

# Scaling Robotics Education: A Systematic Review of Technologies, Frameworks, and Equity Dimensions

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## Abstract

Robotics education is increasingly essential for preparing learners with skills in STEM, programming, and artificial intelligence. Yet, scaling such education equitably remains a global challenge. This study systematically reviews 20 peer reviewed publications (2013–2024) to explore how robotics education is being scaled across five dimensions: technical, pedagogical, institutional, financial, and geographic. Guided by Constructivist Learning Theory, the TPACK framework, and the Digital Divide and Equity Model, the review analyzes the role of cloud platforms, localized content, and connectivity innovations including mobile STEM labs. Cloud tools (e.g., Open Roberta, VEX code VR) support technical scalability, while teacher training through TPACK enhances institutional readiness. Constructivist approaches foster hands on, student centered learning, crucial for pedagogical scalability. However, financial and geographic inclusion remain limited. Solutions like mobile labs and low cost kits show promise but require broader policy support. The study calls for holistic, equity driven strategies to ensure sustainable and inclusive robotics education at scale.

**Key terms:** Robotic Education, Scalability, Theoretical Framework, Equity education, Cloud Computing

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## Background to the Study

Robotics education has emerged as a critical pillar of 21st century STEM learning, equipping learners with the competencies needed for careers in automation, artificial intelligence (AI), and digital systems. It nurtures computational thinking, creativity, collaborative problem solving, and technological fluency—skills essential in a rapidly evolving global economy. As countries strategize for the Fourth Industrial Revolution, expanding access to robotics education has become an urgent imperative (OECD, 2023; UNESCO, 2022). However, achieving scalable and inclusive robotics education remains a significant challenge, particularly in developing regions where infrastructure, teacher capacity, and equitable access remain limited.

Scaling robotics education requires a multidimensional approach that goes beyond expanding numbers. It involves technical scalability (e.g., using cloud based simulators to reach large numbers of learners), pedagogical scalability (adapting instructional models for different learning contexts), institutional scalability (embedding robotics into national curricula and teacher training systems), geographic scalability (extending reach to rural, urban, and marginalized communities), and financial scalability (ensuring affordability and sustainability). Cloud platforms such as Open Roberta, VEX code VR, and Tinker Cad Circuits have become foundational tools for increasing technical and financial scalability by enabling

robotics learning without expensive hardware (Almalki et al., 2023). These tools simulate real world programming environments accessible via low end devices, drastically reducing infrastructure barriers.

However, without localized and context sensitive content, learners may struggle to relate to robotics curricula. Pedagogical scalability thus depends on integrating inclusive and culturally relevant digital content, aligned with frameworks such as TPACK. Moreover, connectivity remains a persistent barrier to digital equity, especially in underserved regions across Africa, Latin America, and Asia (Wachira et al., 2021). In response, Mobile STEM Labs have emerged as an innovative solution. These labs often solar powered and equipped with internet, robotics kits, AI enabled tools, and trained facilitators bring hands on, tech enabled STEM learning to remote and underserved communities. By merging physical outreach with digital tools, mobile labs support all five scalability dimensions simultaneously.

Artificial Intelligence (AI) is also increasingly being used to personalize robotics education at scale. AI powered platforms can provide adaptive feedback, intelligent tutoring, and multilingual content translation, thus enhancing both the learner experience and teacher support. When embedded in cloud simulators or mobile labs, AI enhances engagement, supports differentiated learning paths, and addresses language or skill level gaps in real time. This study investigates how these combined elements cloud, content, connectivity, mobile labs, and AI—interact to enable or constrain scalability in robotics education across diverse settings.

## **2. Theoretical Framework**

To understand and guide the scaling of robotics education in varied and resource constrained settings, this study is grounded in three interrelated theoretical frameworks: Constructivist Learning Theory, Technological Pedagogical Content Knowledge (TPACK), and the Digital Divide and Equity Framework. These models provide a comprehensive foundation for examining how cloud platforms, mobile labs, AI, and localized content can be leveraged to make robotics education both scalable and inclusive.

