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Robotics-Based Learning for STEM Classrooms: A Systematic Review

[1]Christopher Mutseekwa & [2]Kevin Manunure
[1]Rwanda Basic Education Board, Rukara Model School, Kayonza, Rwanda
[2]Department of Education Studies, Hong Kong Baptist University, Kowloon Tong, Hong Kong
[1]chrismutseekwa@gmail.com

Abstract

Robotics has been viewed as a game-changer in contemporary classroom pedagogy. Despite this potential, many K–12 STEM programmes lack engineering design components and rely on teacher-driven approaches. This systematic review aimed to explore the role of educational robotics in shifting classroom pedagogy from teacher-directed instruction toward learner-centred approaches. Analyzing literature from Web of Science and Google Scholar, two reviewers independently screened abstracts and full texts, yielding 72 relevant studies. Data from these sources were analyzed to uncover patterns and gaps. Findings indicate that incorporating robotics into the curriculum encourages learner-centered models, emphasizes systems thinking, and engineering design. Educational Robotics emerges as a multidisciplinary model that not only engages students in computational thinking but also immerses them in foundational concepts of physics, engineering, and computing through the hands-on design and construction of robots. The review highlights robotics' potential to transform classrooms by empowering students and reducing dependence on teacher-centered methods.

Keywords: *control system, Industry 4.0, integrated curriculum, learner-centric, systems thinking, robotics*

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INTRODUCTION

Industry 4.0 has ushered in a technological revolution that has changed the face of human learning. According to Moraes et al. (2023), the term Industry 4.0 entails an increased use of digital technologies that encompasses a wide range of concepts, such as cyber-physical systems (CPS), which integrate computational and communication capabilities with physical processes, smart factories with autonomous systems for self-configuration and self-monitoring, and adaptation to human needs. This is a new industrial model based on digitalization, system interconnection, virtualization, and data exploitation that is enabled through a set of technologies that link the physical world to virtual resources to accomplish intelligent management of the industrial processes (Fuertes et al., 2021). To achieve this feat, technologies such as Robotics, Internet of Things (IoT), Additive Manufacturing, Virtual (VR) and Augmented Reality (AR), Simulation, Systems Integration, Big Data Analytics, Artificial

Corresponding author:
Christopher Mutseekwa chrismutseekwa@gmail.com
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Intelligence (AI), Industrial Security, CPSs, Mobile and Wearable devices, and Cloud Computing are used (Dalenogare et al., 2018; Moraes et al., 2023; Zheng et al., 2021). The expectation is, therefore, for the school curriculum to mold learners to develop skills such as digital literacy, research, creativity, collaboration, critical thinking, decision-making, problem-solving, life-long learning, and communication in tandem with these developments. The emergence of Education 4.0 is the inevitable corollary of this expectation.

The concept of Education 4.0 is closely linked to Industry 4.0. The two concepts intersect in classroom spaces with Education 4.0 as a gateway to Industry 4.0 knowledge (Moraes et al., 2023). Education 4.0 can be seen as a new paradigm that reinterprets the concepts of learning, student, teacher, and school according to the needs of Industry 4.0 (Hımmetoglu et al., 2020). According to Moraes et al. (2022), the implementation of Education 4.0 is guided by several approaches, such as asynchronous and synchronous learning, personalized and flexible learning, project-based learning (PBL), virtual and augmented reality, simulations, data generation and analysis, authentic assessment, and increased accountability systems. For instance, the flipped classroom (FC) has been used as a learning approach that is unbound by time and space. In flipped classrooms, students study materials uploaded online as individuals or as groups at their own pace and later apply the knowledge gained in practical, group-based in-class activities (Zainuddin & Perera, 2019). Thus, the FC approach focuses on student engagement in knowledge construction and provides for student collaboration and knowledge application through group discussion, internet research, hands-on assignments, and projects (Mutseekwa et al., 2024). In this sense, classroom learning becomes a space for simulating Industry 4.0 competences and skill sets such as lifelong learning, process understanding, knowledge interpretation, technology familiarization, equipment operation (technical); creativity, decision-making, analytical and research skills (methodological); communication, networking, cooperation, knowledge transfer (social); and autonomy, organizational skills, responsibility, and flexibility (personal) (Moraes et al., 2023). Given this background, a study of the integration of these technologies in the curriculum disciplines becomes paramount.

