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Trends and research foci of robotics-based STEM education: a systematic review from diverse angles based on the technology-based learning model

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Abstract

Fostering students' competence in applying interdisciplinary knowledge to solve problems has been recognized as an important and challenging issue globally. This is why STEM (Science, Technology, Engineering, Mathematics) education has been emphasized at all levels in schools. Meanwhile, the use of robotics has played an important role in STEM learning design. The purpose of this study was to fill a gap in the current review of research on Robotics-based STEM (R-STEM) education by systematically reviewing existing research in this area. This systematic review examined the role of robotics and research trends in STEM education. A total of 39 articles published between 2012 and 2021 were analyzed. The review indicated that R-STEM education studies were mostly conducted in the United States and mainly in K-12 schools. Learner and teacher perceptions were the most popular research focus in these studies which applied robots. LEGO was the most used tool to accomplish the learning objectives. In terms of application, Technology (programming) was the predominant robotics-based STEM discipline in the R-STEM studies. Moreover, project-based learning (PBL) was the most frequently employed learning strategy in robotics-related STEM research. In addition, STEM learning and transferable skills were the most popular educational goals when applying robotics. Based on the findings, several implications and recommendations to researchers and practitioners are proposed.

Keywords Literature review, STEM education, Robots, Interdisciplinary projects, Twenty-first century skills

Introduction

Over the past few years, implementation of STEM (Science, Technology, Engineering, and Mathematics) education has received a positive response from researchers and practitioners alike. According to Chesloff (2013), the winning point of STEM education is its learning process, which validates that students can use their creativity, collaborative skills, and critical thinking skills. Consequently, STEM education promotes a bridge between learning in authentic real-life scenarios (Erdoğan et al., 2016; Kelley & Knowles, 2016). This is the greatest challenge facing STEM education. The learning experience and real-life situation might be intangible in some areas due to pre- and in-conditioning such as unfamiliarity with STEM content (Moomaw, 2012), unstructured learning activities (Sarama & Clements, 2009), and inadequate preparation of STEM curricula (Conde et al., 2021).

In response to these issues, the adoption of robotics in STEM education has been encouraged as part of an innovative and methodological approach to learning (Bargagna et al., 2019; Ferreira et al., 2018; Kennedy et al., 2015; Köse

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et al., 2015). Similarly, recent studies have reported that the use of robots in school settings has an impact on student curiosity (Adams et al., 2011), arts and craftwork (Sullivan & Bers, 2016), and logic (Bers, 2008). When robots and educational robotics are considered a core part of STEM education, it offers the possibility to promote STEM disciplines such as engineering concepts or even interdisciplinary practices (Okita, 2014). Anwar et. al. (2019) argued that integration between robots and STEM learning is important to support STEM learners who do not immediately show interest in STEM disciplines. Learner interest can elicit the development of various skills such as computational thinking, creativity and motivation, collaboration and cooperation, problem-solving, and other higher-order thinking skills (Evripidou et al., 2020). To some extent, artificial intelligence (AI) has driven the use of robotics and tools, such as their application to designing instructional activities (Hwang et al., 2020). The potential for research on robotics in STEM education can be traced by showing the rapid increase in the number of studies over the past few years. The emphasis is on critically reviewing existing research to determine what prior research already tells us about R-STEM education, what it means, and where it can influence future research. Thus, this study aimed to fill the gap by conducting a systematic review to grasp the potential of R-STEM education.

In terms of providing the core concepts of roles and research trends of R-STEM education, this study explored beyond the scope of previous reviews by conducting content analysis to see the whole picture. To address the following questions, this study analyzed published research in the Web of Science database regarding the technology-based learning model (Lin & Hwang, 2019):

1. In terms of research characteristic and features, what were the location, sample size, duration of intervention, research methods, and research foci of the R-STEM education research?
2. In terms of interaction between participants and robots, what were the participants, roles of the robot, and types of robot in the R-STEM education research?
3. In terms of application, what were the dominant STEM disciplines, contribution to STEM disciplines, integration of robots and STEM, pedagogical interventions, and educational objectives of the R-STEM research?

Literature review

Previous studies have investigated the role of robotics in R-STEM education from several research foci such as the specific robot users (Atman Uslu et al., 2022; Benitti, 2012; Jung & Won, 2018; Spolaôr & Benitti, 2017; van den Berghe et al., 2019), the potential value of R-STEM education (Çetin & Demircan, 2020; Conde et al., 2021; Zhang et al., 2021), and the types of robots used in learning practices (Belpaeme et al., 2018; Çetin & Demircan, 2020; Tselegkaridis & Sapounidis, 2021). While their findings provided a dynamic perspective on robotics, they failed to contribute to the core concept of promoting R-STEM education. Those previous reviews did not summarize the exemplary practice of employing robots in STEM education. For instance, Spolaôr and Benitti (2017) concluded that robots could be an auxiliary tool for learning but did not convey whether the purpose of using robots is essential to enhance learning outcomes. At the same time, it is important to address the use and purpose of robotics in STEM learning, the connections between theoretical pedagogy and STEM practice, and the reasons for the lack of quantitative research in the literature to measure student learning outcomes.

First, Benitti (2012) reviewed research published between 2000 and 2009. This review study aimed to determine the educational potential of using robots in schools and found that it is feasible to use most robots to support the pedagogical process of learning knowledge and skills related to science and mathematics. Five years later, Spolaôr and Benitti (2017) investigated the use of robots in higher education by employing the adopted-learning theories that were not covered in their previous review in 2012. The study's content analysis approach synthesized 15 papers from 2002 to 2015 that used robots to support instruction based on fundamental learning theory. The main finding was that project-based learning (PBL) and experiential learning, or so-called hands-on learning, were considered to be the most used theories. Both theories were found to increase learners' motivation and foster their skills (Behrens et al., 2010; Jou et al., 2010). However, the vast majority of discussions of the selected reviews emphasized positive outcomes while overlooking negative or mixed outcomes. Along the same lines, Jung and Won (2018) also reviewed theoretical approaches to Robotics education in 47 studies from 2006 to 2017. Their focused review of studies suggested that the employment of robots in learning should be shifted from technology to pedagogy. This review paper argued to determine student engagement in robotics education, despite disagreements among pedagogical traits. Although Jung and Won (2018) provided information of teaching approaches applied in robotics education, they did not offer critical discussion on how those approaches were formed between robots and the teaching disciplines.

On the other hand, Conde et. al. (2021) identified PBL as the most common learning approach in their study by reviewing 54 papers from 2006 to 2019. Furthermore, the studies by Çetin and Demircan (2020) and Tselegkaridis and Sapounidis (2021) focused on the types of robots used in STEM education and reviewed 23 and 17 papers, respectively. Again, these studies touted learning engagement as a positive outcome, and disregarded the different perspectives of robot use in educational settings on students' academic performance and cognition. More recently, a meta-analysis by Zhang et. al. (2021) focused on the effects of robotics on students' computational thinking and their attitudes toward STEM learning. In addition, a systematic review by Atman Uslu et. al. (2022) examined the use of educational robotics and robots in learning.

So far, the review study conducted by Atman Uslu et. al. (2022) could be the only study that has attempted to clarify some of the criticisms of using educational robots by reviewing the studies published from 2006 to 2019 in terms of their research issues (e.g., interventions, interactions, and perceptions), theoretical models, and the roles of robots in educational settings. However, they failed to take into account several important features of robots in education research, such as thematic subjects and educational objectives, for instance, whether robot-based learning could enhance students' competence of constructing new knowledge, or whether robots could bring either a motivational facet or creativity to pedagogy to foster students' learning outcomes. These are essential in investigating the trends of technology-based learning research as well as the role of technology in education as a review study is aimed to offer a comprehensive discussion which derived from various angles and dimensions. Moreover, the role of robots in STEM education was generally ignored in the previous review studies. Hence, there is still a need for a comprehensive understanding of the role of robotics in STEM education and research trends (e.g., research issues, interaction issues, and application issues) so as to provide researchers and practitioners with valuable references. That is, our study can remedy the shortcomings of previous reviews (Additional file 1).

The above comments demonstrate how previous scholars have understood what they call "the effectiveness of robotics in STEM education" in terms of innovative educational tools. In other words, despite their useful findings and ongoing recommendations, there has not been a thorough investigation of how robots are widely used from all angles. Furthermore, the results of existing review studies have been less than comprehensive in terms of the potential role of robotics in R-STEM education after taking into account various potential dimensions based on the technology-based model that we propose in this study.

Methods

Resources

The studies in this review were selected from the literature on the Web of Science, our sole database due to its rigorous journal research and qualified studies (e.g., Huang et al., 2022), discussing the adoption of R-STEM education, and the data collection procedures for this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) as referred to by prior studies (e.g., Chen et al., 2021a, 2021b; García-Martínez et al., 2020). Considering publication quality, previous studies (Fu & Hwang, 2018; Martín-Páez et al., 2019) suggested using Boolean expressions to search Web of Science databases. The search terms for "robot" are "robot" or "robotics" or "robotics" or "Lego" (Spolaôr & Benitti, 2017). According to Martín-Páez et. al. (2019), expressions for STEM education include "STEM" or "STEM education" or "STEM literacy" or "STEM learning" or "STEM teaching" or "STEM competencies". These search terms were entered into the WOS database to search only for SSCI papers due to its wide recognition as being high-quality publications in the field of educational technology. As a result, 165 papers were found in the database. The search was then restricted to 2012–2021 as suggested by Hwang and Tsai (2011). In addition, the number of papers was reduced to 131 by selecting only publications of the "article" type and those written in "English". Subsequently, we selected the category "education and educational research" which reduced the number to 60 papers. During the coding analysis, the two coders screened out 21 papers unrelated to R-STEM education. The coding result had a Kappa coefficient of 0.8 for both coders (Cohen, 1960). After the screening stage, a final total of 39 articles were included in this study, as shown in Fig. 1. Also, the selected papers are marked with an asterisk in the reference list and are listed in Appendixes 1 and 2.

Theoretical model, data coding, and analysis

This study comprised content analysis using a coding scheme to provide insights into different aspects of the studies in question (Chen et al., 2021a, 2021b; Martín-Páez et al., 2019). The coding scheme adopted the conceptual framework proposed by Lin and Hwang (2019), comprising "STEM environments", "learners", and "robots", as shown in Fig. 2. Three issues were identified:

(1) In terms of research issues, five dimensions were included: "location", "sample size", "duration of intervention", (Zhong & Xia, 2020) "research methods", (Johnson & Christensen, 2000) and "research foci". (Hynes et al., 2017; Spolaôr & Benitti, 2017).

