often according to the trend analysis. This indicated that design-based learning was considered as a main instructional design for STEM education. This instructional design has become an essential approach to engaging K-12 students in STEM education (Bybee, 2013; National Academy of Engineering & National Research Council, 2014; National Research Council, 2013). Some researchers claimed that students who participate in design-based learning could make meaningful connections between knowledge and skills by solving problems (English & King, 2019; Kelley et al., 2010). Design-based learning engages students in authentic problems and challenges that increase their level of engagement (Sadler et al., 2000), help students learn fundamental scientific principles (Mehalik et al., 2008), and build students' natural and intuitive experience (Fortus et al., 2004). In the process of design, students learn the concepts of science, technology, and mathematics in the process of designing, building, or testing products (Yata et al., 2020). For instance, students have to learn the concept of energy to design a house that produces more renewable energy than it consumes over a period of 1 year (Zheng et al., 2020). It was also found that the majority of selected articles which adopted design-based learning successfully improved learners' engagement, career choice, and STEM literacy (Table 4). The results align with the findings of a previous meta-analysis focusing on STEM education at the middle school level (Thomas & Larwin, 2023). K-12 students' STEM learning successfully improved because the selected articles reported studies conducting design-based learning in K-12 education. For example, Cunningham et al. (2019) successfully implemented design-based learning to improve elementary students' learning outcomes, while Fan et al. (2018) found that design-based learning positively improved secondary students' conceptual knowledge and attitude.

However, the selected articles have not equally used the features of design-based learning such as collaborating, reflecting, and redesigning. We identified that the selected articles mainly used designing, building, and testing to engage students in engineering activities.

One of the explanations for this finding is that researchers may face challenges in implementing a full cycle of design-based learning because of the time limit of instruction, so they only focus on the process of designing, building, and testing. Collaborating, reflecting, and redesigning should be emphasized while adopting effective design-based learning because students could solve complex problems by collaborating with others. With collaboration, the students can learn/solve problems through discussion within the group. This activity allows students to share new ideas and debate with others to generate solutions. Reflecting on the data and experience allows students to make improvements to their model and leads them to redesign it to produce a better model. This process could also grow students' science knowledge (Fortus et al., 2004). This finding hence suggests future studies, and educators emphasize more collaborating, reflecting, and redesigning for design-based learning for STEM instruction.

Moreover, inquiry-based learning, project-based learning, and problem-based learning were adopted in some selected articles. Inquiry-based learning was considered to enable and to promote connections within and across curriculum disciplines and improve students' engagement in STEM education (Attard et al., 2021). Project-based and problem-based learning can be used to engage students in authentic problems (Blumenfeld et al., 1991) and to improve their engagement in STEM education (Beckett et al., 2016). Furthermore, we identified that inquiry-based learning mainly engages students in experimenting, collaborating, and reflecting (Kim, 2016), and project-based learning (Han et al., 2015) mainly engages students in identifying problems and reflecting. This finding reveals the frequently used features of inquiry-based learning and project-based learning. Teachers could use these components of instructional design for preparing their instruction for teaching STEM. Given these findings, it is advisable to explore the integration of inquiry-based, project-based, and problem-based learning alongside design-based learning in STEM education. Such an approach may enhance the effectiveness of STEM education by providing a more comprehensive strategy to improve STEM literacy, engagement, and career choice among K-12 students.

However, we identified that some essentials of these instructional designs have not been included in selected articles. For instance, studies adopting inquiry-based learning rarely asked students to propose their questions, although questioning is one of the frequently used features of inquiry (National Research Council, 2012, 2013). One of the possible explanations for this finding is that students may have a lack of experience with inquiry learning and not know how to formulate meaningful questions, and they may tend to propose low-level factual questions related to their personal interests (Krajcik et al., 1998). Besides, STEM education requires students to engage in complex real-world problems, which requires sufficient ability to propose meaningful questions. Yet, we expect that future studies and teachers should encourage students to propose their own questions because questioning improves students' creativity, critical thinking, and problem solving skills (Hofstein et al., 2005). Teachers could start asking students to propose their own questions once they have experience and ability to propose good questions. Krajcik et al. (1998) suggested providing situations in which students can receive informative and critical feedback from teachers, classmates, and others so as to propose their own significant questions.

