The Role of Robotics in Education: A Comprehensive Review of Technologies, Pedagogies, and Implementation Strategies

Mahesh T R, Jonathan Mathew John, K. Bhavya Prabhaditya, K.S. Chakradhar Reddy, K. Muni Sai Parthu
Jain (Deemed-to-be University), Bangalore, India
Email: {t.mahesh, 21BTRCS155, 21BTRCS167, 21BTRCS156, 21BTRCS157}@jainuniversity.ac.in

***Abstract*—Educational robotics (ER) has emerged as a transformative tool in modern pedagogy, particularly within primary and secondary education. This survey paper presents a comprehensive review of current trends, technologies, pedagogical frameworks, and implementation strategies associated with ER. Drawing upon recent empirical studies, systematic reviews, and longitudinal implementations, this work explores the cognitive, emotional, and curricular impacts of robotics-based learning. Key themes include the development of computational thinking, the role of robot personalization and soft robotics, and the importance of student-centered design. Additionally, challenges related to teacher readiness, equity, infrastructure, and policy integration are critically examined. Case studies from Italy, the United States, and global research databases are synthesized to identify effective practices and barriers to adoption. The paper concludes with future research directions and strategic recommendations for educators, policymakers, and technologists. This review aims to inform stakeholders on the potential of ER to enhance learning outcomes and to contribute to a more inclusive, innovative, and interdisciplinary educational landscape.**

***Index Terms*—Educational Robotics, Computational Thinking, Soft Robotics, Human-Robot Interaction, Pedagogical Innovation**

I. INTRODUCTION

In recent decades, the intersection of robotics and education has become a vibrant and expanding field of inquiry and practice. The integration of robotics into educational environments represents a significant innovation in both pedagogy and learning technology, promising to transform the ways in which students engage with content, develop cognitive and social competencies, and prepare for the demands of an increasingly automated and technology-driven society. This transformation is particularly salient in primary and secondary education, where early exposure to technological systems has been shown to foster critical thinking, creativity, collaboration, and computational literacy—skills that are now widely recognized as essential components of 21st-century education.

Educational robotics (ER) encompasses the use of robotic devices and systems to support teaching and learning processes, typically within science, technology, engineering, and mathematics (STEM) domains. However, its influence extends beyond technical content, touching on broader educational outcomes such as problem-solving ability, language development, self-efficacy, and social-emotional learning. From programmable kits like LEGO Mindstorms and WeDo to humanoid robots capable of personalized interaction, the range of tools available for educators has grown considerably, facilitating diverse modes of student engagement. These platforms serve not only as instructional tools but also as catalysts for experiential, constructionist learning, aligning with educational theories that emphasize active participation and learner agency. The academic interest in educational robotics has mirrored its increasing prevalence in classrooms. Numerous empirical studies, systematic reviews, and meta-analyses have been conducted to assess its efficacy, accessibility, and pedagogical value. For instance, meta-analytic evidence suggests moderate-to-strong effects of ER on students' computational thinking skills and STEM attitudes [2], while experimental studies in authentic classroom settings demonstrate the potential of social robots to foster deeper engagement and personalized learning trajectories [3]. At the same time, bibliometric analyses have revealed a significant upsurge in scholarly output on this topic over the past decade, with research agendas increasingly focusing on curricular integration, technological design, and inclusive practices [7].

Despite these advances, the field remains heterogeneous and fragmented, reflecting both the novelty of the domain and the diversity of educational contexts in which robotics is being deployed. Studies differ considerably in their method- ological rigor, target populations, implementation strategies, and theoretical frameworks, making it challenging to draw generalizable conclusions or develop unified models for effective practice. Furthermore, much of the literature has been concentrated in specific regions and educational levels, often leaving gaps in our understanding of how robotics can be equitably and sustainably integrated across various socio-cultural settings and age groups.

To address these issues, this survey paper aims to provide a comprehensive, structured synthesis of the current state of research and practice on the role of robotics in education. It critically examines both the pedagogical and technological dimensions of ER, drawing on insights from empirical studies, literature reviews, experimental interventions, and theoretical discourses. Specifically, it considers how robotics enhances or reconfigures learning processes; how students perceive, interact with, and benefit from robotic systems; and how educators, designers, and policymakers can collaboratively shape the future of this field. Attention is also paid to recent innovations such as soft robotics, student-centered design of robotic platforms, and the use of adaptive, personalized robots in formal and informal educational settings.

