

**AFFORDABLE, SCREEN-FREE ROBOTICS FOR ENHANCING COMPUTATIONAL THINKING  
IN EARLY STEM EDUCATION: A COMPREHENSIVE REVIEW**

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**Abstract**

This comprehensive review examines the emerging field of affordable, screen-free robotics as an approach to developing computational thinking skills in early STEM education in underserved learning environments. Even though learning benefits exist for educational robots, many challenges still continue to plague widespread adoption in underserved communities. This paper therefore uses a comprehensive thematic literature review of peer-reviewed literature published in the range of 2010 and 2025. The paper therefore attempts to synthesize the research across various disciplines involved in educational robotics. The theoretical foundations that form the foundation of educational robotics were reviewed. In addition, key engineering and mechatronics constraints involved in the development of educational robotics for underserved communities were also reviewed. The review identified significant research gaps which include the feasibility and under-exploration of RFID for tangible programming. This synthesis showed that achieving equitable access to computational thinking education requires a new generation of educational robotics. These solutions must aim to be low-cost, screen-free, locally manufacturable, pedagogically effective, and environmentally sustainable, or any combination of these features. The findings from this review can potentially provide a roadmap for researchers, engineers, and educators working to democratize STEM education through accessible robotic platforms.

**Keywords**

*Educational  
robotics,  
Computational  
thinking,  
Screen-free  
programming,  
Tangible  
interfaces,  
STEM  
education*

**1. INTRODUCTION**

Educational Robotics (ER) has gained significant traction as a vehicle for developing Computational Thinking (CT) and problem-solving skills in early Science Technology Engineering and Mathematics (STEM) education [1, 2]. However, the cost of commercially available ER kits has limited its adoption despite the improvement it can bring to student's learning [3, 4]. Furthermore, the growing body of evidence on the adverse effects of early screen exposure adds another dimension to this challenge [5] and creates demand for robotics solutions that are both screen-free and affordable.

Screen-free robotics is a type of robotics in which learners program robots through tangible physical elements such as blocks, barcodes, or colours rather than digital screens [6, 7]. This form of robotics offers a promising solution to the challenge of accessibility and screen exposure. Despite the growing interest in this field, literature remains scattered across engineering, education, and computer science disciplines with no comprehensive and thematic synthesis of the design, pedagogical, and sustainability dimensions of affordable, screen-free ER for underserved contexts.

This paper addresses that gap by presenting a comprehensive thematic review of screen-free educational robotics. This is done by synthesizing research across theoretical foundations, mechatronics design, tangible programming systems, practical trade-offs, and manufacturing sustainability. The novelty of this review lies therefore in its integrative, cross-disciplinary framing and its specific focus on design constraints relevant to underserved learning environments, this is an angle underrepresented in existing literature.

**2. REVIEW METHODOLOGY**

This review synthesizes research on low-cost, screen-free educational robotics and its role in developing computational thinking, with particular focus on K-12 classrooms in underserved learning environments.

Given the interdisciplinary nature of the field, a thematic literature review approach was adopted to identify key trends, design constraints, and research gaps.

The search strategy targeted peer-reviewed journal articles, conference proceedings, book chapters, and authoritative reports published between 2010 and 2025, with emphasis on publications from the last five years. Primary databases included IEEE Xplore, ACM Digital Library, and Google Scholar. Search terms were combined using Boolean operators (AND, OR) and drew on keywords such as "educational robotics," "computational thinking," "screen-free programming," "tangible interfaces," "affordable robotics," and "underserved communities," among others.

Articles were included if they addressed screen-free or tangible programming methods, affordability, sustainability, or pedagogical impact of educational robotics within K-12 settings and were written in English. Studies focused purely on screen-based or software-only programming, advanced university-level robotics, or non-peer-reviewed sources were excluded.

### **3. THEORETICAL FOUNDATIONS**

For the purposes of this review, the following key terms are defined as used throughout this paper. "Underserved communities" refers to populations that face systemic barriers to accessing quality education, including but not limited to limited electricity, poor internet connectivity, and low household income, particularly prevalent in rural and peri-urban areas of developing nations. "Screen-free" describes educational tools and robotics systems that function entirely without the use of digital screens such as computers, tablets, or smartphones, relying instead on tangible physical interfaces. "Affordable" in this context refers to educational robotics solutions whose unit cost is low enough to be feasibly adopted at scale by schools and communities in resource-constrained settings, broadly aligned with costs under \$50 per unit. "Early STEM education" refers to Science, Technology, Engineering, and Mathematics instruction delivered to learners in the K-12 category, with particular emphasis on foundational years up to approximately age 12.

Wing explains computational thinking as a way of "solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science" [8]. Computational Thinking (CT) has emerged as a foundational skill for the 21st century, enabling individuals to approach complex problems through decomposition, pattern recognition, abstraction, and algorithmic thinking [9–11]. These elements are depicted in Figure 1. Despite its recognized value in early STEM education, integrating CT into curricula remains challenging, particularly in underserved communities where the necessary infrastructure is often absent [12, 13]. Tangible programming, unplugged systems, and low-cost robotics represent promising pedagogical responses to this challenge, as they can introduce CT concepts without reliance on digital devices [14].

Educational Robotics is theoretically grounded in constructivist and constructionist learning frameworks. Piaget's Constructivism emphasizes how children build understanding through active interaction with their environment, progressively refining their mental models through experience. Papert's Constructionism extends this by positioning the act of making tangible artifacts, physical or digital, as central to meaningful learning, enabling learners to externalize and reflect on their thinking [15]. In this framework, the tools, media, and learning environment are not incidental but constitutive of the knowledge construction process [16]. Educational robotics operationalizes these principles by giving learners hands-on, making-centred experiences that simultaneously develop CT competencies. Research confirms that ER interventions can produce significant improvements in learning outcomes across multiple dimensions [17]. Existing kits such as LEGO Mindstorms, Thymio, KIBO, and Arduino-based platforms demonstrate the range of applications possible [1, 18, 19], though their cost and infrastructure requirements continue to limit uptake in resource-constrained settings.