Conclusions

From an instructional design perspective, this study provides crucial insights into practical STEM education approaches. The findings underscore the importance of aligning instructional designs with specific STEM educational goals. The trend analysis revealed a significant increase in focus on engagement, career choice, and STEM literacy from 2014 to 2021, with a particularly sharp rise observed between 2018 and 2021. Each instructional design approach demonstrated unique strengths: design-based learning fosters STEM literacy. In contrast, inquiry-based and project-based learning effectively enhanced engagement and career choice. The study delineates specific features of these instructional designs that contribute to their success, such as building and testing in design-based learning, experimenting and collaborating in inquiry-based learning, and reflecting and problem identification in project-based learning.

Furthermore, this study advocates for a deliberate and systematic application of inquiry-based and project-based learning alongside design-based learning. Such integration is likely to cultivate a more dynamic and interactive learning environment that encourages critical thinking, problem-solving, and collaborative skills among students. The integration of twenty-first century competencies in the instructional design of STEM, though less presented, suggests a potential research space for further exploration of STEM teaching. This study recommends an expanded focus on incorporating these competencies to ensure a holistic educational approach that addresses immediate educational goals and equips students with essential skills for future challenges.

Teachers' limited understanding of STEM instructional design also presents a significant challenge, necessitating targeted professional development initiatives. Educators must comprehend and implement a comprehensive approach that aligns educational goals with appropriate instructional designs to optimize STEM learning outcomes. This approach involves clearly defining learning objectives, such as STEM literacy, selecting suitable instructional designs, and effectively guiding students through the chosen learning process.

The findings in this study furnish instructional designers and educators with a clear framework for developing targeted STEM curricula. The research accentuates the importance of aligning instructional design features with specific educational goals, suggesting that a nuanced, goal-oriented approach to STEM instruction can significantly enhance student outcomes in literacy, engagement, and career readiness. These insights offer a robust foundation for refining and optimizing instructional design strategies in STEM education.

Appendix 1
Description of STEM education goals

STEM education goals	Brief description	Representational articles
Engagement and career choice	The goals of instruction focus on students' emotional responses to learning STEM subjects and pursuing a professional degree in one of the STEM fields	Fan et al. (2018)
STEM literacy	The goals of instruction focus on students' ability to apply concepts from science, technology, engineering, and mathematics to solve problems that cannot be solved with a single subject	Vallera and Bodzin (2020)
21st-century competencies	The goals of instruction focus on students' abilities of critical thinking, creativity, innovation, leadership, and adaptability which can be used to adapt in the twenty-first century	Chen and Lin (2019)

Appendix 2
Description of the elements of instructional design for STEM education

Features	Brief description	Representational articles
Questioning or identifying problems	Students propose questions or identify problems in the STEM activity	Vallera and Bodzin (2020)
Designing	Students design their model	Aranda et al. (2020)
Building	Students build a prototype based on their model	English (2019)
Testing	Students test their design and prototype	Zheng et al., 2020
Redesigning	Students redesign their model after they test it	Lie et al. (2019)
Experimenting	Students engage in hands-on activities in the STEM education	Kim, 2016
Analyzing	Students use mathematics to analyze the data from the STEM activity	Berland et al. (2014)
Collaborating	Students interact or collaborate with other students to solve problems in the STEM activity	English and King (2019)
Reflecting	Students evaluate/assess their experience in the STEM activity	Dasgupta et al. (2019)
Communicating	Students present/share their work to/with the whole class	Chen and Lin (2019)

Acknowledgements
The authors express their sincere gratitude to the editors and reviewers for their invaluable inputs and suggestions, which have significantly enhanced the quality of this work.

Author contributions
SH contributed to the conception of the study, research question, methods, analysis, and interpretation of the data. TC contributed to the data collection, analysis and interpretation of data, and editing of the manuscript. YS contributed to the conception of the study, data analysis and interpretation, and editing of the manuscript. All authors equally contributed to writing, reading, and approving the manuscript.