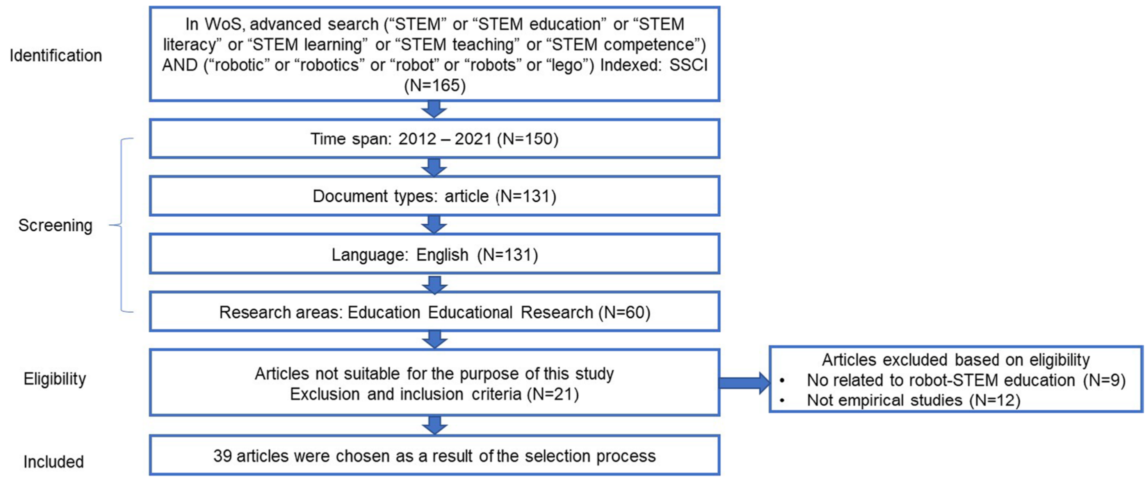

Fig. 1 PRISMA procedure for the selection process

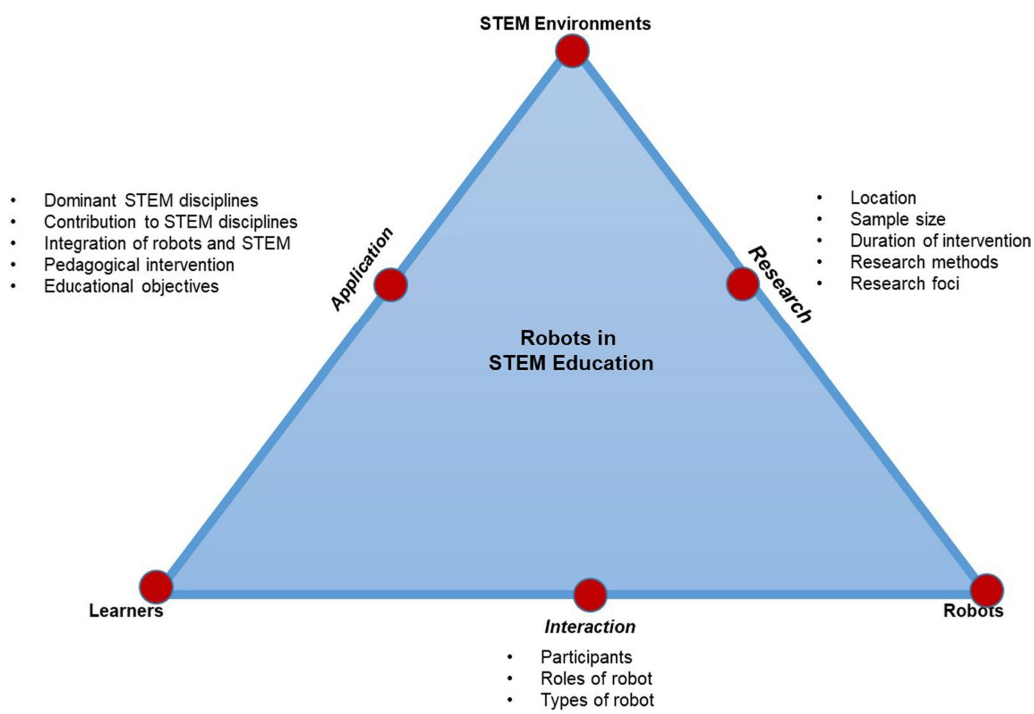

Fig. 2 Model of R-STEM education theme framework

(2) In terms of interaction issues, three dimensions were included: "participants", (Hwang & Tsai, 2011), "roles of the robot", and "types of robot" (Taylor, 1980).
(3) In terms of application, five dimensions were included, namely "dominant STEM disciplines", "integration of robot and STEM" (Martín-Páez et al., 2019), "contribution to STEM disciplines", "pedagogical intervention", (Spolaôr & Benitti, 2017) and "educational objectives" (Anwar et al., 2019). Table 1 shows the coding items in each dimension of the investigated issues.

Figure 3 shows the distribution of the publications selected from 2012 to 2021. The first two publications were found in 2012. From 2014 to 2017, the number of publications steadily increased, with two, three, four, and four publications, respectively. Moreover, R-STEM

Table 1 Coding schemes of the study

Issues	Dimensions	Coding items
Research	Location	Australia, Canada, China, Italy, Israel, Mexico, the Netherlands, Taiwan, Turkey, USA
	Sample size	1–20 people, 21–40 people, 41–60 people, 61–80 people, > 80 people
	Duration of intervention	Less than or equal to 1 day, less than or equal to 4 weeks, less than or equal to 8 weeks, less than or equal to 6 months, less than or equal to 12 months, non-specified
	Research methods	Experimental design, questionnaire or survey, mixed-method, system development
	Research foci	Cognition, affective, psychomotor aspects, learning behavior, correlation, and evaluating robots *Cognition*: learning performance, higher-order skills (problem-solving, critical thinking, logical thinking, creativity), collaboration or teamwork, communication, metacognition *Affective*: technology acceptance, attitude and motivation, self-efficacy, satisfaction or interest, learning perception, preview situation, cognitive load
Interaction	Participants	Kindergarten or preschool, elementary school, junior high or middle school, high school, university students (including pre-service teachers), in-service teachers, and non-specified
	Roles of robot	Tutor, tool, and tutee
	Types of robot	Arduino, Bee-bot, Robo-robo, Kiwi Kits, IRobot Create, LEGO (Mindstorms, bricks, wedo), Nao, Roamers, Dash, Vex, KIBO, non-specified
Application	Dominant STEM discipline	Science, Technology, Engineering, Mathematics, Interdisciplinary
	Contribution to STEM	Science: basic physics, biomechanics, biology, geography information systems, non-specified Technology: programming, internet of things, non-specified Engineering: engineering, mechanics, component design, digital signal process, structure and construction, power and dynamic systems, non-specified Mathematics: mathematics, mathematical methods, non-specified
	Integration of robot and STEM	Content integration, supporting content integration, context integration
	Pedagogical intervention	Project-based learning, constructivism, blended learning, collaborative learning, edutainment, engaged learning, experiential learning, problem-based learning, active construction, metacognitive
	Educational objectives	General benefits of educational robots, learning and transfer skills, creativity and motivation, diversity and broadening participation, and teachers' professional development

education has been increasingly discussed within the last 3 years (2018–2020) with six, three, and ten publications, respectively. The global pandemic in the early 2020s could have affected the number of papers published, with only five papers in 2021. This could be due to the fact that most robot-STEM education research is conducted in physical classroom settings.

Table 2 displays the journals in which the selected papers were published, the number of papers published in each journal, and the journal's impact factor. It can be concluded that most of the papers on R-STEM education research were published in the *Journal of Science Education and Technology*, and the *International Journal of Technology and Design Education*, with six papers, respectively.

Results

Research issues

Location

The geographic distribution of the reviewed studies indicated that more than half of the studies were conducted in the United States (53.8%), while Turkey and China were the location of five and three studies, respectively. Taiwan, Canada, and Italy were indicated to have two studies each. One study each was conducted in Australia, Mexico, and the Netherlands. Figure 4 shows the distribution of the countries where the R-STEM education was conducted.

Sample size

Regarding sample size, there were four most common sample sizes for the selected period (2012–2021): greater than 80 people (28.21% or 11 out of 39 studies), between 41 and 60 (25.64% or 10 out of 39 studies), 1 to 20 people (23.08% or 9 out of 39), and between 21 and 40 (20.51% or 8 out of 39 studies). The size of 61 to 80 people (2.56% or 1 out of 39 studies) was the least popular sample size (see Fig. 5).

Duration of intervention

Regarding the duration of the study (see Fig. 6), experiments were mostly conducted for less than or equal to 4 weeks (35.9% or 14 out of 39 studies). This was followed by less than or equal to 8 weeks (25.64% or 10 out of 39 studies), less than or equal to 6 months (20.51% or 8 out 39 studies), less than or equal to 12 months (10.26% or 4 out of 39 studies), while less than or equal to 1 day (7.69% or 3 out of 39 studies) was the least chosen duration.

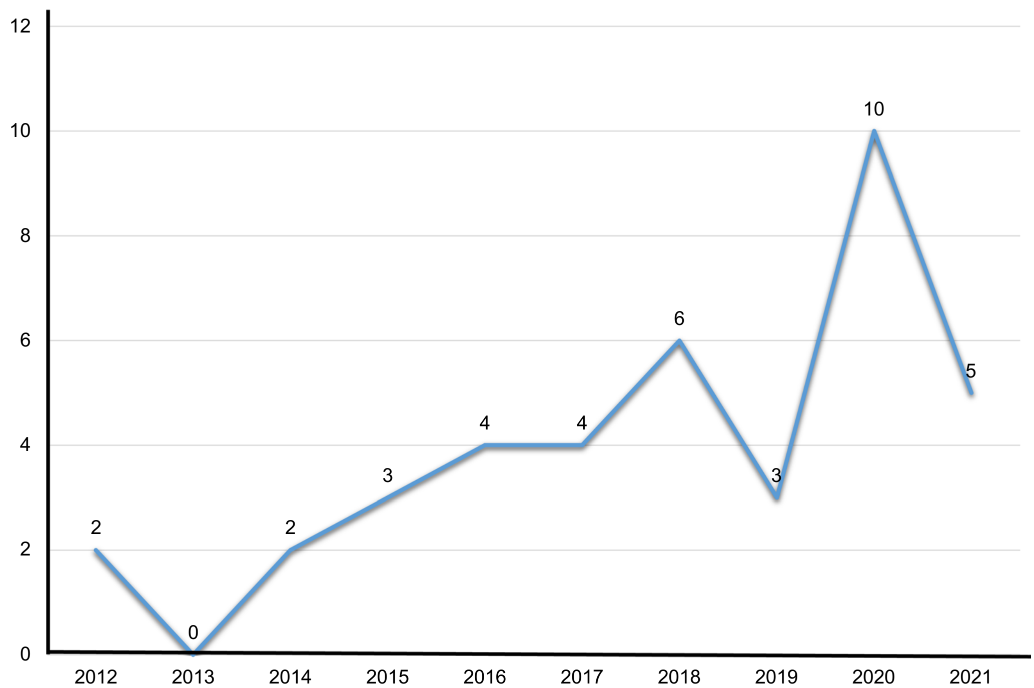

Fig. 3 Number of publications on R-STEM education from 2012 to 2021

Table 2 Journals publishing articles on R-STEM education, 2012–2021 ($N = 39$)