Several definitions of subject integration are presented in the literature. Subject integration is a pedagogical approach aimed at assisting students to see the interconnectedness of topics and apply what they learn across subjects to deepen their understanding of complex concepts. Some broad definitions include “bringing together distinctive components of two or more disciplines” and “relationships between different subject areas, content, and skills” (Nollmeyer et al., 2016 p. 4). Regarding Mathematics and Science integration, Czerniak et al. (1999) suggested that integration infuses mathematical methods in science and scientific methods into mathematics in a manner indistinguishable from whether it is mathematics or science. Citing other authors, Mason (1996) says integration is a knowledge view and curriculum approach that applies methodology and discourse from multiple disciplines to examine central themes/problems across topics. Although several models, such as interdisciplinary, intra-disciplinary, multidisciplinary, and cross-disciplinary integration, are discussed in the literature, Brown (2011, p. 195) argues that the major distinction drawn in the various integration models is that “true” integration requires student involvement in the design process. Limited literature focuses on curriculum integration in which the students are part of the design process. The existing corpus of literature provides two perspectives in positioning robotics within an educational context, that is, regarding robotics as a means or a technological environment to teach other subjects and viewing robotics as a tool to teach robotics itself (Jung & Won, 2018). The authors suggested that research agendas must move beyond the outcome-focused trend to embrace topics that investigate and conceptualise students’ engagement processes in robotics activities (Buckingham, 2013; Jung & Won, 2018). Thus, this review explores how a robotics curriculum can be utilized as a tool for a learner-centric integration model of the STEM disciplines. Specifically, the following questions guide the scoping and synthesis of the literature.

1. What are the conceptual and pedagogical connections between robots, robotics, and educational robotics (ER), and how does ER support competence development in STEM education?
2. What limitations do teacher-centric models of STEM integration present in fostering active learner engagement, particularly in design-based learning contexts?
3. How does educational robotics (ER) facilitate the integration of STEM disciplines in ways that promote meaningful learner participation and engagement?

METHODS AND MATERIALS

Eligibility Criteria and Information Sources

The PRISMA 2020 statement, as outlined by Page et al. (2021), guided the scoping of the literature. We defined clear inclusion and exclusion criteria to guide the selection of studies. Eligible studies included peer-reviewed articles, book chapters, or books published in English that addressed integrated STEM education following teacher or learner-centric models. Studies were excluded if they were reviews, commentaries, editorials, or were not open access. We grouped studies for synthesis based on theoretical frameworks, conceptual focus, and methodological approach, allowing for thematic or quantitative analysis depending on the nature of the included studies. We systematically searched the following databases: PubMed, Scopus, Web of Science, and Google Scholar. Additionally, reference lists of relevant reviews and included articles were hand-searched to identify studies not captured in the database search.

Search Strategy and Study Selection

A comprehensive search strategy was developed in collaboration with a subject librarian, using a combination of controlled vocabulary (e.g., robotics curriculum, robotics and discipline integration, STEM integration, integration approaches) and free-text terms related to iSTEM robotics curriculum. Boolean operators, truncation, and filters were used where appropriate to refine results. The selection process involved two reviewers independently screening titles and abstracts for relevance, followed by full-text screening of potentially eligible articles. Discrepancies were resolved through discussion or by consultation with a third reviewer. No automation tools were used in the screening process. A final selection included 53 empirical studies and 19 that were non-empirical. Most of the studies (N=301) were located through electronic searches. A smaller number were found through hand searches, while additional literature was sourced from libraries. Figure 1 below summarizes the sources that contributed to the final report.

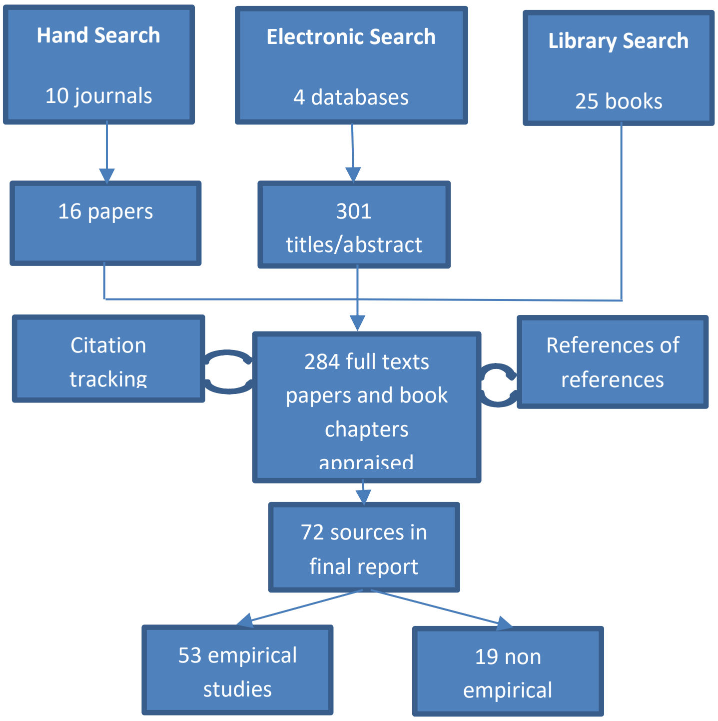


Fig. 1. Flow diagram of the meta-narrative review search. (Adapted from Greenhalgh et al. 2005, 423)