Funding
This work was financially supported by the Institute for Research Excellence in Learning Sciences of National Taiwan Normal University (NTNU) from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan.

Availability of data and materials
No applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declare that they have no competing interests.

Received: 15 April 2024 Accepted: 24 August 2024
Published online: 05 September 2024

References

Amador, J. M., Bragelman, J., & Superfine, A. C. (2021). Prospective teachers' noticing: A literature review of methodological approaches to support and analyze noticing. *Teaching and Teacher Education*. https://doi.org/10.1016/j.tate.2020.103256

Andrews, T. C., Speer, N. M., & Shultz, G. V. (2022). Building bridges: A review and synthesis of research on teaching knowledge for undergraduate instruction in science, engineering, and mathematics. *International Journal of STEM Education, 9*(1), 66. https://doi.org/10.1186/s40594-022-00380-w

Aranda, M. L., Guzey, S. S., & Moore, T. J. (2020). Multidisciplinary discourses in an engineering design-based science curricular unit. *International Journal of Technology and Design Education, 30*(3), 507–529. https://doi.org/10.1007/s10798-019-09517-5

Attard, C., Berger, N., & Mackenzie, E. (2021). The positive influence of inquiry-based learning teacher professional learning and industry partnerships on student engagement with STEM. *Frontiers in Education*. https://doi.org/10.3389/feduc.2021.693221

Barak, M., & Assal, M. (2018). Robotics and STEM learning: Students' achievements in assignments according to the P3 Task Taxonomy-practice, problem solving, and projects. *International Journal of Technology and Design Education, 28*(1), 121–144. https://doi.org/10.1007/s10798-016-9385-9

Beckett, G. H., Hemmings, A., Maltbie, C., Wright, K., Sherman, M., & Sersion, B. (2016). Urban high school student engagement through cincySTEM iTEST projects. *Journal of Science Education and Technology, 25*(6), 995–1007. https://doi.org/10.1007/s10956-016-9640-6

Berland, L., Steingut, R., & Ko, P. (2014). High school student perceptions of the utility of the engineering design process: Creating opportunities to engage in engineering practices and apply math and science content. *Journal of Science Education and Technology, 23*(6), 705–720. https://doi.org/10.1007/s10956-014-9498-4

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist, 26*(3–4), 369–398. https://doi.org/10.1080/00461520.1991.9653139

Boon, N. S. (2019). *Exploring STEM competences for the 21st century*. *Current and Critical Issues in Curriculum, Learning and Assessment 30.* Geneva: IBEU-NESCO. Retrieved June 19, 2022, from https://unesdoc.unesco.org/ark:/48223/pf0000368485.locale=en

Breiner, J. M., Harkness, S. S., Johnson, C. C., & Koehler, C. M. (2012). What is STEM? A discussion about conceptions of STEM in education and partnerships. *School Science and Mathematics, 112*(1), 3–11. https://doi.org/10.1111/j.1949-8594.2011.00109.x

Bryan, L. A., Moore, T. J., Johnson, C. C., & Roehrig, G. H. (2015). Integrated STEM education. In C. C. Johnson, E. E. Peters-Burton, & T. J. Moore (Eds.), *STEM roadmap: A framework for integration* (pp. 23–37). Taylor & Francis.

Bybee, R. W. (2010). Advancing STEM education: A 2020 vision. *Technology and Engineering Teacher, 70*(1), 30–35.

Bybee, R. W. (2013). *The case for STEM education*. NSTA press.

Capraro, R. M., Capraro, M. M., & Morgan, J. (Eds.). (2013). *Project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach* (2nd ed.). Sense.

Capraro, R. M., & Slough, S. W. (2013). Why PBL? Why STEM? Why now? an introduction to STEM project-based learning. In R. M. Capraro, M. M. Capraro, & J. R. Morgan (Eds.), *STEM Project-based learning: An integrated Science, Technology, Engineering, and Mathematics (STEM) approach* (pp. 1–5). Sense Publishers.