Journals	*N*	2020 IF
Journal of Science Education and Technology	6	2.315
International Journal of Technology and Design Education	6	2.177
International Journal of Engineering Education	3	0.969
Journal of Research on Technology in Education	3	2.043
Computers & Education	2	8.538
Educational Technology & Society	2	3.522
Interactive Learning Environments	2	3.928
British Journal of Educational Technology	1	4.929
Computer Applications in Engineering Education	1	1.532
Cultural Studies of Science Education	1	1.167
Education and Information Technologies	1	2.917
Educational Sciences-Theory & Practice	1	0.532
IEEE Transactions on Education	1	2.116
Instructional Science	1	2.620
International Journal of Disability Development and Education	1	1.543
Journal of Computer Assisted Learning	1	3.862
Journal of Educational Computing Research	1	3.088
Journal of Special Education	1	3.122
Journal of Teacher Education	1	5.357
Journal of The Learning Sciences	1	5.171
Research in Science Education	1	5.439
Thinking Skills and Creativity	1	3.106

Research methods

Figure 7 demonstrates the trends in research methods from 2012 to 2021. The use of questionnaires or surveys (35.9% or 14 out of 39 studies) and mixed methods research (35.9% or 14 out of 39 studies) outnumbered other methods such as experimental design (25.64% or 10 out of 39 studies) and system development (2.56% or 1 out of 39 studies).

Research foci

In these studies, research foci were divided into four aspects: cognition, affective, operational skill, and learning behavior. If the study involved more than one research focus, each issue was coded under each research focus.

In terms of cognitive skills, students' learning performance was the most frequently measured (15 out of 39 studies). Six studies found that R-STEM education brought a positive result to learning performance. Two studies did not find any significant difference, while five studies showed mixed results or found that it depends. For example, Chang and Chen (2020) revealed that robots in STEM learning improved students' cognition such as designing, electronic components, and computer programming.

In terms of affective skills, just over half of the reviewed studies (23 out of 39, 58.97%) addressed the students'

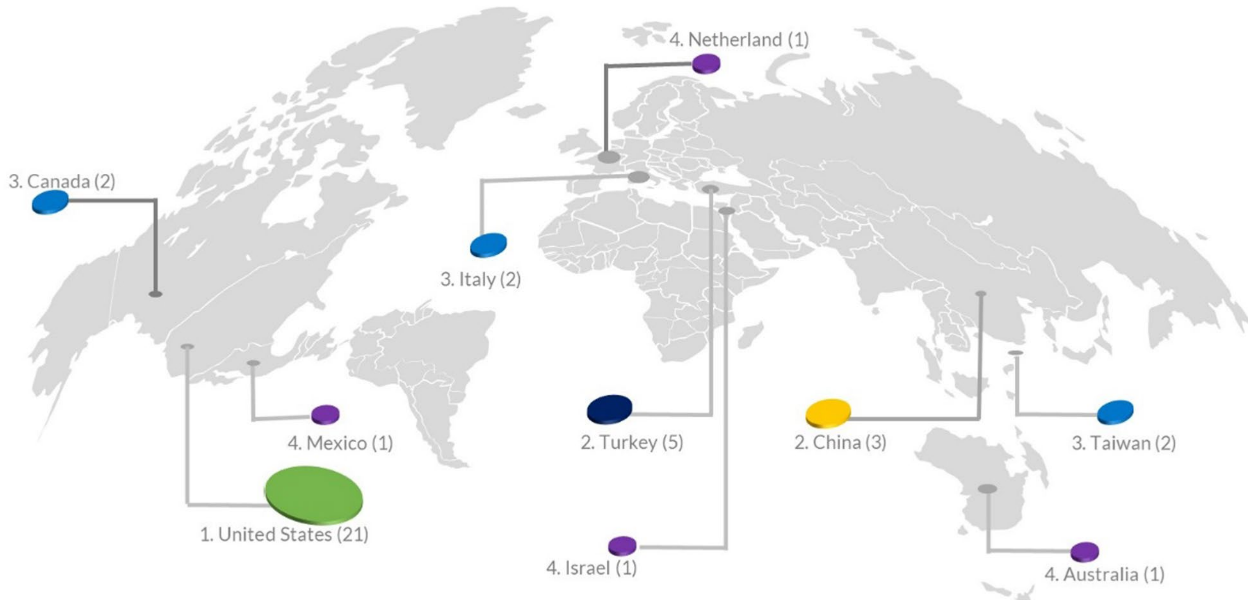

Fig. 4 Locations where the studies were conducted ($N=39$)

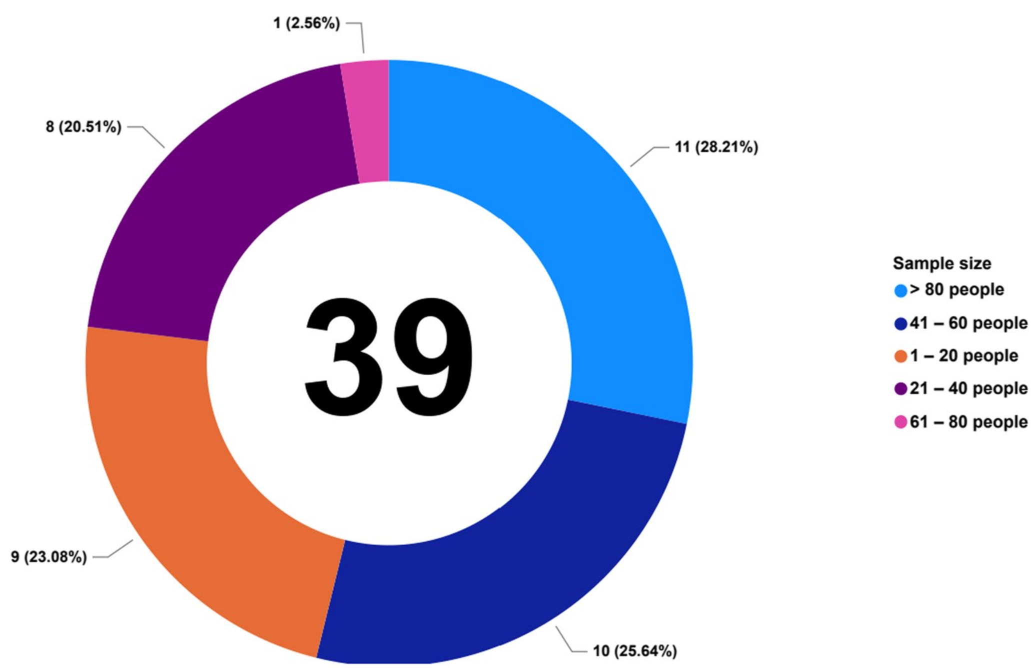

Fig. 5 Sample size across the studies ($N=39$)

or teachers' perceptions of employing robots in STEM education, of which 14 studies showed positive perceptions. In contrast, nine studies found mixed results. For instance, Casey et. al. (2018) determined students' mixed perceptions of the use of robots in learning coding and programming.

Five studies were identified regarding operational skills by investigating students' psychomotor aspects such as construction and mechanical elements (Pérez & López, 2019; Sullivan & Bers, 2016) and building and modeling robots (McDonald & Howell, 2012). Three studies found positive results, while two reported mixed results.

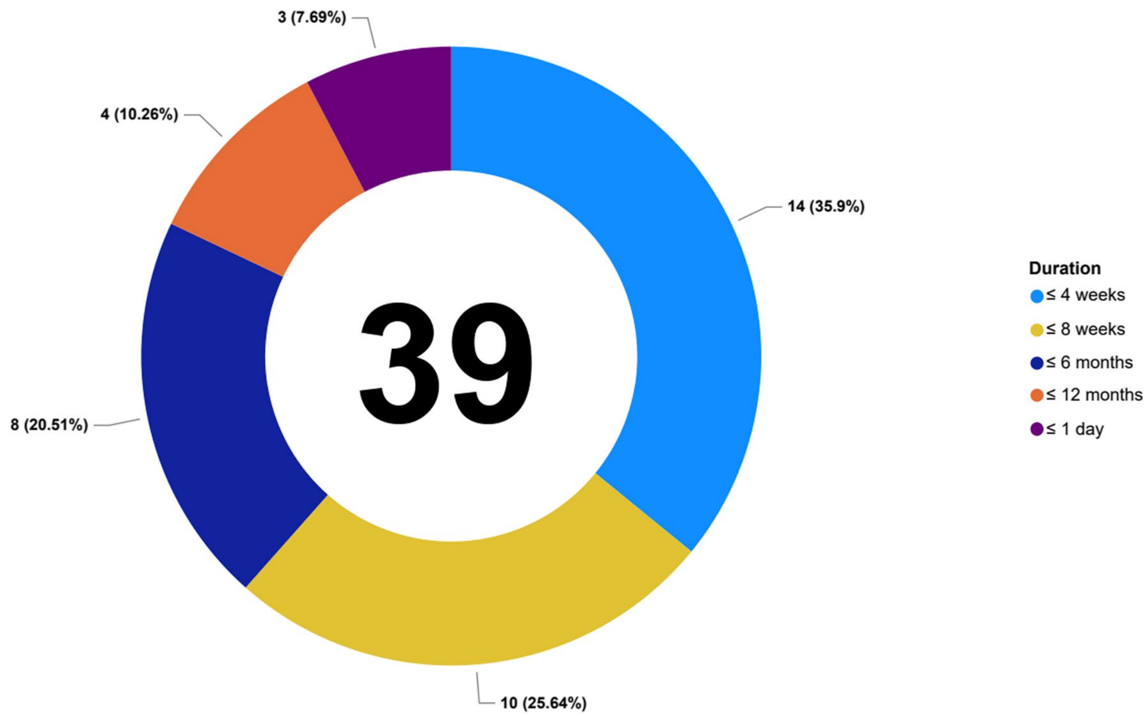

Fig. 6 Duration of interventions across the studies ($N = 39$)

