EDUCATIONAL ROBOTICS IN STEM EDUCATION: A CRITICAL NARRATIVE REVIEW OF CONTEMPORARY EVIDENCE AND FUTURE DIRECTIONS

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ABSTRACT*—Educational robotics has become an important instructional approach for enriching STEM education by providing learners with authentic opportunities to design, construct, and program technological solutions to real-world problems. Unlike conventional technology-assisted instruction, robotics encourages active learning through experimentation, collaboration, and iterative problem-solving, allowing students to connect theoretical concepts with practical applications. This paper critically reviews contemporary research on educational robotics to examine its contribution to STEM learning, the conditions that support effective implementation, and the challenges that continue to influence classroom adoption. The reviewed literature consistently demonstrates that robotics-based learning enhances computational thinking, conceptual understanding, problem-solving, collaboration, and learner engagement when supported by well-designed pedagogical strategies. At the same time, the educational benefits of robotics depend on teacher preparedness, curriculum integration, institutional support, and equitable access to technological resources. Recent studies also indicate a growing shift from viewing robotics solely as a programming tool toward recognizing its broader role in developing technological literacy, interdisciplinary thinking, and innovation. Despite the increasing adoption of robotics across educational settings, further research is needed to strengthen long-term evidence, improve teacher professional development, and expand robotics integration across diverse learning environments. The findings of this review provide evidence-based insights that may inform future research, curriculum development, and instructional practice in STEM education.*

Keywords: Computational thinking, Robotics literacy, Design-based learning, Teacher professional development, Educational innovation

INTRODUCTION

Educational robotics has emerged as one of the most promising innovations in STEM education because it enables learners to connect scientific concepts with authentic design and problem-solving experiences. Rather than limiting instruction to the acquisition of programming skills, robotics creates opportunities for students to design, construct, test, and refine technological solutions while applying knowledge from science, technology, engineering, and mathematics in meaningful contexts. These learning experiences encourage learners to become active participants in knowledge construction, making abstract concepts more tangible through experimentation, collaboration, and iterative design. Recent evidence indicates that educational robotics produces a moderate but significant positive effect on STEM learning, particularly when robotics activities are integrated with well-designed pedagogical approaches rather than being introduced as stand-alone technological tools [1].

The increasing adoption of educational robotics reflects a broader transformation in contemporary education. As societies continue to embrace digital technologies and automation, educational systems are expected to prepare learners with competencies that extend beyond disciplinary knowledge. Computational thinking, critical thinking, creativity, communication, and collaborative problem-solving have become essential learning outcomes that support lifelong learning and workforce readiness. Educational robotics provides an environment where these competencies develop simultaneously through hands-on learning, allowing students to investigate authentic problems, evaluate alternative solutions, and continuously improve their designs. Consequently, robotics has evolved from being viewed primarily as a programming activity to becoming a multidisciplinary instructional approach that supports deeper conceptual understanding and meaningful STEM learning [1, 2].

Recent evidence indicates that the field has entered a new stage of development. While earlier research primarily emphasized programming and computational thinking, current studies increasingly advocate for the development of robotics literacy, a broader educational construct that integrates technological literacy, engineering reasoning, interdisciplinary thinking, ethical awareness, and responsible technology use. A comprehensive systematic review synthesizing 373 studies published between 2000 and 2025 concluded that educational robotics has expanded considerably across educational levels and disciplines. However, the review also found that existing research continues to concentrate on coding-related competencies, whereas engineering design, socio-ethical reasoning, and contextualized applications remain comparatively underrepresented. These findings indicate that educational robotics may be viewed not only as a tool for teaching programming but also as a vehicle for developing broader competencies required in contemporary STEM education [3].

Although the educational benefits of robotics are well documented, successful classroom implementation remains inconsistent across educational contexts. Positive learning outcomes are more frequently observed when robotics activities are supported by learner-centered pedagogies such as project-based learning, inquiry-based learning, collaborative problem-solving, and design-based learning. In contrast, interventions that emphasize the technical operation of robotic platforms without meaningful pedagogical integration tend to produce less consistent improvements in student learning. Recent meta-analytic evidence similarly indicates that instructional design, teacher facilitation, learning duration, and educational level significantly influence the effectiveness of robotics-supported instruction, suggesting that technology alone is insufficient to transform learning experiences [1, 2].