Carreira, S., & Baioa, A. M. (2018). Mathematical modelling with hands-on experimental tasks: On the student's sense of credibility. *ZDM-Mathematics Education, 50*(1–2), 201–215. https://doi.org/10.1007/s11858-017-0905-1

Chen, C. S., & Lin, J. W. (2019). A practical action research study of the impact of maker-centered STEM-PjBL on a rural middle school in Taiwan. *International Journal of Science and Mathematics Education, 17*, S85–S108. https://doi.org/10.1007/s10763-019-09961-8

Cheng, L., Antonenko, P., Ritzhaupt, A. D., & MacFadden, B. (2021). Exploring the role of 3D printing and STEM integration levels in students' STEM career interest. *British Journal of Educational Technology, 52*(3), 1262–1278. https://doi.org/10.1111/bjet.13077

Committee on STEM Education of the National Science & Technology Council. (2018). *Charting a course for success: America's strategy for STEM education*. Executive Office of the President National Science and Technology Council.

Cunningham, C. M., Lachapelle, C. P., Brennan, R. T., Kelly, G. J., Tunis, C. S. A., & Gentry, C. A. (2019). The impact of engineering curriculum design principles on elementary students' engineering and science learning. *Journal of Research in Science Teaching, 57*(3), 423–453. https://doi.org/10.1002/tea.21601

Dasgupta, C., Magana, A. J., & Vieira, C. (2019). Investigating the affordances of a CAD enabled learning environment for promoting integrated STEM learning. *Computers & Education, 129*, 122–142. https://doi.org/10.1016/j.compedu.2018.10.014

Ejiwale, J. (2013). Barriers to successful implementation of STEM education. *Journal of Education and Learning, 7*(2), 63–74.

English, L. D. (2016). STEM education K-12: Perspectives on integration. *International Journal of STEM Education, 3*(1), 3. https://doi.org/10.1186/s40594-016-0036-1

English, L. D. (2017). Advancing elementary and middle school STEM education. *International Journal of Science and Mathematics Education, 15*(1), 5–24. https://doi.org/10.1007/s10763-017-9802-x

English, L. D. (2019). Learning while designing in a fourth-grade integrated STEM problem. *International Journal of Technology and Design Education, 29*(5), 1011–1032. https://doi.org/10.1007/s10798-018-9482-z

English, L. D., & King, D. (2019). STEM integration in sixth grade: Designing and constructing paper bridges. *International Journal of Science and Mathematics Education, 17*(5), 863–884. https://doi.org/10.1007/s10763-018-9912-0

English, L. D., King, D., & Smeed, J. (2017). Advancing integrated STEM learning through engineering design: Sixth-grade students' design and construction of earthquake resistant buildings. *Journal of Educational Research, 110*(3), 255–271. https://doi.org/10.1080/00220671.2016.1264053

Falloon, G., Hatzigianni, M., Bower, M., Forbes, A., & Stevenson, M. (2020). Understanding K-12 STEM education: A framework for developing STEM literacy. *Journal of Science Education and Technology, 29*(3), 369–385. https://doi.org/10.1007/s10956-020-09823-x

Fan, S.-C., Yu, K.-C., & Lin, K.-Y. (2021). A framework for implementing an engineering-focused stem curriculum. *International Journal of Science and Mathematics Education, 19*(8), 1523–1541. https://doi.org/10.1007/s10763-020-10129-y

Fan, S.-C., Yu, K.-C., & Lou, S.-J. (2018). Why do students present different design objectives in engineering design projects? *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-017-9420-5

Finegold, D., & Notabartolo, A. S. (2010). 21st century competencies and their impact: an interdisciplinary literature review. In D. Finegold, M. Gatta, H. Salzman, & S. J. Schurman (Eds.), *Transforming the US workforce development system* (pp. 19–56). Labor and Employment Relations Association.