### **4. ENGINEERING AND MECHATRONICS DESIGN IN EDUCATIONAL ROBOTICS**

#### **4.1. Material Selection and Safety Standards**

The design of educational robotics kits usually involves careful consideration of materials, mechanics, electronics, and power systems. Each of these factors carry cost and safety implications relevant to underserved contexts.

Material selection for ER kits can be informed by toy safety standards such as ASTM F963, given that both products are actively handled by young children [20]. Plastic remains the dominant material due to its low cost and durability, but raises significant environmental and health concerns, particularly regarding toxic chemical content [21, 22].

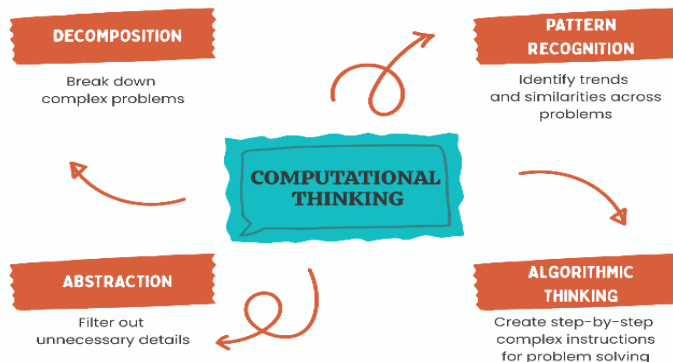


Fig. 1. Core Components of Computational Thinking

Wood presents a safer, biodegradable alternative that is well-suited to low-cost, screen-free ER kits [23, 24]. Mechanical design determines the range of learning activities an ER kit can support. The main robot motion types include wheeled, legged, robotic arm, and modular designs. Each of these carry distinct trade-offs in complexity, cost, and pedagogical applicability, as summarized in Table 1. Figure 2 also shows various brands of educational robotics. Wheeled robots dominate ER applications due to their simplicity and versatility [25, 26], while modular designs, though flexible, tend to be significantly more expensive. The AERobot, for instance, achieved a unit cost of approximately \$10 through a fixed, single-unit design. This is roughly 30 times cheaper than the modular KIBO kit [4, 27]. For underserved contexts, this cost differential strongly favours single-unit, open-source approaches.

Table 1. Educational Robots Motion Types Summary

Robot Type	Advantages	Disadvantages	Examples	Sources
Wheeled Robots	Simple, energy-efficient, cost-effective	Limited terrain adaptability	LEGO Mindstorms, Ozobot	[28]
Legged Robots	Can navigate rough terrain	High power consumption, complex	Boston Dynamics Spot, Hexapods	[29, 30]
Robotic Arms	Precise, used for fine motor skills	Not suitable for mobility	Dobot, Arduino-controlled arms	[31, 32]
Modular Robots	Flexible, customizable	Expensive, complex assembly	KIBO, Cubelets	[5, 33]

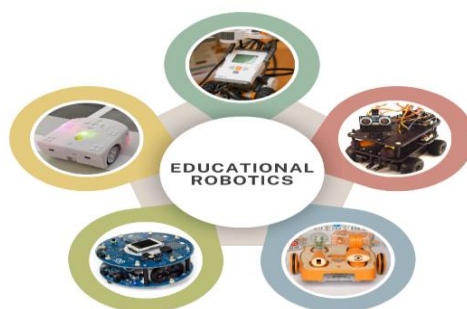


Fig. 2. Various Educational Robots

Electronic and mechatronic integration is central to robot functionality. Microcontrollers such as Arduino (Atmega-based) and ESP32 have become popular choices for low-cost educational robots due to their open-source ecosystems and suitability for low-power applications [34, 35]. Sensors, including distance, light, colour, and weight sensors, enable robots to interact with their physical environment and are particularly critical in screen-free systems, where tangible elements such as barcodes or physical blocks serve as programming inputs [36]. Notably, RFID and NFC technologies represent an underexplored low-cost alternative to barcode and optical tangible programming systems [37, 38]. Actuation is typically achieved through servo, geared DC, or stepper motors depending on the required movement profile [39]. Power management is especially critical in off-grid underserved environments. Most ER kits rely on lithium-ion or lithium-polymer batteries, which offer high energy density but raise cost and sustainability concerns [40, 41]. Emerging alternatives such as supercapacitors and wireless charging remain at early stages of development and warrant further research for ER applications [42].

**5. SCREEN-FREE ROBOTICS**

Screen-free robotics has its conceptual roots in Papert's LOGO Turtle, which introduced the idea of programming a physical robot through simple, tangible commands [43]. As screen-based ER kits came to dominate the market, concerns about early childhood screen exposure renewed interest in screen-free alternatives [44, 45]. This has produced a new generation of tangible programming platforms, of which KIBO is the most extensively researched. KIBO allows children to sequence wooden blocks with printed barcodes to program robot behaviour, demonstrating that young learners can develop meaningful CT competencies without any screen interaction [46]. Kupe's Journey extends this model with a low-cost, locally manufacturable design, further validating the potential of screen-free robotics for underserved contexts [7]. Tangible Programming Systems make screen-free robotics possible by using the physical properties of objects such as shape, colour, barcode, or embedded RFID, to convey programming instructions [47]. This abstraction of coding concepts into physical form has been shown to improve collaboration, problem-solving, and motivation among young learners compared to screen-based methods [48]. The Thymio robot implements a low-cost tangible system using printed icons interpreted through computer vision, while the PROTEAS kit advances this further by integrating both tangible and graphical programming interfaces to scaffold learners' transition toward virtual programming environments [47, 48]. Table 2 presents a comparative overview of key tangible programming interfaces across cost, durability, and functionality.

Table 2. Tangible Programming Interfaces Comparison

System	Programming Method	Cost Profile	Durability	Functionality	Best For
KIBO	Wooden blocks with barcodes	High (proprietary)	High (physical blocks)	Sequencing, basic logic	Well-resourced classrooms
Thymio	Printed icons (computer vision)	Low (open-source, printable)	Medium (paper-based)	Basic commands, visual feedback	Budget-conscious schools
PROTEAS	Hybrid graphical/tangible	Medium	Medium-High	Transition tool (physical→virtual)	Progressive learning environments

**6. PRACTICAL TRADE-OFFS**

**6.1. Balance Between Affordability and Functionality**

A fundamental tension in educational robotics design is the balance between affordability and functionality. Commercial kits like KIBO and Bee-Bot offer rich learning experiences but at costs that effectively exclude underserved communities [5]. Lower-cost alternatives such as Kupe's Journey and the Thymio robot demonstrate that screen-free robotics can maintain strong pedagogical value while significantly reducing cost through locally sourced materials and open-source design philosophies [7, 47]. More research is needed, however, to establish minimum functionality thresholds that can guide the optimization of future low-cost kits.