Beyond instructional design, teacher preparedness and institutional support remain essential for the successful integration of educational robotics. Teachers are expected to design meaningful robotics activities, facilitate collaborative learning, and align robotics experiences with curriculum objectives. However, the implementation of robotics in classrooms continues to be influenced by variations in teachers' technical knowledge, pedagogical competence, and opportunities for professional learning. Existing evidence further indicates that teacher training programs differ considerably in their objectives, duration, instructional approaches, and assessment practices. Programs that integrate technical competencies with pedagogical strategies, curriculum alignment, and authentic classroom applications appear to better support teachers' confidence and readiness to implement educational robotics effectively. These findings underscore the importance of sustained professional development, institutional support, and curriculum planning to promote the long-term integration of educational robotics in schools [4].

Despite the growing body of research on educational robotics, important gaps remain in understanding how robotics can be sustainably integrated into STEM education. Existing studies consistently report positive effects on student learning and engagement; however, comparatively fewer reviews have critically examined how recent developments are reshaping the pedagogical role of robotics while considering the institutional and instructional conditions necessary for long-term implementation. Emerging areas such as robotics literacy, interdisciplinary learning, ethical technology use, and equitable access also continue to receive less attention than traditional programming outcomes. Furthermore, recent educational research highlights the importance of sustained teacher professional development, inquiry-based instructional practices, collaborative learning environments, and effective technology integration in strengthening classroom innovation and supporting meaningful STEM instruction. Collectively, these findings underscore the need for updated evidence syntheses that integrate contemporary research, address persistent implementation challenges, and provide practical directions for future educational research and practice [5, 6].

This critical narrative review synthesizes contemporary evidence on educational robotics in STEM education. Specifically, it aims to (1) examine the current pedagogical applications of educational robotics across STEM learning environments, (2) synthesize evidence regarding its influence on cognitive, affective, and collaborative learning outcomes, (3) analyze the factors that facilitate or constrain successful classroom implementation, and (4) identify emerging directions that may strengthen future research, policy, and instructional practice.

In the lens of critical narrative review, this study prioritized the interpretive synthesis and critical evaluation of contemporary evidence rather than exhaustive study identification or quantitative aggregation. Furthermore, the literature was screened through a structured selection process to ensure the inclusion of relevant, credible, and methodologically sound studies that addressed the objectives of the review.

MATERIALS AND METHODS

Research Design

This study adopted a critical narrative review to synthesize and critically evaluate contemporary research on educational robotics in STEM education. A critical narrative review was considered appropriate because it facilitates the integration and interpretation of evidence from diverse educational contexts while identifying emerging themes, conceptual developments, and gaps in the existing literature. Unlike systematic reviews, which primarily emphasize exhaustive literature retrieval and quantitative synthesis, this approach provides greater flexibility in examining the pedagogical applications, educational outcomes, and implementation challenges associated with educational robotics across different educational settings. The approach is particularly suitable for rapidly evolving areas of educational technology, where critically synthesizing current evidence is essential for informing instructional practice and future research [1,3].

Literature Search Strategy

Relevant literature was systematically identified through comprehensive searches of peer-reviewed journal databases, including Scopus, Web of Science, ScienceDirect, and SpringerLink. The review prioritized studies published between 2020 and 2026 to capture recent developments in educational robotics while including earlier influential studies that remain relevant to the theoretical and conceptual development of the field. The search focused on peer-reviewed journal articles related to educational robotics, STEM education, computational thinking, robotics literacy, educational technology, teacher readiness, technology integration, and instructional innovation, using combinations of these terms as search keywords across the selected databases.

Study Selection

The retrieved publications were screened according to their relevance to the objectives of the review. Eligible studies were peer-reviewed journal articles indexed in Scopus or Web of Science that examined educational robotics or closely related topics within formal educational settings. Empirical studies, systematic reviews, meta-analyses, and theoretical papers that contributed to understanding the pedagogical applications, learning outcomes, implementation factors, and future directions of educational robotics were included. Conference proceedings, editorials, dissertations, book chapters, technical reports, and studies focusing exclusively on industrial robotics or engineering applications without educational relevance were excluded. Preference was given to recent publications with clearly described research methodologies to ensure the credibility, quality, and relevance of the synthesized evidence.