Fleer, M. (2021). When preschool girls engineer: Future imaginings of being and becoming an engineer. *Learning Culture and Social Interaction, 30*, 100372. https://doi.org/10.1016/j.lcsi.2019.100372

Fortus, D., Dershimer, R. C., Krajcik, J., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-based science and student learning. *Journal of Research in Science Teaching, 41*(10), 1081–1110. https://doi.org/10.1002/tea.2004

Gladstone, J. R., & Cimpian, A. (2021). Which role models are effective for which students? A systematic review and four recommendations for maximizing the effectiveness of role models in STEM. *International Journal of STEM Education, 8*(1), 59. https://doi.org/10.1186/s40594-021-00315-x

Gough, D., Oliver, S., & Thomas, J. (2012). Introducing systematic reviews. In D. Gough, S. Oliver, & J. Thomas (Eds.), *An introduction to systematic reviews* (pp. 1–16). Sage.

Grangeat, M., Harrison, C., & Dolin, J. (2021). Exploring assessment in STEM inquiry learning classrooms. *International Journal of Science Education, 43*(3), 345–361. https://doi.org/10.1080/09500693.2021.1903617

Guzey, S. S., Moore, T. J., Harwell, M., & Moreno, M. (2016). STEM integration in middle school life science: Student learning and attitudes. *Journal of Science Education and Technology, 25*(4), 550–560. https://doi.org/10.1007/s10956-016-9612-x

Halawa, S., Hsu, Y.-S., & Zhang, W.-X. (2023). Analysis of physics textbooks through the lens of inquiry practices. *The Asia-Pacific Education Researcher, 32*(4), 497–506. https://doi.org/10.1007/s40299-022-00671-4

Halawa, S., Hsu, Y.-S., & Zhang, W.-X. (2024). Inquiry activity design from Singaporean and indonesian physics textbooks. *Science & Education, 33*(3), 581–607. https://doi.org/10.1007/s11191-022-00396-2

Halawa, S., Hsu, Y.-S., Zhang, W.-X., Kuo, Y.-R., & Wu, J.-Y. (2020). Features and trends of teaching strategies for scientific practices from a review of 2008–2017 articles. *International Journal of Science Education, 42*(7), 1183–1206. https://doi.org/10.1080/09500693.2020.1752415

Han, S., Capraro, R., & Capraro, M. M. (2015). How science, technology, engineering, and mathematics (stem) project-based learning (pbl) affects high, middle, and low achievers differently: The impact of student factors on achievement. *International Journal of Science and Mathematics Education, 13*(5), 1089–1113. https://doi.org/10.1007/s10763-014-9526-0

Henderson, C., Beach, A., & Finkelstein, N. (2011). Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature. *Journal of Research in Science Teaching, 48*(8), 952–984. https://doi.org/10.1002/tea.20439

Hernandez, P. R., Bodin, R., Elliott, J. W., Ibrahim, B., Rambo-Hernandez, K. E., Chen, T. W., & de Miranda, M. A. (2014). Connecting the STEM dots: Measuring the effect of an integrated engineering design intervention. *International Journal of Technology and Design Education, 24*(1), 107–120. https://doi.org/10.1007/s10798-013-9241-0

Hofstein, A., Navon, O., Kipnis, M., & Mamlok-Naaman, R. (2005). Developing students' ability to ask more and better questions resulting from inquiry-type chemistry laboratories. *Journal of Research in Science Teaching, 42*(7), 791–806. https://doi.org/10.1002/tea.20072

Honey, M., Pearson, G., & Schweingruber, H. (Eds.). (2014). *STEM integration in K-12 education: Status, prospects and an agenda for research*. National Academies Press.

Hsu, Y.-S., & Fang, S.-C. (2019). Opportunities and challenges of STEM education. In Y.-S. Hsu & Y.-F. Yeh (Eds.), *Asia-Pacific STEM teaching practices: From theoretical frameworks to practices* (pp. 1–16). Springer Singapore.