The infrastructure challenges of underserved communities compound this affordability problem. Satellite imagery analysis estimates that 1.18 billion people live in energy-poor regions with no measurable electricity consumption [49]. In Nigeria specifically, fewer than 20% of households own a computer [50], and 96% of the world's offline population is concentrated in developing countries [51]. These conditions make screen-based ER solutions practically unviable at scale, and position screen-free robotics as structurally necessary. This means that screen-free robotics solutions are not merely preferable, they are structurally needed alternative for achieving equitable access to CT education in line with UN SDG 4 [52].

Engineering design thinking has emerged as a productive pedagogical context for CT development. Studies show that children engaged in engineering design activities demonstrate measurable CT competency gains [53], and that students building computational models apply abstraction, decomposition, and algorithmic thinking organically [54]. Among available engineering-driven pedagogical models simpler frameworks such as Problem-Based Learning are better suited to resource-constrained environments, as they require lighter teacher training and are more feasibly implemented without extensive institutional support [55].

The choice between open-source and proprietary ER platforms significantly affects cost, adaptability, and accessibility [18, 56]. Proprietary kits like LEGO Mindstorms and VEX Robotics offer structured, curriculum-aligned experiences but are expensive and hardware-locked [57, 58]. Open-source platforms such as Arduino-based robots and Thymio allow full hardware and software modification, enabling locally appropriate adaptations and reducing replacement part costs [59, 60]. Despite these advantages, open-source adoption remains limited by poor documentation, lack of professional support, and legal uncertainties around CAD tool licensing [61, 62]. Scalability and modularity present a related trade-off: while modular designs offer flexibility across learning levels, the hardware complexity required for modularity drives up cost [63]. Single-unit, open-source platforms like AERobot offer a viable middle path, maintaining pedagogical effectiveness without the cost premium of modularity [4]. Table 3 summarizes key screen-free ER studies reviewed, mapping technology, findings, and relevance to the research focus.

Table 3. Screen-Free Educational Robotics Literature Summary

Study	Focus	Technology	Key Findings	Relevance to Research
[64]	Computational thinking through tangible robotics	Cubetto	Embodied learning aids in computational thinking by bridging spatial and representational discontinuities	Supports physical interaction in coding for young learners
[46]	Early childhood robotics education	KIBO	Young children can master programming skills using tangible interfaces	Demonstrates effectiveness of screen-free robotics
[7]	Low-cost, screen-free robotics	Kupe's Journey	Affordable tangible robotics can engage children in computational learning	Highlights low-cost alternatives for underserved communities
[47]	Tangible programming	Thymio	Tangible programming encourages collaboration and engagement	Validates use of non-digital programming interfaces
[48]	Comparing tangible and graphical programming	PROTEAS Kit	Tangible programming results in fewer errors and better debugging among children	Reinforces benefits of tangible over graphical programming
[1]	Robotics and engineering for young children	KIBO	Screen-free programming supports early engineering education	Aligns with developmentally appropriate educational tools
[65]	Algorithmic thinking in young learners	Bee-Bot	Physical programming enhances understanding of sequencing	Strengthens case for screen-free computational thinking
[66]	Gamified coding with robotics	Dash & Botley	Playful robotics promotes engagement and motivation	Shows potential of gamification in tangible

			in learning coding	programming
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**7. MANUFACTURING AND SUSTAINABILITY CONSIDERATIONS**

The manufacturing process and material choices for ER kits have direct implications for cost, safety, sustainability, and accessibility. This is particularly crucial for kits designed for use by young children in underserved environments.

Three manufacturing approaches are most relevant to educational robotics. 3D printing is well-suited to prototyping and small-scale production, offering design flexibility and low tooling costs, though it is time-intensive and produces parts that can be fragile [67, 68]. Laser cutting, commonly applied to wood and acrylic, offers greater accuracy and scalability for medium-volume production and supports the use of more sustainable wooden materials, though it requires significant expertise and capital investment [69, 70]. Injection moulding enables efficient, consistent large-scale production at low per-unit cost, but relies on petrochemical plastics and carries significant environmental concerns [71, 72]. Table 4 synthesizes these methods across material, environmental impact, scalability, and cost.

Table 4. Manufacturing Method Sustainability Synthesis

Method	Material	Environmental Impact	Scalability	Cost at Scale	Sustainability Score
Injection Moulding	Petrochemical plastics	High (non-biodegradable, toxic chemicals)	Excellent	Very Low	Low
Laser Cutting	Wood/Acrylic	Medium-Low (wood=biodegradable; acrylic=plastic)	Good	Medium	Medium-High (for wood)
3D Printing	PLA/ABS plastics	Medium (some biodegradable options)	Poor	High	Medium

Beyond formal manufacturing, Do-It-Yourself (DIY) and open-source fabrication cultures enable local production of ER kits, putting design and assembly in the hands of communities themselves [89]. Prioritizing ease of assembly, disassembly, and repair through standard fasteners and snap-fit joints not only reduces cost but extends kit lifespan, curbs electronic waste, and creates additional learning opportunities [73–75].

Material safety is a non-negotiable dimension of ER kit design. Standards such as ASTM F963 define mechanical, chemical, and flammability requirements for children's products and provide a relevant benchmark for educational robotics [20]. While plastic dominates current kit production due to its durability and low cost, studies have found that many plastic toys contain toxic chemicals exceeding safety limits [76]. Wood, by contrast, is natural, non-toxic, and biodegradable, making it a strong candidate for sustainable, safe ER kit construction [23, 24]. Future research should prioritize locally sourced, biodegradable materials that satisfy existing safety standards while reducing the environmental footprint of ER kit production.