Data Extraction, Variables, and Risk of Bias Assessment

Data were extracted independently by two reviewers using a standardized data extraction form. Extracted data included study design, population characteristics, sample size, intervention/exposure details, outcomes measured, and key findings. We also recorded variables such as funding sources and potential conflicts of interest. For each outcome, we extracted all available data across time points and measurement tools when applicable. Any unclear or missing data were resolved by contacting the study authors. The risk of bias for every included study was evaluated using the Mixed Method Appraisal Tool (MMAT), Version 2018, created by Hong et al. (2018), with two reviewers independently carrying out the assessments and settling any disagreements through consensus. The MMAT checklist was utilized to ask questions such as: Are the data collected relevant to the research questions? Is the interpretation of the results adequately supported by the data? Are the participants representative of the intended population? Do the various components of the study fulfill the quality criteria for each method used? Subsequently, systematic data extraction is conducted to gather important details, such as methodologies, findings, and conclusions from the chosen sources. This data is then analyzed and combined to uncover patterns, trends, and gaps within the literature sources. This process resulted in the findings being reported and organized clearly. Ultimately, the documented findings were critically discussed, offering practical insights.

FINDINGS

Robotics and STEM skills development

Different countries have different standards governing what can be considered a robot. The largest number of robot-related standards has so far been developed by the International Organization for Standardization (ISO) (LEE, 2022). ISO has developed vocabularies such as robots, robotic technology, robotic devices, industrial robots, service robots, autonomy, and others to resolve mismatching and harmonization between different robot groups (LEE, 2022). For instance, a robot is defined as a programmed and actuated mechanism with a degree of autonomy to perform locomotion, manipulation, or positioning, while the vocabulary robotic technology denotes practical application knowledge commonly used in the design of robots or their control systems, especially to raise their degree of autonomy(LEE, 2022). This implies that robots consist of mechanical, electrical, and electronic components such as actuators that translate electrical signals into physical action and sensors that detect physical changes (e.g. pressure, light, distance) in the environment converting them to electrical signals, assuming that robots are supposed to be physical agents, affecting their environment (Haidegger, 2021). Thus, on a general level, reprogrammable devices that are designed to perform tasks can be considered robots, while the term robotics relates to the broader discipline that encompasses the development and study of robots. (Niku, 2019 p. 2) says, "Robotics is the art, knowledge base, and know-how of designing, applying, and using robots in human endevours". Robotics can also be described as a branch of engineering and computer science dealing with the intelligent movement of various robot mechanisms, which can be classified into the following four groups: robot manipulators, robot vehicles, man-robot systems, and biologically inspired robots (Mihelj et al., 2019).

The use of robotics has seen a proliferation in various fields. Diversification has extended to the development and use of medical robotics (Dupont et al., 2021), field robotics (Grift et al., 2008), car robotics (Royakkers & van Est, 2015), and others. This means the use of robots has spread into hospitals, factories, agricultural fields, construction sites, and even private homes. Writing about this proliferation, Keisner et al. (2016, p. 8) note: "…technologists, economists, lawyers, and experts from other disciplines are speculating about the potential uses of robotics innovation and its socio-economic impacts". The field of education has not been spared. Within this realm, the convergence of robotics and education, essentialized in the domain of ER, stands as a transformative force redefining the contours of contemporary learning environments (Alam & Mohanty, 2024). Educational Robotics is a field of study that aims to improve the learning experience of people through the creation, implementation, improvement, and validation of pedagogical activities, tools, and technologies, where robots intersect with pedagogical theory to inform teaching and learning (Angel-Fernandez et al., 2018). Souza et al. (2022) view ER as a multidisciplinary approach that uses computational thinking in the design, assembly, and use of robots based on principles of engineering, computing, mathematics, and physics. While ER is used in other subjects such as languages, art, and special needs education, in the majority of cases, it has been used for teaching Science, Technology, Engineering, Mathematics (STEM), and Computer Science at different levels (Sisman et al., 2021). The inclusion of ER in education can favor the learning process since ludic activities can stimulate computational thinking, contributing to increasing the students' engagement and fascination with STEM domains from the earliest stages of their academic trajectory (Alam & Mohanty, 2024; Souza et al., 2022).

ER encompasses the use of robotics kits, social robots, and toy robots as categories existing within the programmes. To maintain clarity of presentation, this paper focuses on robotics kits. Robotics kits are programmable and allow the learner to create designs, program the robot, and construct blocks (Jung & Won, 2018). While there exists a wide variety of robot kits, such as the Max &

Tobo Coding robot, the Sphero Mini robot from Sphero, the meeperBOT from Meeper Technology, the KIBO robotics kit from Kinder Lab Robotics, and others, the LEGO Education WeDo 2.0 and LEGO Mindstorms robots are common versions (Papadakis, 2020). The Lego Mindstorms kit comprises a smart brick, also known as a programmable brick, sensors, motors, cables, a rechargeable battery, LEGO elements, and programming software. Using such kits, learners design algorithms, design mechanical structures, construct and operate the robots and robotics kits to perform various tasks in collaborative and competitive settings (Papadakis, 2020). According to Tsianos (2008), robotics algorithms are sets of programmed instructions that enable the robot to perceive, reason, and act intelligently within given workspaces. Thus, the primary goal of a robot algorithm is to describe a procedure for controlling a subset of a workspace to navigate, manipulate, or achieve a given goal, say, a spatial arrangement of several physical objects. Engagement with the robotics kits and their features is important in determining the extent of skills development, the nature of collaboration required, and learners' integration levels in the STEM disciplines (Jung & Won, 2018).