Jackson, C., Mohr-Schroeder, M. J., Bush, S. B., Maiorca, C., Roberts, T., Yost, C., & Fowler, A. (2021). Equity-oriented conceptual framework for k-12 STEM literacy. *International Journal of STEM Education, 8*(1), 38. https://doi.org/10.1186/s40594-021-00294-z

Jang, H. (2016). Identifying 21st century STEM competencies using workplace data. *Journal of Science Education and Technology, 25*(2), 284–301. https://doi.org/10.1007/s10956-015-9593-1

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (2015). *STEM road map: A framework for integrated STEM Education*. Routledge.

Kang, J., Salonen, A., Tolppanen, S., Scheersoi, A., Hense, J., Rannikmae, M., & Keinonen, T. (2021). Effect of embedded careers education in science lessons on students' interest, awareness, and aspirations. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-021-10238-2

Kayan-Fadlelmula, F., Sellami, A., Abdelkader, N., & Umer, S. (2022). A systematic review of STEM education research in the GCC countries: Trends, gaps and barriers. *International Journal of STEM Education, 9*(1), 2. https://doi.org/10.1186/s40594-021-00319-7

Kelley, T. R., Brenner, D. C., & Pieper, J. T. (2010). Two approaches to engineering design: Observations in STEM education. *Journal of STEM Teacher Education, 47*(2), 5–40.

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*(1), 11. https://doi.org/10.1186/s40594-016-0046-z

Kim, H. (2016). Inquiry-based science and technology enrichment program for middle school-aged female students. *Journal of Science Education and Technology, 25*(2), 174–186. https://doi.org/10.1007/s10956-015-9584-2

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences, 7*(3–4), 313–350. https://doi.org/10.1080/10508406.1998.9672057

Lamb, R., Akmal, T., & Petrie, K. (2015). Development of a cognition-priming model describing learning in a STEM classroom. *Journal of Research in Science Teaching, 52*(3), 410–437. https://doi.org/10.1002/tea.21200

Lederman, N. G., & Lederman, J. S., et al. (2012). Nature of scientific knowledge and scientific inquiry: Building instructional capacity through professional development. In B. J. Fraser (Ed.), *Second international handbook of science education* (pp. 335–359). Springer.

Lie, R., Guzey, S. S., & Moore, T. J. (2019). Implementing engineering in diverse upper elementary and middle school science classrooms: Student learning and attitudes. *Journal of Science Education and Technology, 28*(2), 104–117. https://doi.org/10.1007/s10956-018-9751-3

Lin, K.-Y., Hsiao, H.-S., Williams, P. J., & Chen, Y.-H. (2020). Effects of 6E-oriented STEM practical activities in cultivating middle school students' attitudes toward technology and technological inquiry ability. *Research in Science & Technological Education, 38*(1), 1–18. https://doi.org/10.1080/02635143.2018.1561432

López, N., Morgan, D. L., Hutchings, Q. R., & Davis, K. (2022). Revisiting critical STEM interventions: A literature review of STEM organizational learning. *International Journal of STEM Education, 9*(1), 39. https://doi.org/10.1186/s40594-022-00357-9

Maltese, A. V., Melki, C. S., & Wiebke, H. L. (2014). The nature of experiences responsible for the generation and maintenance of interest in STEM. *Science Education, 98*(6), 937–962. https://doi.org/10.1002/sce.21132

Maltese, A. V., & Tai, R. H. (2011). Pipeline persistence: Examining the association of educational experiences with earned degrees in STEM among US students. *Science Education, 95*(5), 877–907. https://doi.org/10.1002/sce.20441

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

Martín-Páez, T., Aguilera, D., Perales-Palacios, F. J., & Vílchez-González, J. M. (2019). What are we talking about when we talk about STEM education? *A Review of Literature. Science Education, 103*(4), 799–822. https://doi.org/10.1002/sce.21522

McHugh, M. L. (2012). Interrater reliability: The kappa statistic. *Biochemia Medica, 22*, 276–282.