**8. RESEARCH GAPS & LIMITATIONS**

**8.1. Research Gaps**

This literature review has provided an overview of the current research status with regard to educational robotics (ER) and its contribution towards supporting computational thinking (CT) via early STEM education. Nevertheless, some of the key gaps remain and need to be addressed for enhancing the discipline further, particularly while focusing on underprivileged societies. The following section therefore identifies these gaps and suggests future research and development directions.

Access to educational robotics kits for underserved learning environments is the first and most significant gap. The expensive nature of commercially available kits, such as LEGO Mindstorms and KIBO, despite growing need for ER, is a significant barrier to their adoption [4, 46]. Although less expensive alternatives like Kupe's Journey and AERobot have been tried, more research is needed into scalable single-unit kits made with locally available materials for underserved learning environments [4, 7]. Further research on low-cost, open-source robotics kits for applications at scale in resource-constrained settings would make ER kits more accessible.

Another domain that needs more research is the development of screen-free and tangible programming interfaces for educational robotics as alternatives to popular screen-based platforms. Studies have shown that

these systems can successfully engage young children in computational thinking (CT) without using screens [46, 47]. However, the literature still reveals a significant gap in the robust implementation of RFID technology for tangible programming [46, 47]. While barcode and optical systems are well known, they tend to be less long-lasting and affordable compared to RFID technology [77]. Subsequent research needs to investigate the effectiveness and feasibility of RFID-based systems for the tangible programming interface of screen-free robotics kit as an alternative to barcodes and optical systems.

Material selection and sustainability are yet another glaring gap in literature. Material selection for robotics learning kits is paramount in terms of safety, durability, and eco-friendliness. And despite this, much educational robotics research focus only on the functionality of the robot and less on the safety of materials selected. Even though wood has been identified as a greener and safer alternative to plastic, little data exist on how it behaves in the long term when applied in robotics [20, 23]. Traditional and non-traditional production processes such as injection moulding and 3D printing usually come at a cost to the environment that needs more research. It is important that ER kits align with global sustainability goals [78] therefore, future research should also be directed toward developing sustainable production techniques and biodegradable material usage within ER kits.

Energy efficiency also represents a crucial technical gap, especially in contexts lacking stable power infrastructure. Power consumption by educational robotics kits is a matter of utmost concern, especially in disadvantaged communities where access to stable electricity is limited. While lithium-ion and lithium-polymer batteries have extensive applications, their environmental impact and expense pose challenges [40]. Since studies into other power sources like supercapacitors and development of wireless charging technology is still in its early stages [42] there is a need for further studies to focus on low-power circuit design and optimized motor control systems to decrease energy consumption in ER kits [79].

Pedagogical effectiveness and instructor training are also an essential knowledge gap. Efficient utilization of ER in early STEM education requires carefully planned pedagogical interventions and instructor training. However, there is little evidence present regarding the influence of different engineering-based learning models in enhancing CT abilities among children [53, 54]. Moreover, the absence of standardized teacher training programs within marginalized communities hinders the possibility of ER achieving universal application [80]. Future research needs to prioritize the creation and assessment of easy-to-implement yet effective pedagogical models for early STEM education, as well as teacher training programs and their effects on the successful implementation of ER.

Finally, scalability and customizability continue to be underdeveloped in the design of accessible educational robotics kits. Modular platforms, such as those offered by LEGO Mindstorms and KIBO, offer flexibility and ease but are also more expensive and thus less available to underprivileged communities [1, 4]. More research needs to be conducted on single-unit designs that can balance cost, function, and scalability. Also, other do-it-yourself (DIY) production techniques as well as 3D printing are also capable of enabling local customization and repair of robotics kits at reduced cost and thus should be explored to reduce the overall cost needed to make kits accessible on a large scale [58].

Educational robotics can be an inclusive way of helping young learners to learn computational thinking skills especially for learners in disadvantaged learning settings only if the research gaps identified in this review are addressed collaboratively. The synthesis strongly indicates a need for a new generation of ER solutions that are low-cost, screen-free, and manufactured sustainably using localized supply chains. Therefore, future research should prioritize the development and longitudinal assessment of an integrated, open-source platform that will balance safety, pedagogical effectiveness, and high mechanical reliability against the constraint of being accessible to the most resource-constrained communities worldwide.

## **8.2. Limitations**

This review is subject to several limitations that should be considered when interpreting its findings. First, the search strategy, while comprehensive, was limited to three databases, IEEE Xplore, ACM Digital Library, and Google Scholar, and some other selected literature. This may not have captured all relevant publications indexed elsewhere. Second, only English-language publications were included, which may have introduced a linguistic bias and excluded potentially valuable contributions from non-English-speaking research communities. Third, the thematic rather than systematic approach to synthesis, while appropriate for an interdisciplinary field, means that the findings represent an interpretive rather than exhaustive account of the literature. Finally, given the rapid pace of development in educational robotics, some findings, particularly regarding specific kit costs and available technologies, may have been superseded by more recent developments at the time of reading. Notwithstanding these limitations, the review provides a substantive and timely synthesis of the field with direct relevance to underserved learning contexts.

## 9. CONCLUSION

This review has examined the interdisciplinary landscape of affordable, screen-free educational robotics as a vehicle for developing computational thinking in underserved learning environments. The synthesis reveals that while the pedagogical case for screen-free ER is well-established, significant engineering, sustainability, and pedagogical gaps remain before its promise can be equitably realized.

From a design perspective, the evidence favours single-unit, open-source platforms fabricated from locally available, sustainable materials as the most viable pathway to affordable, safe, and scalable ER kits for resource-constrained contexts. Tangible programming systems, especially those leveraging RFID technology, represent an underexplored frontier that could simultaneously achieve screen-free operation, durability, and low cost. Manufacturing approaches must balance accessibility with safety, adhering to established standards such as ASTM F963 while prioritizing biodegradable materials and repairability.

Pedagogically, simpler engineering-driven models such as Problem-Based Learning are better suited to underserved environments than complex frameworks requiring extensive teacher training. Longitudinal studies assessing both the learning outcomes and material durability of low-cost ER interventions in real classroom settings remain critically absent from literature. Co-designing teacher training programs alongside ER kit development, rather than treating them as separate workstreams, is a direction future research should prioritize.