The paper is organized into ten sections. Following this introduction, Section II lays the theoretical and technological foundation of educational robotics, defining key concepts and tracing their evolution over time. Sections III and IV constitute the first major thematic cluster, addressing the cognitive and curricular implications of robotics. These sections discuss how ER supports computational thinking, problem-solving, collaboration, and affective learning, as well as its integration into curricular frameworks and assessment strategies. Sections V and VI form the second thematic cluster, focusing on the technological and design aspects of ER, including robot morphology, student preferences, and the role of human-robot interaction in shaping learning outcomes. Section VII presents practical implementations and case studies, while Section VIII addresses the multifaceted challenges—technical, pedagogical, social, and institutional—that hinder wider adoption. Section IX synthesizes the findings into a future research agenda, and Section X concludes the paper by reflecting on the implications for theory, policy, and practice.

Through this structured review, the paper seeks to contribute not only to scholarly discourse but also to educational innovation on the ground. By situating robotics within broader educational trends—such as digital transformation, personalized learning, and interdisciplinary teaching—it invites educators and stakeholders to reconsider conventional paradigms and imagine new possibilities. Ultimately, the integration of robotics into education is not merely a matter of introducing novel tools into classrooms; it represents a paradigm shift in how we conceptualize knowledge, teaching, and the learner's role in constructing meaning. As such, the critical examination of this field is both timely and imperative.

II. Foundations of Educational Robotics

Educational robotics (ER) has emerged as a dynamic interdisciplinary field that integrates robotics technology into teaching and learning environments, primarily to enhance cognitive development, technical fluency, and pedagogical innovation. The domain has witnessed accelerated growth in the last two decades, particularly within K–12 and primary education contexts, where robotics has shown notable promise in developing 21st-century skills and improving engagement across science, technology, engineering, and mathematics (STEM) disciplines.

A. *Definitions and Evolution*

Educational robotics refers to the use of programmable physical robotic systems as tools for learning. These systems are designed to support the construction and application of knowledge through interactive and experiential activities. A key characteristic of ER is that it often engages learners in designing, building, programming, and testing robotic systems to solve open-ended problems. This practice-oriented approach aligns with constructivist pedagogies, which emphasize the active role of learners in constructing their own understanding through interaction with their environment [1].

Over time, ER has evolved from basic programmable toys into complex, multimodal platforms capable of fostering interdisciplinary learning. Early applications focused on introducing programming and logic, while more recent innovations have integrated features such as artificial intelligence, adaptive behavior, and soft materials to enable safe and intuitive human–robot interaction. These developments have transformed educational robots from rigid, preconfigured kits to open-ended tools that support creativity, collaboration, and personalization in learning [1].

B. *Theoretical Underpinnings*

Two major educational theories underpin the design and implementation of robotics in learning environments: constructivism and constructionism. Constructivism posits that knowledge is not passively absorbed but actively built by the learner through experience and interaction. Within this paradigm, robotics provides an ideal medium by which students can manipulate real-world artifacts and receive immediate feedback, fostering reflective learning and critical thinking [1].

Constructionism, building upon constructivism, emphasizes the creation of tangible artifacts as a vehicle for learning. In ER contexts, this translates to the physical construction and programming of robotic systems that embody students' ideas and problem-solving strategies. This process of building physical models not only facilitates understanding of abstract concepts but also makes the learning process visible and tangible [1]. Robotics activities thus serve as a bridge between mental models and real-world phenomena, deepening learners' comprehension through embodiment and iteration.

C. *Key Technologies and Platforms*

A range of robotic platforms have been adopted in educational settings, each offering different affordances for learning. Among the most widely used are the LEGO Mindstorms and LEGO WeDo kits. These platforms offer modular components that can be easily assembled and programmed, making them particularly suitable for younger learners. Their compatibility with graphical programming environments and integration with visual and tactile elements have made them effective in fostering creativity, logical reasoning, and hands-on engagement [1].