Several studies have documented the benefits that learners derive from a robotics curriculum. Despite the lack of comprehensive or unified robotics curricula in the majority of K -12 contexts (Berry et al., 2016), the term is herein regarded as school programs that offer robotics as a course component or as an extracurricular activity. The authors of the current paper acknowledge the challenges of setting up standard robotics curricula, particularly in the context of developing countries where resources, such as electricity, internet availability, qualified STEM teachers, and a general lag in technical pedagogical expertise, are limited. However, putting in place such curricula is a coveted endeavor by many schools, even those without electrical installations as part of their infrastructure (Atmatzidou & Demetriadis, 2016; Sullivan & Bers, 2016). This underscores the importance of engaging in discourse on the requirements and benefits of a robotics curriculum. Berry et al., (2016) identified four guiding principles of such a curriculum, as follows: provision of learning objectives and examples of learning modules for various robotics concepts, without focusing on a particular hardware or software platform; presenting a comprehensive set of competencies covering systems thinking, computational thinking, and others that provide a base for effective robotics understanding; promoting a set of competencies for using robotics concepts to teach or reinforce co-curricular concepts (i.e., programming, engineering design, art, math, physics, etc.); and indulging flexibility across the academic levels or robotics experience.

Design-based learning (DBL) and computational thinking are skills rarely nurtured in ordinary school curricula, yet they are critical in envisaged STEM and ER programmes (Saritepeci, 2020). Basu et al. (2016) posit that computational thinking (CT) parallels the core practices of science, technology, engineering, and mathematics (STEM) education and is believed to effectively support students' learning of science and math concepts. However, despite the synergies between CT and STEM education, integrating the two to support synergistic learning remains an important challenge. CT refers to the ideas and representational practices involved in formulating and solving problems, designing systems, and understanding human behavior by drawing on fundamental computing concepts like algorithmic and problem representation, abstraction, machine learning, decomposition, recursion, simulation, and verification (Basu et al., 2016). Computational thinking, along with computational modelling, DBL, and systems thinking, supports the learning of STEM concepts. The four approaches to problem-solving embed the higher-order thinking skills of sequenced analysis, systems analysis, transfer learning, understanding relationships, synthesis, design process, collaboration, and real-world application of theoretical knowledge. CT allows students to develop an understanding of computing and programming competences, thus allowing them to move from being users of technology to producers of information technology (Montiel & Gomez-Zermeño, 2021). From a robotics point of view, CT is the machine learning answer to developmental robotics, inviting the learners to reason out solutions, design systems, compute, adapt, and interact with their environment using a continuous stream of observations (Lesort et al., 2020).

The challenges of teacher-centric STEM integration models

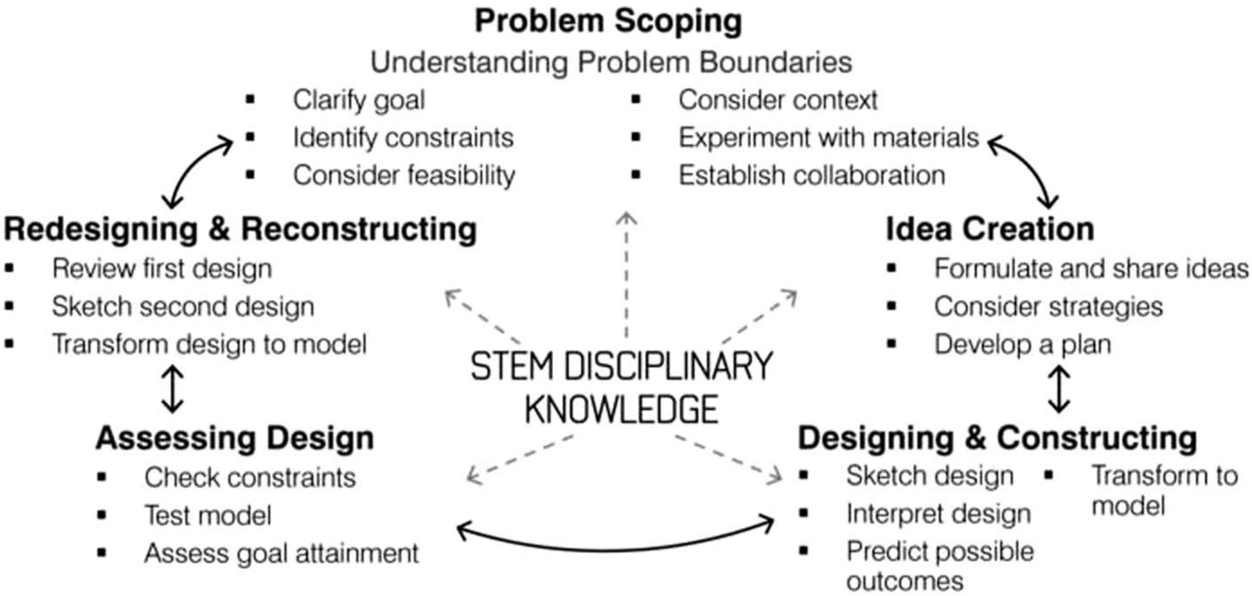
Career pathways are formulated in the early years of a student's education, in primary and high schools, making K-12 contexts critical periods for developing STEM skills and interests (Wang et al., 2017). To capitalize fully on the STEM potential of our students, schools must streamline STEM education and refine their instructional pedagogy through well-grounded integrated STEM (iSTEM) programmes (Margot & Kettler, 2019). Integrated STEM is the seamless amalgamation of content and concepts from multiple STEM disciplines and involves the application of knowledge and practices from multiple STEM disciplines (e.g., Biology, Chemistry, Mathematics, ICT, and Engineering) to learn about or solve transdisciplinary problems (Nadelson & Seifert, 2017). The authors further note that this process requires teachers to plan and design for the integration in ways such that knowledge and process of the specific STEM disciplines are considered simultaneously without regard to the discipline, but rather in the context of a problem, project, or task.