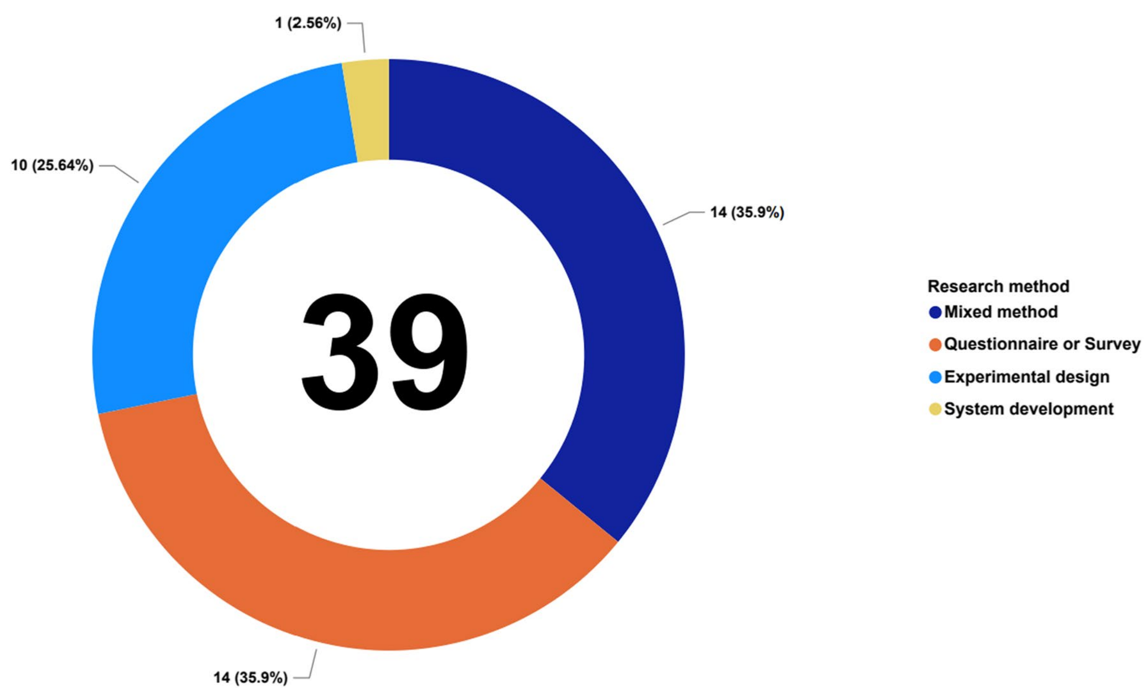

Fig. 7 Frequency of each research method used in 2012–2021

In terms of learning behavior, five out of 39 studies measured students' learning behavior, such as students' engagement with robots (Ma et al., 2020), students' social behavior while interacting with robots (Konijn & Hoorn, 2020), and learner–parent interactions with interactive robots (Phamduy et al., 2017). Three studies showed positive results, while two found mixed results or found that it depends (see Table 3).

Interaction issues

Participants

Regarding the educational level of the participants, elementary school students (33.33% or 13 studies) were the most preferred study participants, followed by high school students (15.38% or 6 studies). The data were similar for preschool, junior high school, in-service teachers, and non-designated personnel (10.26% or 4 studies). College students, including pre-service teachers, were the least preferred study participants. Interestingly, some studies involved study participants from more than one educational level. For example, Ucgul and Cagiltay (2014) conducted experiments with elementary and middle school students, while Chapman et. al. (2020) investigated the effectiveness of robots with elementary, middle, and high school students. One study exclusively investigated gifted and talented students without reporting their levels of education (Sen et al., 2021). Figure 8 shows the frequency of study participants between 2012 and 2021.

The roles of robot

For the function of robots in STEM education, as shown in Fig. 9, more than half of the selected articles used robots as tools (31 out of 39 studies, 79.49%) for which the robots were designed to foster students' programming ability. For instance, Barker et. al. (2014) investigated students' building and programming of robots in hands-on STEM activities. Seven out of 39 studies used robots as tutees (17.95%), with the aim of students and teachers learning to program. For example, Phamduy et. al. (2017) investigated a robotic fish exhibit to analyze visitors' experience of controlling and interacting with the robot. The least frequent role was tutor (2.56%), with only one study which programmed the robot to act as tutor or teacher for students (see Fig. 9).

Types of robot

Furthermore, in terms of the types of robots used in STEM education, the LEGO MINDSTORMS robot was the most used (35.89% or 14 out of 39 studies), while Arduino was the second most used (12.82% or 5 out of 39 studies), and iRobot Create (5.12% or 2 out of 39 studies), and NAO (5.12% or 2 out of 39 studies) ranked third equal, as shown in Fig. 10. LEGO was used to solve STEM problem-solving tasks such as building bridges (Convertini, 2021), robots (Chiang et al., 2020), and challenge-specific game boards (Leonard et al., 2018). Furthermore, four out of 36 studies did not specify the robots used in their studies.

Application issues

The dominant disciplines and the contribution to STEM disciplines

As shown in Table 4, the most dominant discipline in R-STEM education research published from 2012 to 2021 was technology. Engineering, mathematics, and science were the least dominant disciplines. Programming

Table 3 Robots' intervention in learning foci

Skill	Intervention	*N*	Sample research
Cognitive	Learning performance	15	Chapman et. al. (2020)[d]
	Problem-solving	6	Gomoll et. al. (2017)[a]
	Creativity	4	Guven et. al. (2020)[a]
	Collaboration or teamwork	4	Convertini (2021)[a]
	Communication	8	Hennessy Elliott (2020)[a]
	Critical thinking	1	Sen et. al. (2021)[a]
	Higher-order skills	1	Stewart et. al. (2021)[a]
Affective	Technology acceptance or intention of use	8	Barker et. al. (2014)[d]
	Attitude and motivation	10	Leonard et. al. (2016)[c]
	Self-efficacy, confidence, and anticipation performance	9	Castro et. al. (2018)[b]
	Satisfaction or interest	12	Chang et. al. (2022)[c]
	Opinion of learners/teachers	23	Casey et. al. (2018)[d]
	Preview situation	3	Taylor (2018)[d]
Psychomotor aspects (operational skill)		5	McDonald and Howell (2012)[a]
Learning behavior		5	Ma et. al. (2020)[a]

[a] Article(s) resulted positive results

[b] Article(s) resulted negative results

[c] Article(s) resulted no significant difference

[d] Article(s) resulted mixed or depends

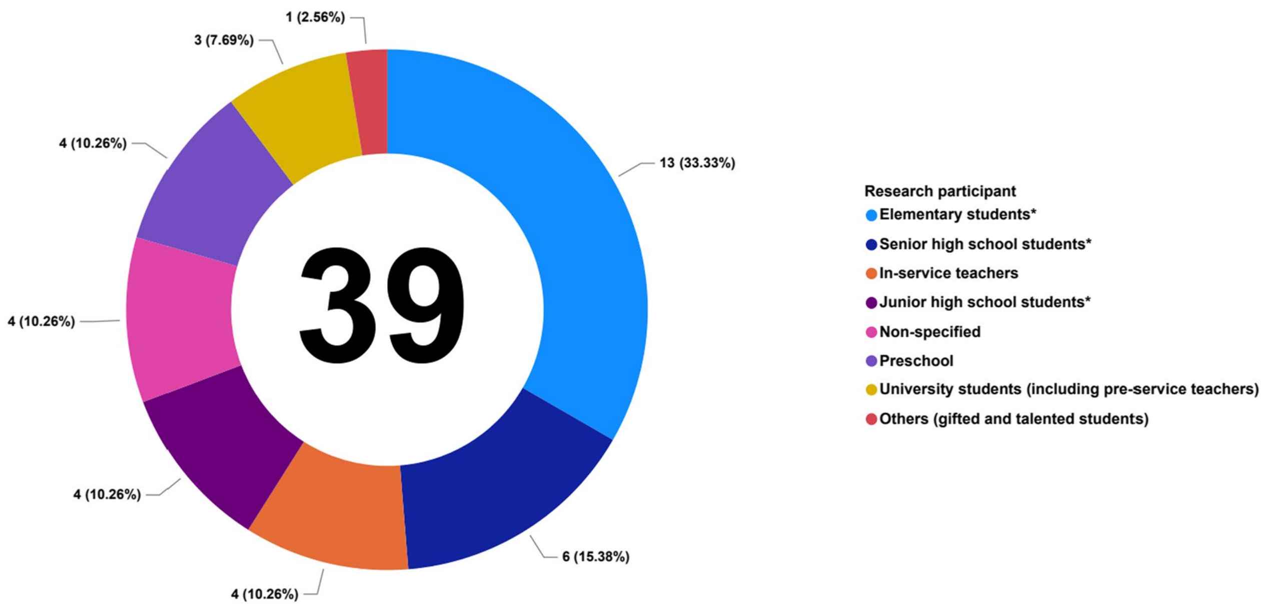

Fig. 8 Frequency of research participants in the selected period

was the most common subject for robotics contribution to the STEM disciplines (25 out of 36 studies, 64.1%), followed by engineering (12.82%), and mathematical method (12.82%). We found that interdisciplinary was discussed in the selected period, but in relatively small numbers. However, this finding is relevant to expose the use of robotics in STEM disciplines as a whole. For example, Barker et. al. (2014) studied how robotics instructional modules in geospatial and programming domains could be impacted by fidelity adherence and exposure to the modules. The dominance of STEM subjects based on robotics makes it necessary to study the way robotics and STEM are integrated into the learning process.

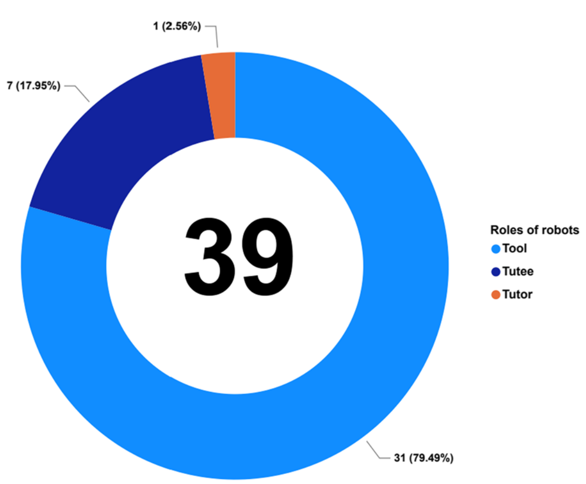

Fig. 9 Frequency of roles of robots

Therefore, the forms of STEM integration are discussed in the following sub-section to report how teaching and learning of these disciplines can have learning goals in an integrated STEM environment.