Soft robotics represents a newer and increasingly influen- tial technological paradigm within ER. Unlike conventional rigid-body robots, soft robots are constructed from flexible, hyperelastic materials such as silicone and polymers. These materials allow for safer, more adaptive interaction with learners, reducing physical risks and broadening accessibility. Soft robots can mimic biological forms and behaviors, enabling interdisciplinary exploration that spans materials science, biology, and mechanical engineering [1]. Their capacity for deformation and compliance makes them suitable for novel educational applications, including wearable robotics and sensitive manipulation tasks, which would be difficult to achieve with traditional robotic systems.

In addition to their mechanical properties, educational robots increasingly integrate multimodal interfaces and adap- tive behaviors to enhance usability and engagement. The morphology, motion dynamics, and personality of robots play crucial roles in shaping student perceptions and learning experiences, with student-centered design emerging as a key consideration in platform development [2].

D. *A Taxonomy of Educational Robotics Approaches*

To better organize the diverse approaches in educational robotics, we propose the following four-dimensional taxonomy (Table I), which classifies existing work by robot type, learning domain, interaction style, and deployment model.

TABLE I: Taxonomy of Educational Robotics Approaches

Dimension	**Categories**	**Description / Examples**
Type of Robot	Humanoid	Socially engaging, bipedal robots (e.g., NAO Zeno) for peer- like emotional interaction [3], [4
	Soft Robotics	Flexible, safe, and cre- ative platforms using si icone/rubber for inte disciplinary tasks [1]
	Modular / LEGO-Based	Rigid kits (e.g., LEGO Mindstorms/WeDo) fo constructivist and STEM learning [1], [5]
	Toy-like / Zoomor-phic	Animal-like or playful forms to increase appea especially in early edu cation [4]
Learning Domain	STEM Education	Emphasis on science, math, engineering, and hands-on experimentation [2], [5]
	Computational Thinking (CT)	Development of abstrac- tion, decomposition, a gorithmic reasoning [2]
	Social-Emotional Learning (SEL)	Activities fostering em- pathy, collaboration, an self-regulation [3]
Interaction Style	Peer-Based Interaction	Robots as equals or collaborators, improvin engagement and trust [3]
	Adaptive / Personal-ized	Behavior adjusts to learner performance preferences, or emotional state [3], [4]
	Scripted / Predefined	Fixed instructional se- quences without runtim adaptation
Deployment Model	Curriculum-Embedded	Fully integrated into core instruction (e.g., mult year programs) [5]
	Workshops / Teacher Training	Short-term, high-impact sessions for educators an students (e.g., STREAM) [6
	Informal / Extracur-ricular Learning	Robotics clubs, camps, and labs for self-directe exploration [4]

III. Cognitive and Social-Emotional Development

A. *Development of Computational Thinking and Problem-Solving Skills*

One of the most documented benefits of ER is its capacity to foster computational thinking (CT) — a critical skill en- compassing abstraction, decomposition, algorithmic thinking, and pattern recognition. ER activities prompt learners to solve open-ended problems using logic, algorithms, and iterative testing. These competencies extend beyond programming and are applicable to disciplines such as mathematics, physics, and even art [2]. As learners design, code, and test robotic systems, they engage in cyclical processes of hypothesis formation and refinement, mirroring authentic scientific inquiry [1].

Moreover, ER promotes collaborative problem-solving and team-based learning. Many robotics programs encourage stu- dents to work in groups, thereby developing communication, negotiation, and coordination skills. The collaborative nature of robotics projects reflects real-world engineering practice and has been found to enhance group cohesion and peer learning [2].

B. *Emotional Engagement and Personalized Learning Through Robots*

In addition to cognitive benefits, ER significantly contributes to student motivation and emotional engagement. The gami- fied, hands-on nature of robotics projects offers a high level of interactivity and challenge, which are known to support intrinsic motivation and perseverance in learning tasks. Robots are often perceived by students as non-threatening and enjoy- able partners in learning, particularly when they exhibit social behaviors such as speech, gesture, and responsiveness [2].

Recent advancements have enabled the personalization of robot behavior, whereby robots adapt their interactions based on the learner's performance, preferences, or emotional state. Such adaptive systems have been shown to increase student acceptance and engagement, particularly when robots assume peer-like roles in the classroom. Studies indicate that students interacting with personalized robotic peers exhibit improved learning outcomes and deeper social connection with the robot, suggesting that personalization can enhance not only academic performance but also social-emotional development [2].