Researchers and practitioners have been working tirelessly to establish the best permutations for iSTEM designs. Cheng & So (2020) identify a typology of integration in STEM learning that can be classified as content integration, pedagogical integration, and learner integration. Content integration occurs at two levels-subject and domain. Subject integration occurs when two or more individual disciplines in STEM are taught at the same time, whilst domain integration represents the application and synthesis that occurs when broad areas such as science, technological, cultural, political, social, and economic domains are thematically integrated during the learning of STEM disciplines (Cheng & So, 2020). This integration approach typically brings in other subjects such as art, culture, entrepreneurship, and others to STEM education, giving rise to science, technology, engineering, art, and mathematics (STEAM) and science, technology, reading, engineering, art, and mathematics (STREAM). Pedagogical integration represents the combination of the various pedagogical approaches to elicit student learning in STEM-related programmes. These approaches can further be classified as methods and cognitive integration. Method integration is a selected combination of advanced learning methods such as project learning, group learning, self-regulated learning, problem-based learning, online learning, and hybrid learning while cognitive integration refers to the integration of various cognitive activities such as observing, measuring, classifying, describing, analyzing, synthesizing, conceptualizing and meta-understanding that can be applied in the STEM learning process (Cheng & So, 2020; Webb & Reynolds, 2013). In Hurley's (2001) integration framework, STEM disciplines can be taught using (1) sequenced, (2) parallel, (3) partial, (4) enhanced, and (5) total immersion approaches. These represent teaching science and mathematics sequentially; science and mathematics taught simultaneously; science and mathematics partially taught together; science or mathematics taught as the major discipline with the other one included to support teaching the major discipline; and science and mathematics taught together as two major disciplines respectively (Guzey et al., 2016).

The teacher plays a pivotal role in bringing about efficacy in the desired iSTEM design approaches. In most cases, the teachers are mere recipients of designs that have emerged through research, yet they are expected to implement these with fidelity. Teachers are expected to implement innovations that originated from researchers outside of the classroom. This is despite research literature on educational innovation suggesting that teachers will be better prepared to implement iSTEM education when they own the designs that they implement (De Meester et al., 2021). The teachers become implementing agents whose skills are brought to bear for the success of the research-based integration approaches. Faced with the need to implement iSTEM approaches, these teachers make use of ill-defined designs to see the job done. The majority of these teachers have been trained to handle one STEM discipline and sometimes cannot readily access prevailing iSTEM designs suggested in the literature (Guzey et al., 2016; McFadden & Roehrig, 2017). The teachers reported in these studies struggled with designing integrated or context-based STEM materials and often remained focused on student engagement for fun and not on how students learn best during integrated learning experiences (De Meester et al., 2021). Stevenson et al. (2024) argue that the integrated nature of STEM education requires teachers to design, blend, and implement curricula across multiple disciplines. However, teachers often lack preparation and experience in teaching multiple disciplines. This means that the success of integration depends largely on the teacher and that the best iSTEM design can fail in the hands of an unskilled teacher (Dong et al., 2020).

Teachers need to have several of the requisite skills for iSTEM education to assist learners in developing the cognitive aspect of integration (Cheng & So, 2020). Evidence from research has given hope to the promise of integrated approaches to STEM education to assist the next generation of students in solving real-world problems by applying concepts that cut across disciplines as well as capacities of critical thinking, collaboration, and creativity (Shernoff et al., 2017). For instance, Fan & Yu (2017) examined the effectiveness of the application of an integrative STEM approach within engineering design practices in high school technology education in Taiwan using a quasi-experimental approach with students studying a STEM engineering module compared to students studying the technology education module. The findings showed that the participants in the STEM engineering module outperformed significantly the participants studying the technology education module in the areas of conceptual knowledge, higher-order thinking skills, problem prediction, and the design project activity. Fan & Yu's (2017) findings support the positive effect of engineering design, a practice embedded in iSTEM education. Other research studies cited in Siew et al. (2016) demonstrated how engineering design problems embedded in the context of iSTEM education in K -12 contexts could scaffold learners through structurally open-ended and highly complex engineering design problems to hone engineering skills and habits in the students.