Ultimately, inclusivity in educational robotics is an engineering problem as much as a pedagogical one. Achieving equitable access to computational thinking education requires a new generation of ER solutions designed from the outset for the most resource-constrained communities. It is only by designing for the margins that we can hope to deliver on the promise of quality STEM education for all.

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## REFERENCES

- [1] A. Sullivan and M. Bers, "Dancing robots: integrating art, music, and robotics in Singapore's early childhood centers," *Int. J. Technol. Des. Educ.*, vol. 28, pp. 325–346, Jan. 2017, doi: 10.1007/s10798-017-9397-0.
- [2] Y.-H. Ching and Y.-C. Hsu, "Educational Robotics for Developing Computational Thinking in Young Learners: A Systematic Review," *TechTrends*, vol. 68, no. 3, pp. 423–434, May 2024, doi: 10.1007/s11528-023-00841-1.
- [3] H. Mwinyi, "Challenges and Opportunities of Implementing Education Technology in Rural and Underserved Areas of Tanzania, Assessing the Sustainability and Educational Impact of Such Initiatives," *Afr. J. Educ. Pract.*, vol. 10, no. 4, pp. 27–39, Oct. 2024, doi: 10.47604/ajep.3031.
- [4] M. Rubenstein, B. Cimino, R. Nagpal, and J. Werfel, "AERobot: An affordable one-robot-per-student system for early robotics education," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, Seattle, WA, USA: IEEE, May 2015, pp. 6107–6113. doi: 10.1109/ICRA.2015.7140056.
- [5] A. Sullivan, M. Elkin, and M. U. Bers, "KIBO robot demo: engaging young children in programming and engineering," in *Proceedings of the 14th International Conference on Interaction Design and Children*, Boston Massachusetts: ACM, Jun. 2015, pp. 418–421. doi: 10.1145/2771839.2771868.
- [6] A. Sullivan and A. Strawhacker, "Screen-Free STEAM: Low-Cost and Hands-on Approaches to Teaching Coding and Engineering to Young Children," in *Embedding STEAM in Early Childhood Education and Care*, C. Cohrssen and S. Garvis, Eds., Cham: Springer International Publishing, 2021, pp. 87–113. doi: 10.1007/978-3-030-65624-9\_5.
- [7] E. Naude, A. Fowler, R. Lemon, and Craig. J. Sutherland, "Kupe's Journey: Building a Low-cost, Screen-free Robotic Programming Environment for Children," in *2023 20th International Conference on Ubiquitous Robots (UR)*, Honolulu, HI, USA: IEEE, Jun. 2023, pp. 710–715. doi: 10.1109/UR57808.2023.10202226.

- [8] J. M. Wing, "Computational thinking," *Commun. ACM*, vol. 49, no. 3, pp. 33–35, Mar. 2006, doi: 10.1145/1118178.1118215.
- [9] V. J. Shute, C. Sun, and J. Asbell-Clarke, "Demystifying computational thinking," *Educ. Res. Rev.*, vol. 22, pp. 142–158, Nov. 2017, doi: 10.1016/j.edurev.2017.09.003.
- [10] Y. Tabesh, "Computational Thinking: A 21st Century Skill," *Olymp. Inform.*, vol. 11, no. 2, pp. 65–70, Jul. 2017, doi: 10.15388/oi.2017.special.10.
- [11] P. J. Denning, "Remaining trouble spots with computational thinking," *Commun. ACM*, vol. 60, no. 6, pp. 33–39, May 2017, doi: 10.1145/2998438.
- [12] S. Basu, G. Biswas, P. Sengupta, A. Dickes, J. Kinnebrew, and D. Clark, "Identifying middle school students' challenges in computational thinking-based science learning," *Res. Pract. Technol. Enhanc. Learn.*, vol. 11, May 2016, doi: 10.1186/s41039-016-0036-2.
- [13] W. Huang and C.-K. Looi, "A critical review of literature on 'unplugged' pedagogies in K-12 computer science and computational thinking education," *Comput. Sci. Educ.*, vol. 31, no. 1, pp. 83–111, Jan. 2021, doi: 10.1080/08993408.2020.1789411.
- [14] G. Saw and C. Agger, "STEM Pathways of Rural and Small-Town Students: Opportunities to Learn, Aspirations, Preparation, and College Enrollment," *Educ. Res.*, vol. 50, pp. 595–606, Jun. 2021, doi: 10.3102/0013189X211027528.
- [15] A. Alanazi, "A Critical Review of Constructivist Theory and the Emergence of Constructionism," *Am. Res. J. Humanit. Soc. Sci.*, 2016, doi: 10.21694/2378-7031.16018.
- [16] P. Haduong, "Designing Constructionist Futures: The Art, Theory, and Practice of Learning Designs," *Harv. Educ. Rev.*, vol. 91, no. 2, pp. 276–278, Jun. 2021, doi: 10.17763/1943-5045-91.2.276.
- [17] K. Wang, G. Sang, L. Huang, S.-H. Li, and J. Guo, "The Effectiveness of Educational Robots in Improving Learning Outcomes: A Meta-Analysis," *Sustainability*, Mar. 2023, doi: 10.3390/su15054637.
- [18] F. Mondada *et al.*, "Bringing Robotics to Formal Education: The Thymio Open-Source Hardware Robot," *IEEE Robot. Autom. Mag.*, vol. 24, no. 1, pp. 77–85, Mar. 2017, doi: 10.1109/MRA.2016.2636372.
- [19] I. M. L. Souza, W. L. Andrade, L. M. R. Sampaio, and A. L. S. O. Araujo, "A Systematic Review on the use of LEGO® Robotics in Education," in *2018 IEEE Frontiers in Education Conference (FIE)*, San Jose, CA, USA: IEEE, Oct. 2018, pp. 1–9. doi: 10.1109/FIE.2018.8658751.
- [20] ASTM International, *Consumer Safety Specification for Toy Safety*, 2021. doi: 10.1520/F0963-17.
- [21] N. Aurisano, L. Huang, L. M. Canals, O. Jolliet, and P. Fantke, "Chemicals of concern in plastic toys," *Environ. Int.*, vol. 146, p. 106194, Oct. 2020, doi: 10.1016/j.envint.2020.106194.
- [22] D.-S. Gul, A. Gul, A. K. Tanoli, T. Ahmed, and M. A. Mirza, "Contamination by hazardous elements in low-priced children's plastic toys bought on the local markets of Karachi, Pakistan," *Environ. Sci. Pollut. Res.*, vol. 29, no. 34, pp. 51964–51975, Jul. 2022, doi: 10.1007/s11356-022-19362-0.
- [23] S. Levesque, M. Robertson, and C. Klimas, "A life cycle assessment of the environmental impact of children's toys," *Sustain. Prod. Consum.*, vol. 31, pp. 777–793, May 2022, doi: 10.1016/j.spc.2022.03.001.
- [24] A. Madar, D. Boşcor, C. Băltescu, and N. Neacşu, "WOODEN VERSUS PLASTIC TOYS," *Ann. - Econ. Ser.*, 2012, Accessed: Mar. 07, 2025. [Online]. Available: <https://www.semanticscholar.org/paper/WOODEN-VERSUS-PLASTIC-TOYS-Madar-Bo%28%99cor/8939e649c72719558e72b13be593d80cc36793de>
- [25] G. G. Jaman, N. Farheen, and M. P. Schoen, "Cost Effective Mobile Robots Navigation and Mapping System for Education," in *2020 Intermountain Engineering, Technology and Computing (IETC)*, Orem, UT, USA: IEEE, Oct. 2020, pp. 1–6. doi: 10.1109/IETC47856.2020.9249154.
- [26] L. Xia and B. Zhong, "A systematic review on teaching and learning robotics content knowledge in K-12," *Comput. Educ.*, vol. 127, pp. 267–282, Dec. 2018, doi: 10.1016/j.compedu.2018.09.007.
- [27] KinderLab-Robotics, "KIBO 10 Kit - KinderLab Robotics, Inc." Accessed: Mar. 10, 2025. [Online]. Available: <https://kinderlabrobotics.com/products/kibo-10-kit/>