Integration of robots and STEM

There are three general forms of STEM integration (see Fig. 11). Of these studies, robot-STEM content integration was commonly used (22 studies, 56.41%), in which robot activities had multiple STEM disciplinary learning objectives. For example, Chang and Chen (2020) employed Arduino in a robotics sailboat curriculum. This curriculum was a cross-disciplinary integration, the objectives of which were understanding sailboats and sensors (Science), the direction of motors and mechanical structures (Engineering), and control programming (Technology). The second most common form was supporting robot-STEM content integration (12 out of 39 studies, 30.76%). For instance, KIBO robots were used in the robotics activities where the mechanical elements content area was meaningfully covered in support of the main programming learning objectives (Sullivan & Bers, 2019). The least common form was robot-STEM context integration (5 out of 39 studies, 12.82%) which was implemented through the robot to situate the disciplinary content goals in another discipline's practices. For example, Christensen et. al. (2015) analyzed the impact of an after-school program that offered robots as part of students' challenges in a STEM competition environment (geoscience and programming).

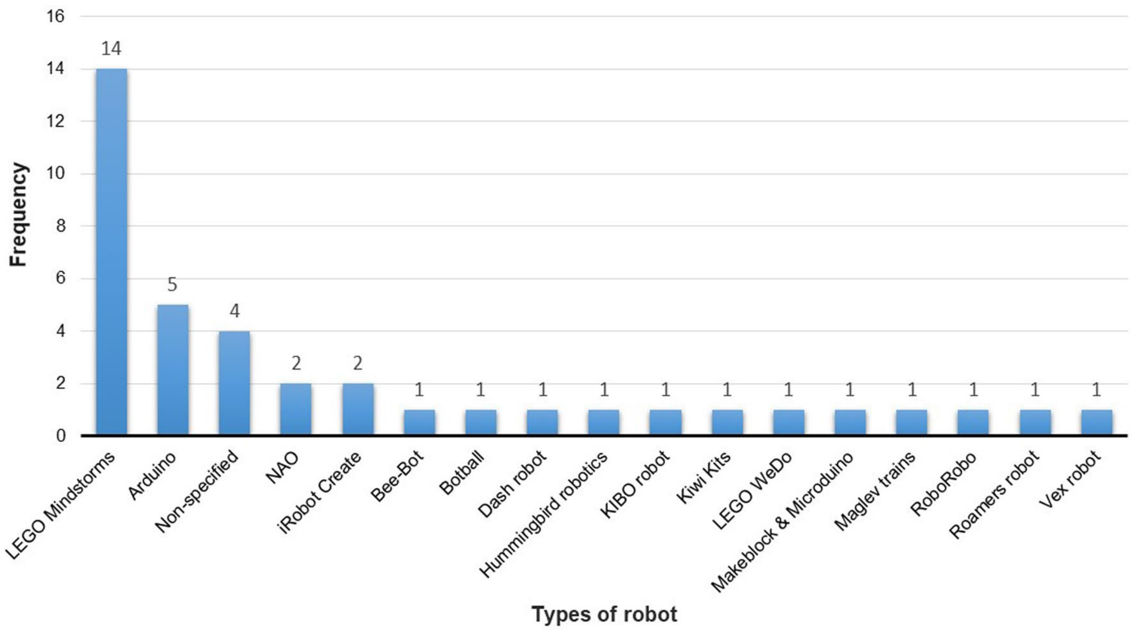

Fig. 10 Frequency of types of robots used

Table 4 The dominant robot-based STEM disciplines

Disciplines	Subject matter	*N*	Sample research
Science	Basic Physics	2	Chang and Chen (2020)[a]
	Biomechanics	1	Bernstein et. al. (2022)
	Biology	1	Phamduy et. al. (2017)
	Geography Information System (GIS)	1	Barker et. al. (2014)[a]
Technology	Programming	25	Kim et. al. (2015), Barak and Assal (2018)[a]
	Non-specified	2	Chiang et. al. (2020)
Engineering	Engineering	5	Ryan et. al. (2017), McDonald and Howell (2012)[a]
	Mechanics	2	Pérez and López (2019)[a]
	Component design	3	Ayar (2015)[a]
	Digital signal process	2	Sullivan and Bers (2016)
	Power and dynamical system	1	Stewart et. al. (2021)
	Structure and construction	4	Li et. al. (2016), Gomoll et. al. (2017)[a]
Mathematics	Mathematics	2	Ucgul and Cagiltay (2014)[a]
	Mathematical methods	5	Konijn and Hoorn (2020), Chang and Chen (2022)[a]
Interdisciplinary		3	Luo et. al. (2019)

[a] Some articles were focused on cross-subject matters or disciplines

Pedagogical interventions

In terms of instructional interventions, as shown in Fig. 12, project-based learning (PBL) was the preferred instructional theory for using robots in R-STEM education (38.46% or 15 out 39 studies), with the aim of motivating students or robot users in the STEM learning activities. For example, Pérez and López (2019) argued that using low-cost robots in the teaching process increased students' motivation and interest in STEM areas. Problem-based learning was the second most used intervention in this dimension (17.95% or 7 out of 39 studies). It aimed to improve students' motivation by giving them an early insight into practical Engineering and Technology. For example, Gomoll et. al. (2017) employed robots to connect students from two different areas to work collaboratively. Their study showed the importance of robotic engagement in preliminary learning activities. Edutainment (12.82% or 5 out of 39 studies) was the third

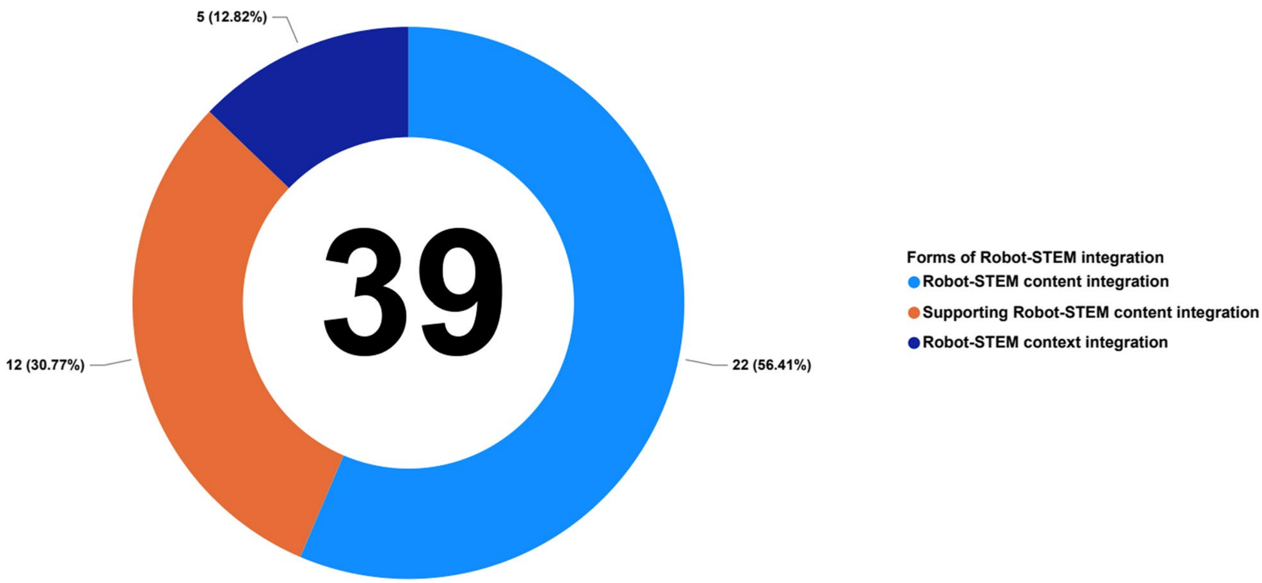

Fig. 11 The forms of robot-STEM integration

most used intervention. This intervention was used to bring together students and robots and to promote learning by doing. Christensen et. al. (2015) and Phamduy et. al. (2017) were the sample studies that found the benefits of hands-on and active learning engagement; for example, robotics competitions and robotics exhibitions could help retain a positive interest in STEM activities.

Educational objectives

As far as the educational objectives of robots are concerned (see Fig. 13), the majority of robots are used for learning and transfer skills (58.97% or 23 out of 39 studies) to enhance students' construction of new knowledge. It emphasized the process of learning through inquiry, exploration, and making cognitive associations

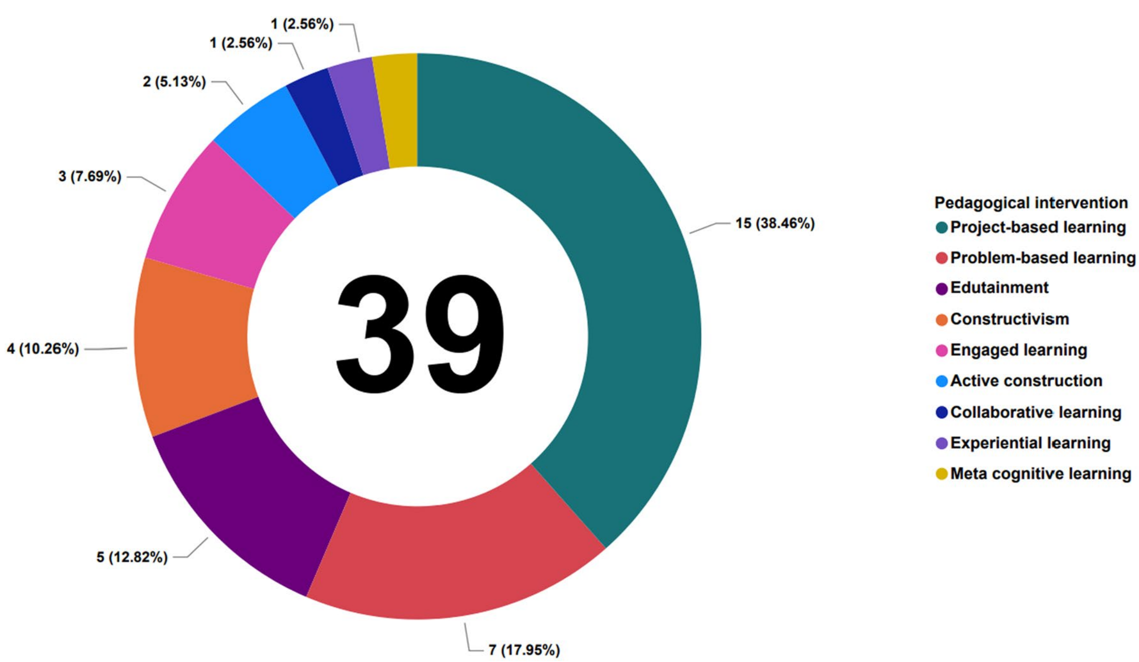

Fig. 12 The pedagogical interventions in R-STEM education

with prior knowledge. Chang and Chen's (2020) is a sample study on how learning objectives promote students' ability to transfer science and engineering knowledge learned through science experiments to design a robotics sailboat that could navigate automatically as a novel setting. Moreover, it also explicitly aimed to examine the hands-on learning experience with robots. For example, McDonald and Howell (2012) described how robots engaged with early year students to better understand the concepts of literacy and numeracy.