The engineering design process typically infuses the crucial element of computational thinking, and it includes 1) defining the design task, 2) brainstorming, 3) designing, 4) building, 5) testing, 6) redesigning, and 7) sharing (Eguchi, 2014). English et al. (2017) provide a more detailed description of the engineering design cycle.



The engineering design cycle (Source: English et al., 2017)

At the centre of the design cycle is STEM disciplinary knowledge. However, there has been widespread concern over the underrepresentation of engineering in integrated STEM (iSTEM) education (De Meester et al., 2021). Engineering often receives less emphasis compared to science and mathematics. Many science teachers struggle to incorporate engineering into their curricula due to a lack of familiarity with engineering design and practices, leading to inconsistent implementation and varying levels of student achievement in engineering-related tasks like robotics (Kelley & Knowles, 2016; Selcen Guzey et al., 2017).

Robotics as learner-centric

ER presents the students with an in-built iSTEM education, typically incorporating the sciences, technology, engineering, and mathematics. Robotics building is an example of a one-ready opportunity for students to engage in scientific concepts (gear levers, distance, speed, acceleration, momentum, force); technological literacy (Programming languages contextualize the process of cause and effect through algorithms); engineering design (Steps in engineering design to create a project and to solve a problem); mathematical thinking (Robotics components such as bricks, gear, tires, etc. possess a variety of mathematical qualities); and Project-Based Learning (Integrating the scientific concept, technological literacy, engineering design and mathematical thinking to complete a project in 21st-century learning environment) all packaged in the designed encounters (Hussin et al., 2019). Although ER is mediated by teachers as facilitators, it represents a 'true' integration process espoused by Brown (2011, p. 195). This integration approach does not necessarily take the teacher out of the equation but firmly assigns him/her a facilitation role while placing the learner in a position of control. The learner plays a central role in decision-making, designing, communicating, researching, creating algorithms, testing solutions, and establishing team relationships.

Since authentic integration requires student involvement in the design process, students should be hands-on in the design of robots, which presents many challenges (Brown, 2011). Learning from

Wedeward & Bruder (2002), who successfully incorporated robotics into secondary education, integrated ER implementation challenges may include: 1. Robots require sophisticated controller boards, even simpler versions, demanding financial resources that many schools cannot meet (Theodoropoulos et al., 2017). 2. Robotics requires dedicated support facilities, such as websites, which can be challenging for countries without stable and convenient internet services. 3. Robotics requires significant long-term investment in human capital, including teachers and teacher trainers. There is currently a shortage of teachers skilled in robotics, and colleges offering relevant courses often target engineering careers, not teaching. To realize ER, dedicated teacher training courses, professional development programs, and a sufficient supply of competent teachers are needed. An integrated network of human capital at different levels, i.e., practicing engineers, university engineering departments, undergraduate engineering students, mentors, teachers, and students, is essential. Cross-pollination between school education and academic research was emphasized by Screpanti et al. (2021).

In cases where financing of ER is made available, students draw upon the diversity of activities presented to accrue several benefits. A typical package for a Robotics curriculum is provided by McGrath et al. (2008). The authors report on a BUILT IT marine project that uses a LEGO Mindstorm kit, an NXT programmable brick, and other components to engage students in STEM. This curriculum covers two years and is divided into two phases- The ROV and NXT curricula. Teachers are trained and inducted into the nuances of the course. The induction culminates in some pilot lessons. They plan for the implementation of twenty lessons spanning over four to five weeks, preparing the makeshift pools and curriculum-pacing and testing schedules. Students are assigned into teams of 4-5 students to engage in various activities, inclusive of building, testing, and controlling the robots using LEGO bricks, motors, propellers, cables, wire-guided switches, and others (McGrath et al., 2008). The second phase is called the NXT curriculum. Teachers are professionally developed to guide learners using the project-based, team-based, engineering design, and CT approaches. In this phase, the learners are introduced to the language of programming. Wire-guided switches are replaced with programmable NXT intelligent bricks and sensors to manipulate underwater robots. The two phases of the curriculum provide opportunities for learners to engage in four broad activities: robot design, innovation projects, robot games, and core values. The first two activities focus on innovation through the engineering design process. Learners engage in the identification of the problem or mission strategy; design robot programmes or create solutions to the identified problems; create models, prototypes, robots, and/or coding solutions; test and improve in the iterate stage; and communicate solutions and impact (Master, 2023). The robot games take the learners through building mission models, reviewing the missions and rules, designing and building a robot, exploring coding options, and competing at an event. The Master (2023) document points out that as learners engage in these activities, they acquire certain core values through teamwork, inclusion, discovery, creating innovative and impactful solutions, and celebrating success.