Following the application of the inclusion and exclusion criteria, the retrieved publications underwent a staged screening process based on their relevance to the objectives of the review. Titles and abstracts were initially examined to determine their alignment with educational robotics in STEM education, after which potentially relevant articles were assessed in full text. Only peer-reviewed journal articles that satisfied the eligibility criteria were retained for critical synthesis. This selection process ensured that the review incorporated contemporary, relevant, and methodologically sound evidence to address the research objectives.

Data Analysis and Synthesis

Each selected article was examined to extract information related to its research objectives, educational context, participants, instructional approach, research methodology, principal findings, implementation challenges, and recommendations for future research and practice. The extracted evidence was analyzed using thematic synthesis, in which findings from multiple studies were systematically compared and integrated to identify recurring patterns, areas of agreement, contrasting perspectives, and emerging trends across the literature. Rather than presenting individual studies separately, the evidence was critically synthesized to develop a comprehensive understanding of the pedagogical applications, educational outcomes, and implementation factors associated with educational robotics in STEM education. This analytical approach has been widely adopted in recent educational robotics reviews because it facilitates a deeper interpretation of the relationships among instructional strategies, learner outcomes, teacher preparedness, and contextual factors influencing successful implementation [1], [3].

The synthesized evidence was subsequently organized into four interrelated themes: (1) educational robotics as a transformative pedagogical approach in STEM education, (2) learning outcomes associated with robotics-supported instruction, (3) teacher readiness and factors influencing successful implementation, and (4) emerging challenges and future directions. This thematic organization enabled a critical interpretation of the current evidence by highlighting areas of consensus, identifying inconsistencies, and revealing research gaps that may inform future research and educational practice.

Table 1. Summary of the Synthesized Evidence on Educational Robotics in STEM Education

Theme	Key Findings	Representative Studies
Educational Robotics as a Transformative Pedagogical Approach	Robotics promotes learner-centered, interdisciplinary STEM learning through project-, inquiry-, and design-based approaches.	[1], [3], [7], [8]
Learning Outcomes Associated with Educational Robotics	Robotics enhances computational thinking, conceptual understanding, problem-solving, collaboration, motivation, and engagement.	[2], [9], [10], [11]
Teacher Readiness and Successful Implementation	Effective integration depends on teacher competence, professional development, curriculum alignment, and institutional support.	[4], [6], [9]
Emerging Challenges and Future Directions	Future efforts may strengthen robotics literacy, equitable access, interdisciplinary integration, and sustainable implementation.	[1], [3], [12]

RESULTS AND DISCUSSION

Educational Robotics as a Transformative Pedagogical Approach in STEM Education

Educational robotics has emerged as a valuable pedagogical approach in STEM education by enabling students to learn through designing, building, programming, and testing solutions to authentic problems. Unlike traditional teacher-centered instruction, robotics encourages learners to actively construct knowledge, apply concepts across STEM disciplines, and refine their understanding through hands-on exploration and continuous experimentation. The reviewed literature consistently highlights robotics as an effective platform for learner-centered pedagogies, particularly project-based, inquiry-based, collaborative, and design-based learning. These instructional approaches create meaningful learning experiences that strengthen students' engagement, encourage interdisciplinary thinking, and promote the practical application of STEM concepts in real-world contexts [1, 7, 8].

Recent literature also suggests that the role of educational robotics extends beyond programming instruction. Robotics activities help students develop computational thinking, creativity, communication, teamwork, and engineering reasoning while encouraging them to approach problems from different perspectives. However, several studies observed that many classroom applications still concentrate on coding activities, with less emphasis on interdisciplinary learning and authentic engineering design. This indicates that robotics has greater educational potential when integrated across the broader STEM curriculum rather than being treated as a stand-alone programming activity [3].

The literature shows that educational robotics serves as a meaningful pedagogical approach that strengthens STEM learning by connecting theory with practice. Its success, however, depends on how well robotics activities are designed and integrated into instruction. Simply introducing robotics into the classroom is unlikely to improve learning unless it is supported by appropriate teaching strategies and purposeful curriculum integration.