- [28] M. C. Balaton, L. F. Da Silva, and P. S. Carvalho, "Teaching kinematics with OZOBOT: a proposal to help improve student's graph interpretation skills," *Phys. Educ.*, vol. 55, no. 5, p. 055009, Sep. 2020, doi: 10.1088/1361-6552/ab97a4.
- [29] S. Zimmermann, R. Poranne, and S. Coros, "Go Fetch! - Dynamic Grasps using Boston Dynamics Spot with External Robotic Arm," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, Xi'an, China: IEEE, May 2021, pp. 4488–4494. doi: 10.1109/ICRA48506.2021.9561835.
- [30] I. Zournatzis, K. Koutsoukis, K. Machairas, A. Kecskeméthy, and E. Papadopoulos, "Maera: A Hybrid Wheeled-Legged Robot Designed for Research and Education," pp. 247–261, 2020, doi: 10.1007/978-3-030-67411-3\_22.
- [31] K. Chenchireddy, R. Dora, G. B. Mulla, V. Jegathesan, and S. A. Sydu, "Development of robotic arm control using Arduino controller," *IAES Int. J. Robot. Autom. IJRA*, vol. 13, no. 3, p. 264, Sep. 2024, doi: 10.11591/ijra.v13i3.pp264-271.
- [32] B. Hagen, L. Ricke, N. Null, N. Null, N. Null, and N. Null, "Effectiveness and Usability of the Dobot Magician Robotic Arm," *John Heinrichs Sch. Creat. Act. Day*, 2023, doi: 10.58809/RXHD8373.
- [33] R. Q. Figueroa, D. A. Zamorano, G. J. Martínez, and A. Adamatzky, "A Turing Machine Constructed with Cubelets Robots," *J. Robot. Netw. Artif. Life*, vol. 5, no. 4, p. 265, 2019, doi: 10.2991/jrnal.k.190220.013.
- [34] K. C. Sum, K.-H. Ng, W.-K. Lam, H.-Y. Chui, and C. F. Li, "Microcontroller Based Platforms For STEM Education," in *2023 IEEE Integrated STEM Education Conference (ISEC)*, Laurel, MD, USA: IEEE, Mar. 2023, pp. 214–217. doi: 10.1109/ISEC57711.2023.10402172.
- [35] H. K. Kondaveeti, N. K. Kumaravelu, S. D. Vanambathina, S. E. Mathe, and S. Vappangi, "A systematic literature review on prototyping with Arduino: Applications, challenges, advantages, and limitations," *Comput. Sci. Rev.*, vol. 40, p. 100364, May 2021, doi: 10.1016/j.cosrev.2021.100364.
- [36] T. Sapounidis and S. Demetriadis, "Educational Robots Driven by Tangible Programming Languages: A Review on the Field," in *Educational Robotics in the Makers Era*, vol. 560, D. Alimisis, M. Moro, and E. Menegatti, Eds., in *Advances in Intelligent Systems and Computing*, vol. 560, Cham: Springer International Publishing, 2017, pp. 205–214. doi: 10.1007/978-3-319-55553-9\_16.
- [37] W. Luo, X. Deng, F. Zhang, Y. Wen, and D. J. Kadhim, "Positioning and guiding educational robots by using fingerprints of WiFi and RFID array," *EURASIP J. Wirel. Commun. Netw.*, vol. 2018, no. 1, p. 170, Dec. 2018, doi: 10.1186/s13638-018-1183-5.
- [38] O. Miglino, A. Di Ferdinando, R. Di Fuccio, A. Rega, and C. Ricci, "Bridging Digital and Physical Educational Games Using RFID/NFC Technologies," *J. E-Learn. Knowl. Soc.*, vol. Vol 10, p. No 3 (2014): Focus on: Learning in Smart Environments, Sep. 2014, doi: 10.20368/1971-8829/959.
- [39] C. Zeng, H. Zhou, W. Ye, and X. Gu, "iArm: Design an Educational Robotic Arm Kit for Inspiring Students' Computational Thinking," *Sensors*, vol. 22, no. 8, p. 2957, Apr. 2022, doi: 10.3390/s22082957.
- [40] A. A. Chellal, J. Braun, J. Lima, J. Gonçalves, and P. Costa, "Modeling of a Lithium-Ion Battery for Enhanced Power Management in Robotics Domain," in *2023 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*, Tomar, Portugal: IEEE, Apr. 2023, pp. 126–131. doi: 10.1109/ICARSC58346.2023.10129626.
- [41] D. Zhou, D. Shanmukaraj, A. Tkacheva, M. Armand, and G. Wang, "Polymer Electrolytes for Lithium-Based Batteries: Advances and Prospects," *Chem*, vol. 5, no. 9, pp. 2326–2352, Sep. 2019, doi: 10.1016/j.chempr.2019.05.009.
- [42] C. Gao *et al.*, "A seamlessly integrated device of micro-supercapacitor and wireless charging with ultrahigh energy density and capacitance," *Nat. Commun.*, vol. 12, no. 1, p. 2647, May 2021, doi: 10.1038/s41467-021-22912-8.
- [43] D. Catlin, M. Blamires, and J.-J. Cabibihan, "Educational Robots: Past, Present, Future," in *Social Robots in Education*, vol. 1194, G. Lampropoulos and S. Papadakis, Eds., in *Studies in Computational Intelligence*, vol. 1194, Cham: Springer Nature Switzerland, 2025, pp. 399–426. doi: 10.1007/978-3-031-82915-4\_16.