IV. Curricular Integration and Learning Outcomes

A. *Robotics Across STEM Disciplines*

Educational robotics serves as a multidisciplinary platform that aligns closely with STEM objectives. In science education, robotics activities can simulate environmental processes or demonstrate principles of motion and force. In technology and engineering, students engage directly with system design and control logic. Mathematics is reinforced through calibration, measurement, and algorithmic implementation. Such integra- tion supports contextualized learning, where abstract concepts are grounded in physical tasks and applications [2].

Furthermore, robotics platforms provide a unique opportunity to implement inquiry-based and project-based learning approaches. Students are encouraged to pose questions, test solutions, and iterate designs — all essential features of scientific literacy and engineering thinking. By engaging with tangible, responsive systems, learners receive immediate feedback, allowing for rapid refinement of their understanding and methods.

B. Learning Assessments and Meta-Analytical Findings

Quantitative analyses have demonstrated that ER positively impacts learning outcomes, particularly in the development of CT skills. A meta-analysis covering studies from 2010 to 2019 reported a moderate overall effect of ER on computational thinking (SMD = 0.48), while the effect on STEM attitudes was smaller but still present (SMD = 0.01) [2]. The data further suggests that ER is more effective in primary education settings (SMD = 0.27) than in middle school (SMD = 0.04), possibly due to the novelty and engagement factor in younger learners [2].

Interestingly, short-term interventions yielded stronger effects (SMD = 0.35) compared to longer-term implementations, pointing toward the importance of carefully structured activities and frequent feedback loops in ER programs. These findings underscore the need for targeted curriculum design and evidence-based evaluation frameworks to maximize the benefits of robotics in education.

V. Design of Robotic Platforms for Education

The design of educational robotics platforms plays a pivotal role in shaping students' learning experiences. A student-centered approach to design emphasizes aligning robotic platforms with learner expectations, cognitive styles, and affective engagement. As educational robotics adopts a constructivist and constructionist framework, platforms must support autonomy, creativity, and iteration. Research has shown that student-centered environments allow learners to observe the effects of their actions and revise strategies, thereby reinforcing a sense of agency and ownership over their learning process [1].

Students often express clear preferences regarding robotic platforms, favoring designs that are humanoid, bipedal, and anthropomorphic in nature. These traits enhance social presence and improve learners' receptiveness to the robot as a learning companion [3]. Integrating such expectations into the design encourages intrinsic motivation and supports collaborative activity in STEM disciplines. Factors such as morphology, mobility, interactivity, and personality must be considered carefully. Robots that are personable—e.g., using the child's name or exhibiting playful behavior—are perceived as more engaging and approachable [3].

Furthermore, educational design must consider the developmental needs of the target age group. In one study, children with no prior exposure to robotics described their ideal robot companions as interactive, socially intelligent, and capable of responding to their educational needs [4]. By incorporating such expectations into platform development, designers can improve acceptance and support deeper engagement in learning activities, as summarized in Table II.

TABLE II: Design Priorities and Educational Outcomes

Design Priority	Educational Impact
Personalization (e.g., names adaptive behavior)	Boosts engagement, emotiona connection, and memory reten- tion
Soft Materials	Safer for young or diverse learners lowers physical and psychologica barriers.
Humanoid/Toy-like Morphol- ogy	Enhances social presence an approachability; improves comfo and participation.
Modularity	Reduces learning curve; en courages creativity and itera- tiv prototyping.
Multimodal Interaction (e.g voice, gestures)	Supports embodied learning an inclusive communication.

A. Soft vs. Rigid Robotics

While rigid-body robotics has traditionally dominated the educational landscape through platforms such as LEGO Mindstorms, recent research highlights the pedagogical potential of soft robotics. Rigid robots are advantageous in teaching topics such as kinematics, control systems, and programming. However, they also present limitations in terms of safety, complexity, and adaptability [1].

Soft robots, constructed from hyperelastic materials such as silicone and rubber, provide a more flexible, safe, and tactile interaction model. These properties make them especially suited for younger learners or inclusive learning environments. Soft robotics supports interdisciplinary learning, combining elements of mechanical design, material science, biology, and electronics [1]. Furthermore, because soft robots are often fabricated using accessible tools like 3D printers and silicone molds, they also introduce students to fabrication and prototyping skills—enabling a more holistic understanding of engineering processes.