McLure, F. I., Tang, K.-S., & Williams, P. J. (2022). What do integrated STEM projects look like in middle school and high school classrooms? A systematic literature review of empirical studies of iSTEM projects. *International Journal of STEM Education, 9*(1), 73. https://doi.org/10.1186/s40594-022-00390-8

Means, B., Wang, H., Wei, X., Lynch, S., Peters, V., Young, V., & Allen, C. (2017). Expanding STEM opportunities through inclusive STEM-focused high schools. *Science Education, 101*(5), 681–715. https://doi.org/10.1002/sce.21281

Mehalik, M. M., Doppelt, Y., & Schuun, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education, 97*(1), 71–85. https://doi.org/10.1002/j.2168-9830.2008.tb00955.x

Møller, A. M., & Myles, P. S. (2016). What makes a good systematic review and meta-analysis? *BJA British Journal of Anaesthesia, 117*(4), 428–430. https://doi.org/10.1093/bja/aew264

National Academy of Engineering and National Research Council. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. National Academies Press.

National Research Council. (2011). *Successful K-12 STEM education: Identifying effective approaches in science, technology, engineering, and mathematics*. National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. The National Academies Press.

National Research Council. (2013). *Monitoring progress toward successful K-12 STEM education: A nation advancing?* National Academies Press. https://doi.org/10.17226/13509

Nguyen, K. A., Borrego, M., Finelli, C. J., DeMonbrun, M., Crockett, C., Tharayil, S., Shekhar, P., Waters, C., & Rosenberg, R. (2021). Instructor strategies to aid implementation of active learning: A systematic literature review. *International Journal of STEM Education, 8*(1), 9. https://doi.org/10.1186/s40594-021-00270-7

Preininger, A. M. (2017). Embedded mathematics in chemistry: A case study of students' attitudes and mastery. *Journal of Science Education and Technology, 26*(1), 58–69. https://doi.org/10.1007/s10956-016-9651-3

Priemer, B., Eilerts, K., Filler, A., Pinkwart, N., Rösken-Winter, B., Tiemann, R., & Zu Belzen, A. U. (2020). A framework to foster problem-solving in STEM and computing education. *Research in Science & Technological Education, 38*(1), 105–130. https://doi.org/10.1080/02635143.2019.1600490

Sadler, P. M., Coyle, H. P., & Schwartz, M. (2000). Engineering competitions in the middle school classroom: Key elements in developing effective design challenges. *Journal of the Learning Sciences, 9*(3), 299–327. https://doi.org/10.1207/S15327809JLS0903_3

Sanders, M. (2009). STEM, STEM education, STEMmania. *The Technology Teacher, 68*(4), 20–26.

Sanders, M. E., & Wells, J. (2006). *Integrative STEM education course syllabi & instructional materials: STEM education foundations*. In STEM Education Trends & Issues, STEM Education Seminar.

Schütte, K., & Köller, O. (2015). 'Discover, understand, implement, and transfer': Effectiveness of an intervention programme to motivate students for science. *International Journal of Science Education, 37*(14), 2306–2325. https://doi.org/10.1080/09500693.2015.1077537

Shaughnessy, J. M. (2013). Mathematics in a STEM context. *Mathematics Teaching in the Middle School, 18*(6), 324. https://doi.org/10.5951/mathteacmiddscho.18.6.0324

Sinatra, G. M., Mukhopadhyay, A., Allbright, T. N., Marsh, J. A., & Polikoff, M. S. (2017). Speedometry: A vehicle for promoting interest and engagement through integrated STEM instruction. *Journal of Educational Research, 110*(3), 308–316. https://doi.org/10.1080/00220671.2016.1273178

Smyrnaiou, Z., Georgakopoulou, E., & Sotiriou, S. (2020). Promoting a mixed-design model of scientific creativity through digital storytelling—the CCQ model for creativity. *International Journal of STEM Education, 7*(1), 25. https://doi.org/10.1186/s40594-020-00223-6

Stehle, S. M., & Peters-Burton, E. E. (2019). Developing student 21st Century skills in selected exemplary inclusive STEM high schools. *International Journal of STEM Education, 6*(1), 39. https://doi.org/10.1186/s40594-019-0192-1