Creativity and motivation were found to be educational objectives in R-STEM education for seven out of 39 studies (17.94%). It was considered from either the motivational facet of social trend or creativity in pedagogy to improve students' interest in STEM disciplines. For instance, these studies were driven by the idea that employing robots could develop students' scientific creativity (Guven et al., 2020), confidence and presentation ability (Chiang et al., 2020), passion for college and STEM fields (Meyers et al., 2012), and career choice (Ayar, 2015).

The general benefits of educational robots and the professional development of teachers were equally found in four studies each. The first objective, the general benefits of educational robotics, was to address those studies that found a broad benefit of using robots in STEM education without highlighting the particular focus. The sample studies suggested that robotics in STEM could promote active learning and improve students' learning experience through social interaction (Hennessy Elliott, 2020) and collaborative science projects (Li et al., 2016). The latter, teachers' professional development, was addressed by four studies (10.25%) to utilize robots to enhance teachers' efficacy. Studies in this category discussed how teachers could examine and identify distinctive instructional approaches with robotics work (Bernstein et al., 2022), design meaningful learning instruction (Ryan et al., 2017) and lesson materials (Kim et al., 2015), and develop more robust cultural responsive self-efficacy (Leonard et al., 2018).

Discussion

This review study was conducted using content analysis from the WOS collection of research on robotics in STEM education from 2012 to 2021. The findings are discussed under the headings of each research question.

RQ 1: In terms of research, what were the location, sample size, duration of intervention, research methods, and research foci of the R-STEM education research?

About half of the studies were conducted in North America (the USA and Canada), while limited studies were found from other continents (Europe and the Asia Pacific). This trend was identified in the previous study on robotics for STEM activities (Conde et al., 2021). Among 39 studies, 28 (71.79%) had fewer than 80 participants, while 11 (28.21%) had more than 80 participants. The intervention's duration across the studies was almost equally divided between less than or equal to a month (17 out of 39 studies, 43.59%) and more than a month (22 out of 39 studies, 56.41%). The rationale behind the most

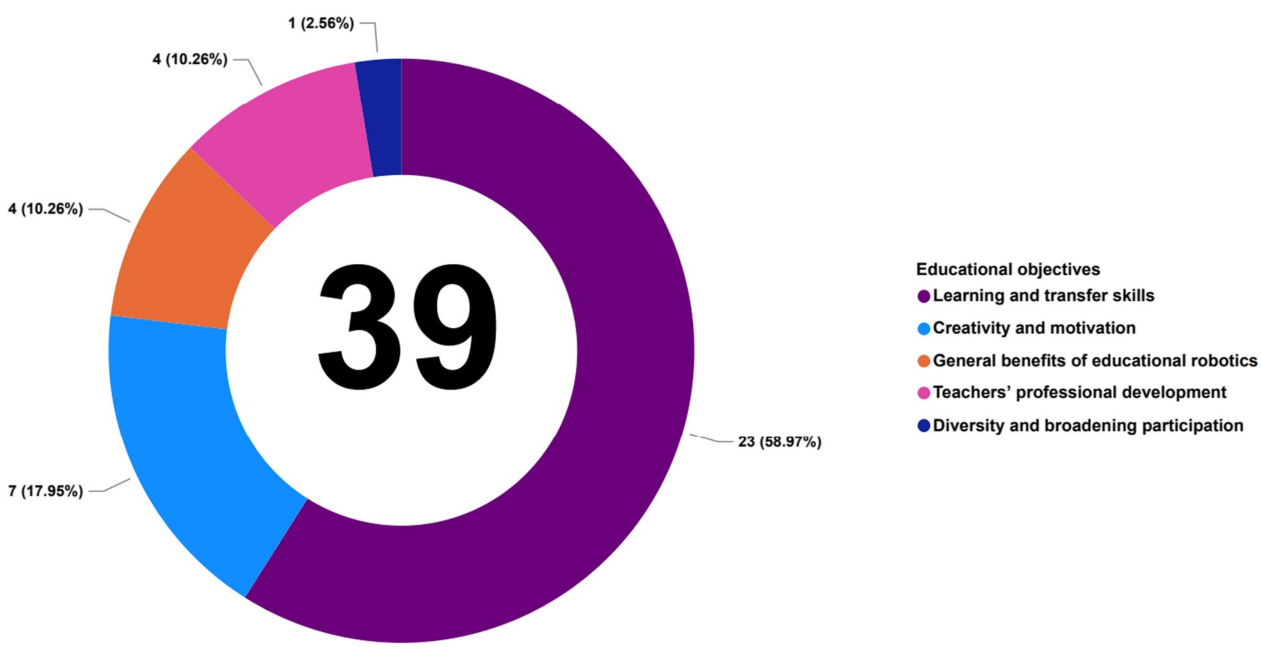

Fig. 13 Educational objectives of R-STEM education

popular durations is that these studies were conducted in classroom experiments and as conditional learning. For example, Kim et. al. (2018) conducted their experiments in a course offered at a university where it took 3 weeks based on a robotics module.

A total of four different research methodologies were adopted in the studies, the two most popular being mixed methods (35.89%) and questionnaires or surveys (35.89%). Although mixed methods can be daunting and time-consuming to conduct (Kucuk et al., 2013), the analysis found that it was one of the most used methods in the published articles, regardless of year. Chang and Chen (2022) embedded a mixed-methods design in their study to qualitatively answer their second research question. The possible reason for this is that other researchers prefer to use mixed methods as their research design. Their main research question was answered quantitatively, while the second and remaining research questions were reported through qualitative analysis (Casey et al., 2018; Chapman et al., 2020; Ma et al., 2020; Newton et al., 2020; Sullivan & Bers, 2019). Thus, it was concluded that mixed methods could lead to the best understanding and integration of research questions (Creswell & Clark, 2013; Creswell et al., 2003).

In contrast, system development was the least used compared to other study designs, as most studies used existing robotic systems. It should be acknowledged that the most common outcome we found was to enable students to understand these concepts as they relate to STEM subjects. Despite the focus on system development, the help of robotics was identified as increasing the success of STEM learning (Benitti, 2012). Because limited studies focused on system development as their primary purpose (1 out of 39 studies, 2.56%), needs analyses may ask whether the mechanisms, types, and challenges of robotics are appropriate for learners. Future research will need further design and development of personalized robots to fill this part of the research gap.

About half of the studies (23 studies, 58.97%) were focused on investigating the effectiveness of robots in STEM learning, primarily by collecting students' and teachers' opinions. This result is more similar to Belpaeme et al. (2018) finding that users' perceptions were common measures in studies on robotics learning. However, identifying perceptions of R-STEM education may not help us understand exactly how robots' specific features afford STEM learning. Therefore, it is argued that researchers should move beyond such simple collective perceptions in future research. Instead, further studies may compare different robots and their features. For instance, whether robots with multiple sensors, a sensor, or without a sensor could affect students' cognitive, metacognitive, emotional, and motivational in STEM areas (e.g., Castro et al., 2018). Also, there could be instructional strategies embedded in R-STEM education that can lead students to do high-order thinking, such as problem-solving with a decision (Özüorçun & Bicen, 2017), self-regulated and self-engagement learning (e.g., Li et al., 2016). Researchers may also compare the robotics-based approach with other technology-based approaches (e.g., Han et al., 2015; Hsiao et al., 2015) in supporting STEM learning.

RQ 2: In terms of interaction, what were the participants, roles of the robots, and types of robots of the R-STEM education research?

The majority of reviewed studies on R-STEM education were conducted with K-12 students (27 studies, 69.23%), including preschool, elementary school, junior, and high school students. There were limited studies that involved higher education students and teachers. This finding is similar to the previous review study (Atman Uslu et al., 2022), which found a wide gap among research participants between K-12 students and higher education students, including teachers. Although it is unclear why there were limited studies conducted involving teachers and higher education students, which include pre-service teachers, we are aware of the critical task of designing meaningful R-STEM learning experiences which is likely to require professional development. In this case, both pre- and in-service teachers could examine specific objectives, identify topics, test the application, and design potential instruction to align well with robots in STEM learning (Bernstein et al., 2022). Concurrently, these pedagogical content skills in R-STEM disciplines might not be taught in the traditional pre-service teacher education and particular teachers' development program (Huang et al., 2022). Thus, it is recommended that future studies could be conducted to understand whether robots can improve STEM education for higher education students and teachers professionally.

Regarding the role of robots, most were used as learning tools (31 studies, 79.48%). These robots are designed to have the functional ability to command or program some analysis and processing (Taylor, 1980). For example, Leonard et. al. (2018) described how pre-service teachers are trained in robotics activities to facilitate students' learning of computational thinking. Therefore, robots primarily provide opportunities for learners to construct knowledge and skills. Only one study (2.56%), however, was found to program robots to act as tutors or teachers for students. Designing a robot-assisted system has become common in other fields such as language learning (e.g., Hong et al., 2016; Iio et al., 2019) and special education (e.g., Özdemir & Karaman, 2017) where the robots instruct the learning activities for students. In contrast, R-STEM education has not looked at the robot as a tutor, but has instead focused on learning how to build robots (Konijn & Hoorn, 2020). It is argued that robots with features as human tutors, such as providing personalized guidance and feedback, could assist during problem-solving activities (Fournier-Viger et al., 2013). Thus, it is worth exploring in what teaching roles the robot will work best as a tutor in STEM education.

When it comes to types of robots, the review found that LEGO dominated robots' employment in STEM education (15 studies, 38.46%), while the other types were limited in their use. It is considered that LEGO tasks are more often associated with STEM because learners can be more involved in the engineering or technical tasks. Most researchers prefer to use LEGO in their studies (Convertini, 2021). Another interesting finding is about the cost of the robots. Although robots are generally inexpensive, some products are particularly low-cost and are commonly available in some regions (Conde et al., 2021). Most preferred robots are still considered exclusive learning tools in developing countries and regions. In this case, only one study offered a low-cost robot (Pérez & López, 2019). This might be a reason why the selected studies were primarily conducted in the countries and continents where the use of advanced technologies, such as robots, is growing rapidly (see Fig. 4). Based on this finding, there is a need for more research on the use of low-cost robots in R-STEM instruction in the least developed areas or regions of the world. For example, Nel et. al. (2017) designed a STEM program to build and design a robot which exclusively enabling students from low-income household to participate in the R-STEM activities.

RQ 3: In terms of application, what were the dominant STEM disciplines, contribution to STEM disciplines, integration of robots and STEM, pedagogical interventions, and educational objectives of the R-STEM research?