Learning Outcomes Associated with Educational Robotics

The reviewed literature consistently demonstrates that educational robotics enhances students' learning experiences and academic development by engaging them in authentic design and problem-solving activities. Through these experiences, learners strengthen conceptual understanding, computational thinking, critical thinking, and problem-solving skills while actively applying knowledge in meaningful contexts. These learning gains are more evident when robotics is integrated with inquiry-based and project-based instructional approaches that encourage learners to explore, test, refine, and reflect on their solutions throughout the learning process. Recent evidence further suggests that well-designed robotics activities, supported by appropriate instructional strategies and guided learning experiences, produce more meaningful and sustained learning outcomes [9, 10].

Educational robotics also has a positive influence on students' motivation and engagement. Learning activities that involve designing and programming robots encourage curiosity, active participation, and confidence because students can immediately observe the results of their decisions and improve their work through continuous feedback. Collaborative robotics projects further enhance communication, teamwork, and shared decision-making, allowing learners to develop interpersonal skills alongside technical competencies [2, 11].

Despite these encouraging findings, the educational benefits of robotics are not always consistent across learning environments. Variations in instructional strategies, teacher facilitation, curriculum alignment, and access to learning resources often influence student outcomes. These findings suggest that the effectiveness of educational robotics depends less on the technology itself and more on the quality of the learning experiences that teachers create.

Teacher Readiness and Factors Influencing Successful Implementation

Teacher readiness remains one of the most important factors influencing the successful implementation of educational robotics. Beyond learning how to operate robotics platforms, teachers require the pedagogical knowledge to design meaningful learning experiences that connect robotics activities with curriculum objectives and students' learning needs. Existing evidence indicates that effective teacher preparation extends beyond technical training to include curriculum integration, inquiry-based pedagogy, collaborative learning strategies, and authentic classroom implementation. Continuous professional development and supportive institutional environments further strengthen teachers' confidence and instructional competence, enabling them to integrate educational robotics more effectively into STEM instruction. These findings reinforce the importance of sustained teacher development and institutional support in promoting meaningful and sustainable robotics integration [4, 6, 9].

Successful implementation also depends on institutional support. Schools that provide appropriate learning resources, administrative support, and opportunities for professional learning are more likely to sustain robotics initiatives over time. In contrast, limited access to equipment, inadequate infrastructure, and insufficient training continue to restrict implementation in many educational settings. These findings emphasize that educational robotics may be viewed as a shared institutional responsibility rather than solely the responsibility of individual teachers.

Emerging Challenges and Future Directions

Although educational robotics continues to gain recognition as an effective instructional approach, several challenges continue to influence its successful implementation. Variations in robotics platforms, instructional approaches, intervention duration, and assessment methods make it difficult to compare findings across studies and establish consistent evidence for best practices. In addition, limited access to technological resources, unequal digital infrastructure, and insufficient opportunities for continuous professional development remain significant barriers, particularly in resource-constrained schools. Recent educational research further suggests that successful technology integration depends not only on access to appropriate learning resources but also on sustained teacher support, institutional commitment, and strategies that promote equitable and meaningful implementation. Addressing these challenges is essential to maximize the educational potential of robotics and support its long-term integration into STEM education [1, 3, 12].

Future research may move beyond examining whether educational robotics improves learning and instead explore how different instructional models, teacher competencies, and educational contexts influence its long-term effectiveness. Greater attention may also be given to interdisciplinary learning, ethical applications of emerging technologies, and equitable access to robotics education. Addressing these areas will contribute to more inclusive and sustainable robotics integration while preparing learners with the knowledge, skills, and adaptability required in an increasingly technology-driven society.

CONCLUSION

Educational robotics has become an important approach to STEM education, creating meaningful opportunities for students to learn through exploration, collaboration, and real-world problem-solving. The reviewed literature shows that robotics supports the development of computational thinking, conceptual understanding, creativity, and collaboration when integrated into well-designed, learner-centered instruction. These benefits, however, depend not only on the technology itself but also on effective teaching, curriculum alignment, and institutional support.

The review further highlights that teacher preparedness and continuous professional development are essential for maximizing the educational value of robotics. At the same time, challenges related to access, instructional design, and long-term implementation continue to influence its adoption across educational settings.

In a nutshell, educational robotics offers significant potential to strengthen STEM teaching and learning when supported by sound pedagogical practices. Future research may continue exploring sustainable implementation strategies and broader interdisciplinary applications to ensure that robotics remains an inclusive and effective tool for preparing learners for an increasingly technology-driven world.

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