One notable concern with traditional kits is that students tend to spend the majority of their time programming rather than engaging with physical design tasks, thereby limiting creative exploration. Soft robotics, by contrast, encourages stu- dents to consider the mechanical structure and material behav- ior, offering richer opportunities for hands-on learning [1]. As educational goals expand to include more than programming proficiency, the role of soft robotics as a complementary or alternative approach is increasingly relevant.

VI. Human-Robot Interaction and Personalization

Effective educational robots must not only deliver content but also engage learners as interactive peers. Human-robot interaction (HRI) in education is enriched through personalization—adapting robot behavior to the learner's preferences, emotional state, and prior performance. In a two-week classroom study, robots that personalized their speech, behavior, and instructional strategies led to increased learning gains among primary school students, particularly when the content was novel [3].

Personalization included aligning verbal and non-verbal cues with the learner's responses, modifying difficulty levels based on student performance, and fostering social closeness through conversational engagement. Robots employing informal, peer-like dialogue and calling students by name were more effective at building rapport, leading to higher engagement and retention of information [3]. These findings support the hypothesis that adaptive behavior and personalized interaction improve the educational value of robotic systems. Longitudinal studies further demonstrate that while the novelty of robots may decline after a week, consistent use of personalized robots maintains motivation and participation. Even in classrooms where teachers received no special training, the robots were accepted and used effectively as learning tools [3].

VII. Implementation in Educational Contexts

The effective implementation of educational robotics (ER) relies heavily on structured, context-aware interventions that are supported by teacher training and curriculum integration. In one longitudinal initiative in Italy, robotics was introduced as a core curricular subject spanning five years of primary education. Students began with basic logic and mechanical interaction using LEGO WeDo kits and later progressed to designing and programming autonomous robots with LEGO NXT. Teachers reported increased student engagement, collaboration, and problem-solving capacity, and the program was marked by close cooperation between schools, universities, and industry partners [5].

Similarly, in the United States, the STREAM workshop introduced K–12 educators to a range of robotics platforms through immersive sessions that connected robotics with core STEM areas. Participants gained hands-on experience in science data collection using iSense, programming with LEGO Mindstorms, and engineering tasks such as building pneumatic catapults. The workshop emphasized real-world application, curricular integration, and the sharing of best practices among educators [6]. These implementations highlight the need for professional development opportunities and underscore the impact of robotics when aligned with pedagogical goals and teacher capacity.

Additionally, soft robotics workshops have been leveraged as a means of exposing students to novel technologies. Through fabrication, design, and programming, students en- gaged with interdisciplinary content that included biology, mechanics, and materials science. These experiences offered unique learning outcomes by emphasizing creativity and inno- vation in engineering tasks [1].

VIII. Challenges and Barriers to Adoption

Despite promising outcomes, the widespread adoption of educational robotics (ER) is hindered by several barriers. A persistent issue is teacher readiness. In many cases, educators lack sufficient training in robotics or programming, making it difficult to incorporate ER into classroom practice. Even in successful programs, such as the one reported by Scaradozzi et al., long-term sustainability depended on continual teacher support and professional development [5].

Technical limitations also persist. Rigid robotics platforms may present safety risks, be cost-prohibitive, or require infrastructure not readily available in all schools. Although soft robotics offer a safer and often more accessible alternative, they still demand access to fabrication tools and specialized knowledge that many institutions lack [1].

Equity and inclusion present further challenges. Research shows that students' perceptions of robots are influenced by gender, morphology, and sociocultural factors. For example, girls tend to prefer robots with toy-like appearances, emphasizing the importance of inclusive design principles. Without attention to such preferences, ER may inadvertently alienate underrepresented groups [4].

Geographic disparities in ER adoption also limit its global reach. As Mart´ınez Rojas et al. point out, most research is concentrated in North America and Europe, with limited representation from Latin America, Africa, or Southeast Asia. This imbalance highlights the need for context-specific solutions and open-access materials that support broader participation [7].

IX. Research Gaps and Strategic Future Directions

Despite significant advances in educational robotics (ER), several critical gaps remain that must be addressed to ensure equitable, effective, and sustainable deployment in diverse educational settings. Based on our synthesis of the literature, we identify five primary areas requiring further investigation and propose corresponding strategic directions.