While Technology and Engineering are the dominant disciplines, this review found several studies that directed their research to interdisciplinary issues. The essence of STEM lies in interdisciplinary issues that integrate one discipline into another to create authentic learning (Hansen, 2014). This means that some researchers are keen to develop students' integrated knowledge of Science, Technology, Engineering, and Mathematics (Chang & Chen, 2022; Luo et al., 2019). However, Science and Mathematics were given less weight in STEM learning activities compared to Technology and Engineering. This issue has been frequently reported as a barrier to implementing R-STEM in the interdisciplinary subject. Some reasons include difficulties in pedagogy and classroom roles, lack of curriculum integration, and a limited opportunity to embody one learning subject into others (Margot & Kettler, 2019). Therefore, further research is encouraged to treat these disciplines equally, so is the way of STEM learning integration.

The subject-matter results revealed that "programming" was the most common research focus in R-STEM research (25 studies). Researchers considered programming because this particular topic was frequently emphasized in their studies (Chang & Chen, 2020, 2022; Newton et al., 2020). Similarly, programming concepts were taught through support robots for kindergarteners (Sullivan & Bers, 2019), girls attending summer camps (Chapman et al., 2020), and young learners with disabilities (Lamptey et al., 2021). Because programming simultaneously accompanies students' STEM learning, we believe future research can incorporate a more dynamic and comprehensive learning focus. Robotics-based STEM education research is expected to encounter many interdisciplinary learning issues.

Researchers in the reviewed studies agreed that the robot could be integrated with STEM learning with various integration forms. Bryan et. al. (2015) argued that robots were designed to develop multiple learning goals from STEM knowledge, beginning with an initial learning context. It is parallel with our finding that robot-STEM content integration was the most common integration form (22 studies, 56.41%). In this form, studies mainly defined their primary learning goals with one or more anchor STEM disciplines (e.g., Castro et al., 2018; Chang & Chen, 2020; Luo et al., 2019). The learning goals provided coherence between instructional activities and assessments that explicitly focused on the connection among STEM disciplines. As a result, students can develop a deep and transferable understanding of interdisciplinary phenomena and problems through emphasizing the content across disciplines (Bryan et al., 2015). However, the findings on learning instruction and evaluation in this integration are inconclusive. A better understanding of the embodiment of learning contexts is needed, for instance, whether instructions are inclusive, socially relevant, and authentic in the situated context. Thus, future research is needed to identify the quality of instruction and evaluation and the specific characteristics of robot-STEM integration. This may place better provision of opportunities for understanding the form of pedagogical content knowledge to enhance practitioners' self-efficacy and pedagogical beliefs (Chen et al., 2021a, 2021b).

Project-based learning (PBL) was the most used instructional intervention with robots in R-STEM education (15 studies, 38.46%). Blumenfeld et al. (1991) credited PBL with the main purpose of engaging students in investigating learning models. In the case of robotics, students can create robotic artifacts (Spolaôr & Benitti, 2017). McDonald and Howell (2012) used robotics to develop technological skills in lower grades. Leonard et. al. (2016) used robots to engage and develop students' computational thinking strategies in another example. In the aforementioned study, robots were used to support learning content in informal education, and both teachers and students designed robotics experiences aligned with the curriculum (Bernstein et al., 2022). As previously mentioned, this study is an example of how robots can cover STEM content from the learning domain to support educational goals.

The educational goal of R-STEM education was the last finding of our study. Most of the reviewed studies focused on learning and transferable skills as their goals (23 studies, 58.97%). They targeted learning because the authors investigated the effectiveness of R-STEM learning activities (Castro et al., 2018; Convertini, 2021; Konijn & Hoorn, 2020; Ma et al., 2020) and conceptual knowledge of STEM disciplines (Barak & Assal, 2018; Gomoll et al., 2017; Jaipal-Jamani & Angeli 2017). They targeted transferable skills because they require learners to develop individual competencies in STEM skills (Kim et al., 2018; McDonald & Howell, 2012; Sullivan & Bers, 2016) and to master STEM in actual competition-related skills (Chiang et al., 2020; Hennessy Elliott, 2020).

Conclusions and implications

The majority of the articles examined in this study referred to theoretical frameworks or certain applications of pedagogical theories. This finding contradicts Atman Uslu et. al. (2022), who concluded that most of the studies in this domain did not refer to pedagogical approaches. Although we claim the employment pedagogical frameworks in the examined articles exist, those articles primarily did not consider a strict instructional design when employing robots in STEM learning. Consequently, the discussions in the studies did not include how the learning–teaching process affords students' positive perceptions. Therefore, both practitioners and researchers should consider designing learning instruction using robots in STEM education. To put an example, the practitioners may regard students' zone of proximal development (ZPD) when employing robot in STEM tasks. Giving an appropriate scaffolding and learning contents are necessary for them to enhance their operational skills, application knowledge and emotional development. Although the integration between robots and STEM education was founded in the reviewed studies, it is worth further investigating the disciplines in which STEM activities have been conducted. This current review found that technology and engineering were the subject areas of most concern to researchers, while science and mathematics did not attract as much attention. This situation can be interpreted as an inadequate evaluation of R-STEM education. In other words, although those studies aimed at the interdisciplinary subject, most assessments and evaluations were monodisciplinary and targeted only knowledge. Therefore, it is necessary to carry out further studies in these insufficient subject areas to measure and answer the potential of robots in every STEM field and its integration. Moreover, the broadly consistent reporting of robotics generally supporting STEM content could impact practitioners only to employ robots in the mainstream STEM educational environment. Until that point, very few studies had investigated the prominence use of robots in various and large-scale multidiscipline studies (e.g., Christensen et al., 2015).

Another finding of the reviewed studies was the characteristic of robot-STEM integration. Researchers and practitioners must first answer why and how integrated R-STEM could be embodied in the teaching–learning process. For example, when robots are used as a learning tool to achieve STEM learning objectives, practitioners are suggested to have application knowledge. At the same time, researchers are advised to understand the pedagogical theories so that R-STEM integration can be flexibly merged into learning content. This means that the learning design should offer students' existing knowledge of the immersive experience in dealing with robots and STEM activities that assist them in being aware of their ideas, then building their knowledge. In such a learning experience, students will understand the concept of STEM more deeply by engaging with robots. Moreover, demonstration of R-STEM learning is not only about the coherent understanding of the content knowledge. Practitioners need to apply both flexible subject-matter knowledge (e.g., central facts, concepts and procedures in the core concept of knowledge), and pedagogical content knowledge, which specific knowledge of approaches that are suitable for organizing and delivering topic-specific content, to the discipline of R-STEM education. Consequently, practitioners are required to understand the nature of robots and STEM through the content and practices, for example, taking the lead in implementing innovation through subject area instruction, developing collaboration that enriches R-STEM learning experiences for students, and being reflective practitioners by using students' learning artifacts to inform and revise practices.

Limitations and recommendations for future research

Overall, future research could explore the great potential of using robots in education to build students' knowledge and skills when pursuing learning objectives. It is believed that the findings from this study will provide insightful information for future research.

The articles reviewed in this study were limited to journals indexed in the WOS database and R-STEM education-related SSCI articles. However, other databases and indexes (e.g., SCOPUS, and SCI) could be considered. In addition, the number of studies analyzed was relatively small. Further research is recommended to extend the review duration to cover the publications in the coming years. The results of this review study have provided directions for the research area of STEM education and robotics. Specifically, robotics combined with STEM education activities should aim to foster the development of creativity. Future research may aim to develop skills in specific areas such as robotics STEM education combined with the humanities, but also skills in other humanities disciplines across learning activities, social/interactive skills, and general guidelines for learners at different educational levels. Educators can design career readiness activities to help learners build self-directed learning plans.

Appendix 1. Summary of selected studies from the angle of research issue

#	Authors	Dimension				
		Location	Sample size	Duration of intervention	Research methods	Research foci
1	Convertini (2021)	Italy	21–40	≤ 1 day	Experimental design	Problem solving, collaboration or teamwork, and communication
2	Lamptey et. al. (2021)	Canada	41–60	≤ 8 weeks	Mixed method	Satisfaction or interest, and learning perceptions
3	Üçgül and Altıok (2022)	Turkey	41–60	≤ 1 day	Questionnaire or survey	Attitude and motivation, learning perceptions
4	Sen et. al. (2021)	Turkey	1–20	≤ 4 weeks	Experimental design	Problem solving, critical thinking, logical thinking, creativity, collaboration or teamwork, and communication
5	Stewart et. al. (2021)	USA	> 80	≤ 6 months	Mixed method	Higher order thinking skills, problem-solving, technology acceptance, attitude and motivation, and learning perceptions
6	Bernstein et. al. (2022)	USA	1–20	≤ 1 day	Questionnaire or survey	Attitude and motivation, and learning perceptions
7	Chang and Chen (2020)	Taiwan	41–60	≤ 8 weeks	Mixed method	Learning performance, problem-solving, satisfaction or interest, and operational skill
8	Chang and Chen (2022)	Taiwan	41–60	≤ 8 weeks	Experimental design	Learning perceptions, and operational skill
9	Chapman et al. (2020)	USA	> 80	≤ 8 weeks	Mixed method	Learning performance, and learning perceptions
10	Chiang et. al. (2020)	China	41–60	≤ 4 weeks	Questionnaire or survey	Creativity, and self-efficacy and confidence
11	Guven et. al. (2020)	Turkey	1–20	≤ 6 months	Mixed method	Creativity, technology acceptance, attitude and motivation, self-efficacy or confidence, satisfaction or interest, and learning perception
12	Hennessy Elliott (2020)	USA	1–20	≤ 12 months	Experimental design	Collaboration, communication, and preview situation
13	Konijn and Hoorn (2020)	Netherlands	41–60	≤ 4 weeks	Experimental design	Learning performance, and learning behavior
14	Ma et. al. (2020)	China	41–60	≤ 6 months	Mixed method	Learning performance, learning perceptions, and learning behavior