- [44] M. U. Bers, "Coding, playgrounds and literacy in early childhood education: The development of KIBO robotics and ScratchJr," in *2018 IEEE Global Engineering Education Conference (EDUCON)*, Tenerife: IEEE, Apr. 2018, pp. 2094–2102. doi: 10.1109/EDUCON.2018.8363498.
- [45] G. Lissak, "Adverse physiological and psychological effects of screen time on children and adolescents: Literature review and case study," *Environ. Res.*, vol. 164, pp. 149–157, Jul. 2018, doi: 10.1016/j.envres.2018.01.015.
- [46] A. Sullivan and M. U. Bers, "Robotics in the early childhood classroom: learning outcomes from an 8-week robotics curriculum in pre-kindergarten through second grade," *Int. J. Technol. Des. Educ.*, vol. 26, no. 1, pp. 3–20, 2015, doi: 10.1007/s10798-015-9304-5.
- [47] A. Mussati, C. Giang, A. Piatti, and F. Mondada, "A Tangible Programming Language for the Educational Robot Thymio," in *2019 10th International Conference on Information, Intelligence, Systems and Applications (IISA)*, PATRAS, Greece: IEEE, Jul. 2019, pp. 1–4. doi: 10.1109/IISA.2019.8900743.
- [48] T. Sapounidis, S. Demetriadis, and I. Stamelos, "Evaluating children performance with graphical and tangible robot programming tools," *Pers. Ubiquitous Comput.*, vol. 19, no. 1, pp. 225–237, Jan. 2015, doi: 10.1007/s00779-014-0774-3.
- [49] B. Min *et al.*, "Lost in the dark: A survey of energy poverty from space," *Joule*, vol. 8, no. 7, pp. 1982–1998, Jul. 2024, doi: 10.1016/j.joule.2024.05.001.
- [50] World Bank, *Digital Progress and Trends Report 2023*. The World Bank, 2024. doi: 10.1596/978-1-4648-2049-6.
- [51] International Telecommunication Union, *Measuring Digital Development: Facts and Figures 2021*. International Telecommunication Union, 2021. Accessed: Mar. 09, 2025. [Online]. Available: <https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2021.pdf>
- [52] United Nations, "Transforming our world: the 2030 Agenda for Sustainable Development," United Nations, 2015. Accessed: Oct. 30, 2025. [Online]. Available: <https://sdgs.un.org/2030agenda>
- [53] H. Ehsan, A. P. Rehmat, and M. E. Cardella, "Computational thinking embedded in engineering design: capturing computational thinking of children in an informal engineering design activity," *Int. J. Technol. Des. Educ.*, vol. 31, no. 3, pp. 441–464, Jul. 2021, doi: 10.1007/s10798-020-09562-5.
- [54] J. A. Lyon and A. J. Magana, "The use of engineering model-building activities to elicit computational thinking: A design-based research study," *J. Eng. Educ.*, vol. 110, no. 1, pp. 184–206, Jan. 2021, doi: 10.1002/jee.20372.
- [55] K. Edström and A. Kolmos, "PBL and CDIO: complementary models for engineering education development," *Eur. J. Eng. Educ.*, vol. 39, no. 5, pp. 539–555, Sep. 2014, doi: 10.1080/03043797.2014.895703.
- [56] F. Arvin, J. Espinosa, B. Bird, A. West, S. Watson, and B. Lennox, "Mona: an Affordable Open-Source Mobile Robot for Education and Research," *J. Intell. Robot. Syst.*, vol. 94, no. 3–4, pp. 761–775, Jun. 2019, doi: 10.1007/s10846-018-0866-9.
- [57] V. Chaudhary, V. Agrawal, P. Sureka, and A. Sureka, "An Experience Report on Teaching Programming and Computational Thinking to Elementary Level Children Using Lego Robotics Education Kit," *2016 IEEE Eighth Int. Conf. Technol. Educ. T4E*, pp. 38–41, Dec. 2016, doi: 10.1109/T4E.2016.016.
- [58] C. Vandeveld, F. Wyffels, M.-C. Ciocci, B. Vanderborcht, and J. Saldien, "Design and evaluation of a DIY construction system for educational robot kits," *Int. J. Technol. Des. Educ.*, vol. 26, no. 4, pp. 521–540, Nov. 2016, doi: 10.1007/s10798-015-9324-1.
- [59] A. C. R. Ribeiro, D. A. C. Barone, and L. E. P. Mizusaki, "ROBO+EDU: Project and Implementation of Educational Robotics in Brazillian Public Schools," in *Robot Intelligence Technology and Applications 3*, vol. 345, J.-H. Kim, W. Yang, J. Jo, P. Sincak, and H. Myung, Eds., in *Advances in Intelligent Systems and Computing*, vol. 345., Cham: Springer International Publishing, 2015, pp. 495–503. doi: 10.1007/978-3-319-16841-8\_45.
- [60] T. Darrah, N. M. Hutchins, and G. Biswas, "Design and Development of a Low-Cost Open-Source Robotics Education Platform," 2018. [Online]. Available: <https://api.semanticscholar.org/CorpusID:52043657>