A. *Lack of Longitudinal Evidence*

Most existing studies evaluate ER interventions over very short periods (e.g., single workshops or 1–2 week deployments) and report immediate gains in computational thinking or engagement [2], [3]. However, the long-term impact of sustained ER exposure on student learning trajectories, retention of 21st-century skills, and career interests remains largely unexamined.

Strategic direction: Design and fund multi-year, cohort-based studies that track cognitive, affective, and behavioral outcomes from early primary through secondary levels, using mixed methods and standardized instruments to measure growth over time.

B. *Geographic and Socioeconomic Disparities*

Bibliometric and systematic reviews reveal a predominance of ER research in high-income countries, with scant representation from low-resource or rural contexts [7]. This geographic bias limits our understanding of how ER can be adapted to settings with limited infrastructure, variable internet access, or non-Western pedagogical traditions.

Strategic direction: Encourage and support ER pilots in underrepresented regions by developing low-cost, unplugged, or locally fabricated platforms (e.g., soft robotics prototypes) and by partnering with NGOs and local school systems to co-design culturally relevant curricula.

C. Teacher Readiness and Professional Development

Effective ER integration hinges on teachers' confidence and competence in robotics, yet few studies address long-term professional development models [5], [**?**]. One-off workshops (e.g., STREAM) generate initial enthusiasm but lack follow-up and in-classroom coaching, leading to uneven adoption and limited curricular alignment.

Strategic direction: Develop scaffolded PD programs incorporating peer mentorship, online communities of practice, and just-in-time mobile support. Conduct comparative studies to determine which PD structures most effectively translate into classroom practice.

D. Inclusive Design and Equity

Evidence indicates that student engagement with robots is influenced by morphology, gender norms, and social roles [4]. For example, girls often prefer toy-like or socially expressive robots, whereas boys may engage more with machine-like or competitive scenarios. Without deliberate inclusive design, ER risks reinforcing existing participation gaps.

Strategic direction: Adopt participatory design methods that involve diverse student populations in co-creating robot appearances, behaviors, and tasks. Systematically evaluate how these design choices affect motivation and learning across gender, cultural, and ability groups.

E. Absence of Unified Conceptual Frameworks

While numerous ER studies report positive outcomes, the field lacks a cohesive theoretical model linking robot characteristics, pedagogical strategies, and learning outcomes. Most contributions are ad hoc or descriptive, making it difficult to generalize findings or guide new implementations.

Strategic direction: Propose and validate a meta-model (e.g., an "ER Input–Mediator–Outcome" framework) that specifies how variables such as robot type, interaction style, and curriculum integration jointly influence cognitive and socio-emotional metrics. Empirically test the framework across multiple sites and age groups.

F. Summary of Recommendations

- **Longitudinal Studies:** Fund and publish multi-year, mixed-methods research tracking ER effects from pri- mary through secondary education.
- **Global Equity:** Create and evaluate low-cost, culturally tailored ER prototypes in underserved regions.
- **Sustained PD:** Implement tiered professional develop- ment with ongoing mentoring and community support.
- **Participatory Design:** Engage diverse learners in co-design to ensure inclusive robot morphologies and interactions.
- **Meta-Model Development:** Formulate and empirically validate a unified theoretical framework connecting ER design variables to learning outcomes.

Addressing these gaps will advance both the science and practice of educational robotics, ensuring that ER fulfills its potential to enhance learning for all students, regardless of context or background.

X. Conclusion

Educational robotics holds immense promise as a transformative force in primary and secondary education. By fostering computational thinking, creativity, collaboration, and engagement, robotics can enrich student learning across disciplines. The diversity of platforms—from rigid to soft robotics—provides flexible entry points tailored to different educational needs.

However, the success of ER depends on more than just the technology. Real-world case studies reveal that implementation is most effective when coupled with robust teacher training, inclusive design, and curricular alignment. Key challenges—such as technical complexity, gender inclusivity, geographic disparity, and institutional readiness—must be addressed through research, policy, and practice.

Future progress will depend on longitudinal studies, refined assessment models, teacher-centered innovations, and strategic policy interventions. As robotics continues to shape the technological landscape, education systems must prepare students not just to use robots—but to learn, create, and collaborate through them.

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