Strobel, J., Wang, J., Weber, N. R., & Dyehouse, M. (2013). The role of authenticity in design-based learning environments: The case of engineering education. *Computers & Education, 64*, 143–152. https://doi.org/10.1016/j.compedu.2012.11.026

Struyf, A., De Loof, H., Boeve-de Pauw, J., & Van Petegem, P. (2019). Students' engagement in different STEM learning environments: Integrated STEM education as promising practice? *International Journal of Science Education, 41*(10), 1387–1407. https://doi.org/10.1080/09500693.2019.1607983

Sullivan, A., & Bers, M. U. (2019). Investigating the use of robotics to increase girls' interest in engineering during early elementary school. *International Journal of Technology and Design Education, 29*(5), 1033–1051. https://doi.org/10.1007/s10798-018-9483-y

Thomas, D. R., & Larwin, K. H. (2023). A meta-analytic investigation of the impact of middle school STEM education: Where are all the students of color? *International Journal of STEM Education, 10*(1), 43. https://doi.org/10.1186/s40594-023-00425-8

U.S. Department of Education. (2016). *STEM 2026: A vision for innovation in STEM education*. U.S. Department of Education.

Vallera, F. L., & Bodzin, A. M. (2020). Integrating STEM with AgLIT (Agricultural literacy through innovative technology): The efficacy of a project-based curriculum for upper-primary students. *International Journal of Science and Mathematics Education, 18*(3), 419–439. https://doi.org/10.1007/s10763-019-09979-y

Vongkulluksn, V. W., Matewos, A. M., Sinatra, G. M., & Marsh, J. A. (2018). Motivational factors in makerspaces: A mixed methods study of elementary school students' situational interest, self-efficacy, and achievement emotions. *International Journal of STEM Education, 5*(1), 43. https://doi.org/10.1186/s40594-018-0129-0

Vossen, T. E., Henze, I., Rippe, R. C. A., Van Driel, J. H., & De Vries, M. J. (2018). Attitudes of secondary school students towards doing research and design activities. *International Journal of Science Education, 40*(13), 1629–1652. https://doi.org/10.1080/09500693.2018.1494395

Wilson, K. (2021). Exploring the challenges and enablers of implementing a STEM project-based learning programme in a diverse junior secondary context. *International Journal of Science and Mathematics Education, 19*(5), 881–897. https://doi.org/10.1007/s10763-020-10103-8

Wu, Y., Guo, S., & Zhu, L. (2019). Design and implementation of data collection mechanism for 3D design course based on xAPI standard. *Interactive Learning Environments, 28*(5), 602–619. https://doi.org/10.1080/10494820.2019.1696842

Yata, C., Ohtani, T., & Isobe, M. (2020). Conceptual framework of STEM based on Japanese subject principles. *International Journal of STEM Education, 7*(1), 12. https://doi.org/10.1186/s40594-020-00205-8

Zheng, J., Xing, W., Zhu, G., Chen, G., Zhao, H., & Xie, C. (2020). Profiling self-regulation behaviors in STEM learning of engineering design. *Computers & Education*. https://doi.org/10.1016/j.compedu.2019.103669

Publisher's Note

Suarman Halawa is a researcher at the Research Center for Education at the National Research and Innovation Agency in Jakarta, Indonesia. He received his Ph.D. degree from the Graduate Institute of Science Education at the National Taiwan Normal University, Taiwan. His research interests are teaching strategies, learning strategies, STEM education, scientific practices, learning technology, and learning interests.

Tzu-Chiang Lin is an Assistant Professor at the Center for Teacher Education at National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan. He obtained his Ph.D. degree from Department of Life Science, National Taiwan Normal University, Taiwan. His research interests include biology education, science teacher education, TPACK, scaffolding, and conception of learning science.

Ying-Shao Hsu is a Professor at the Graduate Institute of Science Education and the Department of Earth Science at National Taiwan Normal University in Taipei, Taiwan. She received her Ph.D. degree from the Department of Curriculum and Instruction at Iowa State University, USA. Her research focuses on Socio-Scientific Issues (SSI), inquiry learning, science curriculum design, metacognition, and STEM education.