- [61] V. V. Patel, M. V. Liarokapis, and A. M. Dollar, "Open Robot Hardware: Progress, Benefits, Challenges, and Best Practices," *IEEE Robot. Autom. Mag.*, vol. 30, no. 3, pp. 123–148, Sep. 2023, doi: 10.1109/MRA.2022.3225725.
- [62] V. R. Sanchez, P. N. Ayuso, J. A. Galindo, and D. Benavides, "Open Source Adoption Factors—A Systematic Literature Review," *IEEE Access*, vol. 8, pp. 94594–94609, 2020, doi: 10.1109/ACCESS.2020.2993248.
- [63] M. Oksana and V. Petrenko, "Developing a Concept of Available Multi-Functional Modular Robot for Education and Research," 2019. [Online]. Available: <https://api.semanticscholar.org/CorpusID:208231492>
- [64] R. Sinha, H. Swanson, J. Clarke-Midura, J. F. Shumway, V. R. Lee, and S. Chandrasekharan, "From Embodied Doing to Computational Thinking in Kindergarten: A Punctuated Motor Control Model," in *Proceedings of the 2023 Symposium on Learning, Design and Technology*, Evanston IL USA: ACM, Jun. 2023, pp. 1–10. doi: 10.1145/3594781.3594794.
- [65] S. Evripidou, A. Amanatiadis, K. Christodoulou, and S. A. Chatzichristofis, "Introducing Algorithmic Thinking and Sequencing Using Tangible Robots," *IEEE Trans. Learn. Technol.*, vol. 14, no. 1, pp. 93–105, Feb. 2021, doi: 10.1109/TLT.2021.3058060.
- [66] K. Heljakka, P. Ihamaki, P. Tuomi, and P. Saarikoski, "Gamified Coding: Toy Robots and Playful Learning in Early Education," in *2019 International Conference on Computational Science and Computational Intelligence (CSCI)*, Las Vegas, NV, USA: IEEE, Dec. 2019, pp. 800–805. doi: 10.1109/CSCI49370.2019.00152.
- [67] I. Chavdarov, K. Yovchev, B. Naydenov, and V. Hrosinkov, "3D Printed DELTA Robot for Educational Purposes," in *2024 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, Split, Croatia: IEEE, Sep. 2024, pp. 1–6. doi: 10.23919/SoftCOM62040.2024.10721779.
- [68] T. Rayna and L. Striukova, "From rapid prototyping to home fabrication: How 3D printing is changing business model innovation," *Technol. Forecast. Soc. Change*, vol. 102, pp. 214–224, Jan. 2016, doi: 10.1016/j.techfore.2015.07.023.
- [69] A. A. Amiri Moghadam *et al.*, "Laser Cutting as a Rapid Method for Fabricating Thin Soft Pneumatic Actuators and Robots," *Soft Robot.*, vol. 5, no. 4, pp. 443–451, Aug. 2018, doi: 10.1089/soro.2017.0069.
- [70] E. Porras, D. Esenarro, L. Chang, W. Morales, C. Vargas, and J. Sucasaca, "Toward Cost-Effective Timber Shell Structures through the Integration of Computational Design, Digital Fabrication, and Mechanical Integral 'Half-Lap' Joints," *Buildings*, vol. 14, no. 6, p. 1735, Jun. 2024, doi: 10.3390/buildings14061735.
- [71] P. Zhao *et al.*, "Intelligent Injection Molding on Sensing, Optimization, and Control," *Adv. Polym. Technol.*, vol. 2020, pp. 1–22, Mar. 2020, doi: 10.1155/2020/7023616.
- [72] W. M. Cheung, J. T. Leong, and P. Vichare, "Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products," *J. Clean. Prod.*, vol. 167, pp. 759–775, Nov. 2017, doi: 10.1016/j.jclepro.2017.08.208.
- [73] K. Kimble *et al.*, "Benchmarking Protocols for Evaluating Small Parts Robotic Assembly Systems," *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 883–889, Apr. 2020, doi: 10.1109/LRA.2020.2965869.
- [74] M. Chen and O. A. Ogunseitan, "Zero E-waste: Regulatory impediments and blockchain imperatives," *Front. Environ. Sci. Eng.*, vol. 15, no. 6, p. 114, Dec. 2021, doi: 10.1007/s11783-021-1402-x.
- [75] K. Mitsuhashi, "Redesign of Basic Module and Modular Robot Assembly for Educational Tool," *2024 IEEE 18th Int. Conf. Adv. Motion Control AMC*, pp. 1–6, Feb. 2024, doi: 10.1109/AMC58169.2024.10505651.
- [76] O. T. Fatunsin, T. O. Oluseyi, D. Drage, M. A.-E. Abdallah, A. Turner, and S. Harrad, "Children's exposure to hazardous brominated flame retardants in plastic toys," *Sci. Total Environ.*, vol. 720, p. 137623, Jun. 2020, doi: 10.1016/j.scitotenv.2020.137623.
- [77] Y. Duroc and S. Tedjini, "RFID: A key technology for Humanity," *Comptes Rendus Phys.*, vol. 19, no. 1–2, pp. 64–71, Jan. 2018, doi: 10.1016/j.crhy.2018.01.003.

- [78] M. R. Khosravani and T. Reinicke, “On the environmental impacts of 3D printing technology,” *Appl. Mater. Today*, vol. 20, p. 100689, Sep. 2020, doi: 10.1016/j.apmt.2020.100689.
- [79] Z. Wan, A. S. Lele, and A. Raychowdhury, “Circuit and System Technologies for Energy-Efficient Edge Robotics: (Invited Paper),” in *2022 27th Asia and South Pacific Design Automation Conference (ASP-DAC)*, Taipei, Taiwan: IEEE, Jan. 2022, pp. 275–280. doi: 10.1109/ASP-DAC52403.2022.9712531.
- [80] D. Schina, V. Esteve-González, and M. Usart, “An overview of teacher training programs in educational robotics: characteristics, best practices and recommendations,” *Educ. Inf. Technol.*, vol. 26, no. 3, pp. 2831–2852, May 2021, doi: 10.1007/s10639-020-10377-z.