#	Authors	Dimension				
		Location	Sample size	Duration of intervention	Research methods	Research foci
15	Newton et. al. (2020)	USA	> 80	≤ 6 months	Mixed method	Attitude and motivation, and self-efficacy and confidence
16	Luo et. al. (2019)	USA	41–60	≤ 4 weeks	Questionnaire or survey	Technology acceptance, attitude and motivation, and self-efficacy
17	Pérez and López (2019)	Mexico	21–40	≤ 6 months	System development	Operational skill
18	Sullivan and Bers (2019)	USA	> 80	≤ 8 weeks	Mixed method	Attitude and motivation, satisfaction or interest, and learning behavior
19	Barak and Assal (2018)	Israel	21–40	≤ 6 months	Mixed method	Learning performance, technology acceptance, self-efficacy, and satisfaction or interest
20	Castro et. al. (2018)	Italy	> 80	≤ 8 weeks	Questionnaire or survey	Learning performance, and self-efficacy
21	Casey et. al. (2018)	USA	> 80	≤ 12 months	Questionnaire or survey	Learning satisfaction
22	Kim et. al. (2018)	USA	1–20	≤ 4 weeks	Questionnaire or survey	Problem solving, and preview situation
23	Leonard et. al. (2018)	USA	41–60	≤ 12 months	Questionnaire or survey	Learning performance, self-efficacy, and learning perceptions
24	Taylor (2018)	USA	1–20	≤ 1 day	Experimental design	Learning performance, and preview situation
25	Gomoll et. al. (2017)	USA	21–40	≤ 8 weeks	Experimental design	Problem solving, collaboration, communication
26	Jaipal-Jamani and Angeli (2017)	Canada	21–40	≤ 4 weeks	Mixed method	Learning performance, self-efficacy, and satisfaction or interest
27	Phamduy et. al. (2017)	USA	> 80	≤ 4 weeks	Mixed method	Satisfaction or interest, and learning behavior
28	Ryan et. al. (2017)	USA	1–20	≤ 12 months	Questionnaire or survey	Learning perceptions
29	Gomoll et. al. (2016)	USA	21–40	≤ 6 months	Experimental design	Satisfaction or interest, and learning perceptions
30	Leonard et. al. (2016)	USA	61–80	≤ 4 weeks	Mixed method	Attitude and motivation, and self-efficacy
31	Li et. al. (2016)	China	21–40	≤ 8 weeks	Experimental design	Learning performance, and problem-solving,
32	Sullivan and Bers (2016)	USA	41–60	≤ 8 weeks	Experimental design	Learning performance, and operational skill
33	Ayar (2015)	Turkey	> 80	≤ 4 weeks	Questionnaire or survey	Attitude and motivation, satisfaction or interest, and learning perceptions
34	Christensen et. al. (2015)	USA	> 80	≤ 6 months	Questionnaire or survey	Technology acceptance, satisfaction or interest, and learning perceptions
35	Kim et al. (2015)	USA	1–20	≤ 4 weeks	Mixed method	Learning performance, satisfaction or interest, and learning perceptions
36	Barker et. al. (2014)	USA	21–40	≤ 4 weeks	Questionnaire or survey	Technology acceptance, attitude and motivation, and learning perceptions
37	Ucgul and Cagiltay (2014)	Turkey	41–60	≤ 4 weeks	Questionnaire or survey	Learning performance, satisfaction or interest, and learning perceptions

#	Authors	Dimension				
		Location	Sample size	Duration of intervention	Research methods	Research foci
38	McDonald and Howell (2012)	Australia	1–20	≤ 8 weeks	Mixed method	Learning performance, operational skills, and learning behavior
39	Meyers et. al. (2012)	USA	> 80	≤ 4 weeks	Questionnaire or survey	Learning perceptions

Appendix 2. Summary of selected studies from the angles of interaction and application

#	Authors	Interaction				Application			
		Participants	Role of robot	Types of robot	Dominant STEM discipline	Contribution to STEM	Integration of robot and STEM	Pedagogical intervention	Educational objectives
1	Convertini (2021)	Preschool or Kindergarten	Tutee	LEGO (Mindstorms)	Engineering	Structure and construction	Context integration	Active construction	Learning and transfer skills
2	Lamptey et. al. (2021)	Non-specified	Tool	LEGO (Mindstorms)	Technology	Programming	Supporting content integration	Problem-based learning	Learning and transfer skills
3	Üçgül and Altıok (2022)	Junior high school students	Tool	LEGO (Mindstorms)	Technology	Programming	Content integration	Project-based learning	Creativity and motivation
4	Sen et. al. (2021)	Others (gifted and talented students)	Tutee	LEGO (Mindstorms)	Technology	Programming, and Mathematical methods	Supporting content integration	Problem-based learning	Learning and transfer skills
5	Stewart et. al. (2021)	Elementary school students	Tool	Botball robot	Technology	Programming, and power and dynamical system	Content integration	Project-based learning	Learning and transfer skills
6	Bernstein et. al. (2022)	In-service teachers	Tool	Non-specified	Science	Biomechanics	Content integration	Project-based learning	Teachers' professional development
7	Chang and Chen (2020)	High school students	Tool	Arduino	Interdisciplinary	Basic Physics, Programming, Component design, and mathematical methods	Content integration	Project-based learning	Learning transfer and skills
8	Chang and Chen (2022)	High school students	Tool	Arduino	Interdisciplinary	Basic Physics, Programming, Component design, and mathematical methods	Content integration	Project-based learning	Learning transfer and skills
9	Chapman et. al. (2020)	Elementary, middle, and high school students	Tool	LEGO (Mindstorms) and Maglev trains	Engineering	Engineering	Content integration	Engaged learning	Learning transfer and skills
10	Chiang et. al. (2020)	Non-specified	Tool	LEGO (Mindstorms)	Technology	Non-specified	Context integration	Edutainment	Creativity and motivation
11	Guven et. al. (2020)	Elementary school students	Tutee	Arduino	Technology	Programming	Content integration	Constructivism	Creativity and motivation
12	Hennessy Elliott (2020)	Students and teachers	Tool	Non-specified	Technology	Non-specified	Supporting content integration	Collaborative learning	General benefits of educational robotics

#	Authors	Interaction				Application			
		Participants	Role of robot	Types of robot	Dominant STEM discipline	Contribution to STEM	Integration of robot and STEM	Pedagogical intervention	Educational objectives
13	Konijn and Hoorn (2020)	Elementary school students	Tutor	Nao robot	Mathematics	Mathematical methods	Supporting content integration	Engaged learning	Learning and transfer skills
14	Ma et. al. (2020)	Elementary school students	Tool	Microduino and Makeblock	Engineering	Non-specified	Content integration	Experiential learning	Learning and transfer skills
15	Newton et. al. (2020)	Elementary school students	Tool	LEGO (Mindstorms)	Technology	Programming	Supporting content integration	Active construction	Learning and transfer skills
16	Luo et. al. (2019)	Junior high or middle school	Tool	Vex robots	Interdisciplinary	Programming, Engineering, and Mathematics	Content integration	Constructivism	General benefits of educational robots
17	Pérez and López (2019)	High school students	Tutee	Arduino	Engineering	Programming, and mechanics	Content integration	Project-based learning	Learning and transfer skills
18	Sullivan and Bers (2019)	Kindergarten and Elementary school students	Tool	KIBO robots	Technology	Programming	Context integration	Project-based learning	Learning and transfer skills
19	Barak and Assal (2018)	High school students	Tool	Non-specified	Technology	Programming, mathematical methods	Content integration	Problem-based learning	Learning and transfer skills
20	Castro et. al. (2018)	Lower secondary	Tool	Bee-bot	Technology	Programming	Content integration	Problem-based learning	Learning and transfer skills
21	Casey et. al. (2018)	Elementary school students	Tool	Roamers robot	Technology	Programming	Content integration	Metacognitive learning	Learning and transfer skills
22	Kim et. al. (2018)	Pre-service teachers	Tool	Non-specified	Technology	Programming	Supporting content integration	Problem-based learning	Learning and transfer skills
23	Leonard et. al. (2018)	In-service teachers	Tool	LEGO (Mindstorms)	Technology	Programming	Supporting content integration	Project-based learning	Teachers' professional development
24	Taylor (2018)	Kindergarten and elementary school students	Tool	Dash robot	Technology	Programming,	Content integration	Problem-based learning	Learning and transfer skills
25	Gomoll et. al. (2017)	Middle school students	Tool	iRobot create	Technology	Programming, and structure and construction	Content integration	Problem-based learning	Learning and transfer skills
26	Jaipal-Jamani and Angeli (2017)	Pre-service teachers	Tool	LEGO WeDo	Technology	Programming	Supporting content integration	Project-based learning	Learning and transfer skills
27	Phamduy et. al. (2017)	Non-specified	Tutee	Arduino	Science	Biology	Context integration	Edutainment	Diversity and broadening participation
28	Ryan et. al. (2017)	In-service teachers	Tool	LEGO (Mindstorms)	Engineering	Engineering	Content integration	Constructivism	Teacher's professional development
29	Gomoll et. al. (2016)	Non-specified	Tool	iRobot create	Technology	Programming	Content integration	Project-based learning	Learning and transfer skill
30	Leonard et. al. (2016)	Middle school students	Tool	LEGO (Mindstorms)	Technology	Programming	Content integration	Project-based learning	Learning and transfer skill
31	Li et. al. (2016)	Elementary school students	Tool	LEGO Bricks	Engineering	Structure and construction	Supporting content integration	Project-based learning	General benefits of educational robotics

#	Authors	Interaction				Application			
		Participants	Role of robot	Types of robot	Dominant STEM discipline	Contribution to STEM	Integration of robot and STEM	Pedagogical intervention	Educational objectives
32	Sullivan and Bers (2016)	Kindergarten and Elementary school students	Tool	Kiwi Kits	Engineering	Digital signal process	Content integration	Project-based learning	Learning and transfer skill
33	Ayar (2015)	High school students	Tool	Nao robot	Engineering	Component design	Content integration	Edutainment	Creativity and 34motivation
34	Christensen et. al. (2015)	Middle and high school students	Tutee	Non-specified	Engineering	Engineering	Context integration	Edutainment	Creativity and motivation
35	Kim et. al. (2015)	Pre-service teachers	Tool	RoboRobo	Technology	Programming	Supporting content integration	Engaged learning	Teachers' professional development
36	Barker et. al. (2014)	In-service teachers	Tool	LEGO (Mindstorms)	Technology	Geography information system, and programming	Supporting content integration	Constructivism	Creativity and motivation
37	Ucgul and Cagiltay (2014)	Elementary and Middle school students	Tool	LEGO (Mindstorms)	Technology	Programming, mechanics, and mathematics	Content integration	Project-based learning	General benefits of educational robots
38	McDonald and Howell (2012)	Elementary school students	Tool	LEGO WeDo	Technology	Programming, and students and construction	Content integration	Project-based learning	Learning and transfer skills
39	Meyers et. al. (2012)	Elementary school students	Tool	LEGO (Mindstorms)	Engineering	Engineering	Supporting content integration	Edutainment	Creativity and motivation

Abbreviations

STEM Science, technology, engineering, and mathematics
R-STEM Robotics-based STEM
PBL Project-based learning

Supplementary Information

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Additional file 1. Coded papers.

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Author contributions

DD, MR and GJ conceptualized the study. MR wrote the outline and DD wrote draft. DD, MR and GJ contributed to the manuscript through critical reviews. DD, MR and GJH revised the manuscript. DD, MR and GJ finalized the manuscript. DD edited the manuscript. MR and GJ monitored the project and provided adequate supervision. DD, MR and JC contributed with data collection, coding, analyses and interpretation. All authors read and approved the final manuscript.

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Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests

The authors declare that they have no competing interests.

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