Discussion

The findings of this review reinforce the growing recognition of Educational Robotics (ER) as a viable and inherently integrative platform for promoting STEM education in K–12 settings. Drawing on Souza et al. (2022), ER emerges as a multidisciplinary model that not only engages students in computational thinking but also immerses them in foundational concepts of physics, engineering, mathematics, and computing through the hands-on design and construction of robots. While ER has been applied in diverse educational domains such as language arts and special education (Sisman et al., 2021), its most prominent and effective applications have consistently centered on STEM and Computer Science instruction. What distinguishes ER in this context is its natural embodiment of the iSTEM approach, where disciplines are not taught in isolation but are interwoven into project-based learning experiences.

As highlighted by Hussin et al. (2019), robotics projects offer a one-stop platform for students to explore scientific principles, develop technological literacy through coding, apply engineering design processes, and exercise mathematical reasoning, all within an active, student-centered learning environment. This learner-centric orientation does not diminish the role of the teacher but redefines it, positioning educators as facilitators while students take charge of decision-making, problem-solving, and collaboration. The systematic review thus underscores ER's potential to operationalize a truly integrated and learner-driven STEM pedagogy.

Despite these celebrated successes of the ER curriculum, challenges remain. Integrating robotics in education is predominantly facilitated by teachers who have received little or no training on the best approaches to tracking learning progress in the discipline. This shortcoming stems from the absence of assessment models that guide teachers on key focus areas and methods for evaluating student learning in a robotics-based environment (Screpanti et al., 2021). As a result, students may not fully grasp robotics' underlying concepts and practical applications. To address this, developing comprehensive assessment frameworks is essential. These frameworks should provide clear guidelines for instructional strategies, evaluation criteria, and technology integration into educational practice (Screpanti et al., 2021). Contrary to the general belief that ER is exclusively related to STEM subjects, Karypi (2018) argues that ER can also be applied to other subjects, such as literature, history, social sciences, dance, music, and the arts. This broader application provides students with cooperation, expression, innovation, and critical thinking opportunities. However, due to the misconception that ER is solely a STEM-related subject, integrating ER across various domains can be challenging. Teachers in less-represented subjects like history may be less receptive, possibly due to negative attitudes stemming from a lack of preparedness and competence.

There is a growing realization that technologies such as Robotics and AI are here to stay (Brynjolfsson & Mcafee, 2017). These are technologies that will drive the Industrial Revolution 4.0 (Dalenogare et al., 2018). Given this background, there is a need to project how the education arena will respond to these developments in creating a future workforce for IR 4.0. This section provides a trajectory for ER that can assist STEM practitioners and curriculum planners in establishing a base for the much-needed future developments in the area. The future of ER lies in self-regulated learning (SRL). SRL is viewed as an approach that gives more autonomy and responsibility to learners to self-pace and direct their learning. Although there is no consensus among scholars on the set of terms describing SRL that can be used interchangeably, it is sometimes known by other names, such as personalized learning, adaptive learning, self-paced instruction, and self-directed learning (Shemshack & Spector, 2020). In the context of ER, SRL occurs at two levels. Firstly, at the team level, learners engage in task completion as a team, drawing their parameters for the tasks, assigning each other roles, managing the time, and peer-assessing each other to build strong teams. Secondly, they engage in SRL individually as they manage their time completing assigned tasks, researching, self-assessing their conceptualisation, and reflecting deeply on the impact of actions on their significant others in metacognitive processes. The ability of students to shift from traditional learning modes that rely heavily on teachers as information sources towards an active SRL approach that places greater autonomy on students to self-direct their learning is critical in securing the endeavoured future of ER. This stems from the observation that students rely heavily on teachers as information sources. They struggle with ER approaches that place high levels of learning responsibility on their shoulders due to a lack of motivation, failure to manage distractions, a lack of self-discipline, limited metacognitive awareness, and a perceived lack of control (Hartelt & Martens, 2024). Metacognitive awareness is one’s awareness of their capabilities in understanding a concept and the context in which it is used (Hartelt & Martens, 2024). Thus, an absence of this cognitive skill reduces the learners’ ability to make shifts toward learner-centric ER.

Technology can be a useful tool for enhancing SRL. Several studies (Alfredo et al., 2024; Sembey et al., 2024) have demonstrated how SRL and personalized learning approaches seamlessly integrate with emerging technologies such as Learning Analytics, robotics, AI, machine learning (ML), Extended Reality (XR) applications, virtual reality, augmented reality, and others. For instance, ML, which is regarded as a sub-discipline of AI, uses algorithms as system enablers to learn from the experiences of processing large amounts of data. (W. Wang & Siau, 2019) argue that machine learning is an automated process that enables Information Technology (IT) applications to analyze large data sets, recognize emerging patterns, and learn from the data patterns to provide support for conjectures used for decision-making. The creation of novel algorithms and the expansion of existing ones to complex codes enhance personalized applications that online platforms such as Language Apps, Facebook, YouTube, Amazon, Netflix, and TikTok rely on to refashion and personalize the uploaded content (Zanker et al., 2019). Despite concerns over AI and analytic technologies' reduced transparency, algorithmic bias, and potential threats to human autonomy (Alfredo et al., 2024), adaptive robotics tutors have been reported to be supportive drivers of SRL that result in students' learning gains (Pilley, 2016).

Alam & Mohanty (2024) have attempted to provide a glimpse into the future of ER through the framework of the Integrated Constructive Robotics in Education (ICRE) model. The ICRE model coalesces constructivist and constructionist principles that emphasize hands-on and active engagement with robotics technology to revolutionize the ER landscape. The model frames ER as anchored on learner-centrism, alignment to curricula, and adaptability and flexibility principles that can be supported through (1) teacher pedagogical training, (2) technological integration, (3) Community engagement, (4) assessment, and (5) inclusivity. Using engineering design and project-based learning, students engage in self-directed projects that foster creativity, innovation, self- and peer assessment, collaboration, community engagement, construction, and interdisciplinary exploration (Alam & Mohanty, 2024). The learning is leveraged through technology integration, a central tenet of the model. According to Alam and Mohanty (2024), the integration of emerging technologies such as AI, Robotics Tutors, and ChatGPT within ER ensures compatibility with the requirements of Education 4.0. Xu et al. (2024) observe that ChatGPT is an emerging technology that can generate reliable data and furnish ER environments that aid learners' metacognitive skills, inclusive of motivation, self-efficacy, and self-determination.

Robotic technology is not within the reach of many countries or educational institutions. Due to the schools' funding challenges, most ER activities are privately sponsored by companies such as Kinder Lab Robotics, LEGO Education WeDo 2.0, and LEGO Mindstorms. Some areas, particularly in developing countries, remain unconnected to the internet and without electricity. Despite that, future expansions in the field of ER are expected. The current limited provision of the ER curriculum means that the majority of teachers lack the skills to integrate the discipline. They are not trained to handle the ER learner-centric approaches that are needed to assist learners' active engagement. Perhaps it is time for teacher education to reflect on the role they should play in this puzzle because capacity building would be needed for both in-service and preservice teacher development. The teacher education courses for such capacity-building programmes could focus on developing teachers' ER facilitation capabilities, inclusive of honing learners' skills in SRL. Capacity building is also needed for schools to play more distinct roles in the design and offering of ER. It may perhaps imply greater cooperation between schools and private sponsors such as First Logo to cede more autonomy and capacity that enables as many schools as possible to offer ER curricula. More active involvement for schools in ER activities implies a greater proliferation of the discipline to subjects other than STEM. The available research evidence pointing to ER in subjects like history, languages, arts, and others, coupled with the inherent communication, collaboration, creativity, research, and innovation capabilities embedded in ER, means an envisaged transformative shift from a focus on STEM to the more inclusive STEAM and STREAM integrative dimensions.

CONCLUSION

The findings of this systematic review affirm that educational robotics (ER) provides a robust platform for authentic integrated STEM learning, while also advancing emerging pedagogical priorities such as self-directed learning (SDL) and learner agency. As demonstrated in the analysis, STEM integration models that incorporate ER engage learners more deeply in design, construction, and inquiry than traditional STEM approaches. Through hands-on robotics tasks, learners apply scientific concepts, develop technological literacy, and engage in mathematical reasoning within iterative engineering design cycles. Crucially, ER was shown to function as a powerful mediator of integrative learning, supporting interdisciplinary models such as STEM, STEAM, and STREAM by blending creativity, critical thinking, and problem-solving with collaborative design practices. Consistent with Brown's (2011) learner-centred integration model, ER does not eliminate the teacher's role but repositions it toward facilitation while granting learners greater decision-making autonomy. This shift fosters key 21st-century competences, including collaboration, communication, and computational thinking, while also cultivating persistence and innovation through design thinking. The review further highlights that the future of ER in education is closely tied to technology-enhanced SDL, where AI-driven platforms such as ChatGPT, Robotics Tutor, and other intelligent tutoring systems can personalise learning and scaffold problem-solving during robotics projects. In this evolving landscape, ER emerges not just as a teaching tool but as a transformative pedagogy that empowers learners as active creators of knowledge.

Based on these findings, several pedagogical recommendations emerge to strengthen the integration of Educational Robotics (ER) in teaching and learning. First, teachers should adopt a constructivist and inquiry-based pedagogy where learners are actively engaged in problem-solving tasks rather than following step-by-step instructions. ER activities should be structured around engineering design cycles that allow for iterative testing, reflection, and redesign, thereby promoting deep conceptual understanding and resilience. Second, educators should scaffold learning progressively, moving from guided exploration toward self-directed learning, where learners plan, monitor, and evaluate their own robotics projects. Third, ER should be integrated across subjects through interdisciplinary project-based learning to make science, mathematics, technology, arts, and literacy meaningful and connected to real-life contexts. Fourth, teachers should deliberately cultivate learner agency by giving students voice and choice in task selection, design decisions, and solution strategies. Finally, teacher professional development must prioritise digital pedagogy competences, including the effective use of AI tools to personalise learning and support collaborative knowledge construction in robotics classrooms.

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