**Constructivist Learning Theory**, especially Papert’s constructionism, emphasizes learning through hands-on creation and exploration. Robotics education aligns naturally with this theory, offering students opportunities to build, program, and test robotic systems to solve authentic problems. In areas where physical kits are unavailable, cloud based platforms simulate the experience digitally, maintaining constructivist integrity. A UNESCO supported initiative in Ghana (2021), for example, used cloud simulators in schools without physical robotics kits. Despite infrastructure constraints, students engaged deeply in the design thinking process, illustrating how cloud tools can retain the core pedagogical value of hands-on learning. Similarly, Mobile STEM Labs restore tactile, project based learning experiences in remote communities where even digital access is scarce—bringing the “constructionist classroom” directly to underserved learners.

The **TPACK framework** helps explain how teachers integrate content, pedagogy, and technology in their instruction. In the context of robotics education, TPACK enables educators to bridge robotics programming with meaningful classroom instruction. Institutional scalability hinges on developing teacher capacity through TPACK aligned professional development. In Kenya, for instance, teachers who participated in government led TPACK training were better equipped to embed robotics simulations and mobile lab activities into their curricula (MoE

Kenya, 2022). AI technologies are now being deployed to support TPACK by providing teachers with smart lesson planning tools, automated feedback systems, and performance analytics that help adjust instruction in real time.

The **Digital Divide and Equity Framework** (van Dijk, 2020) outlines the multilayered barriers to digital participation—access, skills, usage, and outcomes. Even with advanced platforms, scalable education will not be inclusive if learners lack infrastructure, digital literacy, or meaningful engagement opportunities. MobileFirst platforms, solar powered mobile labs, and offline friendly robotics kits are essential to bridging these gaps. In Indonesia, for example, a robotics program using AI powered simulations accessible via mobile phones with offline capabilities allowed rural students to engage in robotics education with minimal internet access (ADB, 2021). These innovations embody the framework’s emphasis on designing inclusive systems that are responsive to learners’ contexts and capabilities.

Together, these three frameworks emphasize that scalability in robotics education is not just a question of technical infrastructure, but also of pedagogy, equity, and teacher empowerment. They provide the conceptual foundation for analyzing how cloud platforms, AI tools, localized content, and mobile labs interact to enhance or inhibit the growth of inclusive robotics education globally.

### 3. Methodology

This study utilized a systematic literature review to examine how robotics education is being scaled across global contexts through cloud technologies, localized content, AI integration, and connectivity strategies, including mobile STEM labs. Adhering to PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta Analyses), the review addressed four core research questions:

1. What technological approaches (e.g., cloud robotics, AI) have been used to scale access to robotics education?
2. How has digital content been localized and adapted for broader adoption in different contexts?
3. What connectivity innovations including mobile STEM labs have facilitated equitable access to robotics education in underserved areas?
4. What dimensions of scalability (technical, pedagogical, institutional, financial, geographic) are most and least addressed in the existing literature?

Eligible studies were peer reviewed, published in English between 2013 and 2024, and focused on K–12 or community level robotics education initiatives involving at least one scalability strategy. Exclusion criteria eliminated opinion pieces, studies solely targeting higher education, or those with no explicit scalability component.

A structured search was conducted across Scopus, Web of Science, IEEE Xplore, ERIC, Springer Link, and Google Scholar, using key terms such as:

“robotics education” OR “educational robotics” AND “cloud computing” OR “AI” OR “mobile lab” AND “scaling” OR “expansion” OR “access” AND “digital content” OR “localized content” AND “connectivity” OR “digital divide.”

The screening process consisted of three stages: (1) title and abstract filtering, (2) full text review, and (3) quality appraisal using the Mixed Methods Appraisal Tool (MMAT). A standardized data extraction matrix was used to capture relevant attributes including

publication details, geography, education level, platform used, scalability types addressed, and key outcomes.

The data were analyzed using a combination of narrative synthesis and descriptive statistics, allowing the identification of patterns and gaps across five key themes: (1) cloud based and AI powered access, (2) content localization, (3) connectivity innovations including mobile labs, (4) teacher capacity, and (5) scalability impact across dimensions. Despite the robust review design, limitations include the exclusion of grey literature and non-English sources, which may have overlooked innovative local projects. However, this review offers a comprehensive and timely synthesis of how AI, mobile delivery models, and digital tools are shaping the future of scalable, inclusive robotics education.

### Scalability Mapping of Peer Reviewed Research in Robotics Education

#	Publication Details	Scalability Type(s)	Scalable Contribution
1	Murphy et al. (2022), ZHAW	Technical	Cloud based delivery enables scalable robotics labs without hardware.
2	Zubrycki & Granosik (2018), RiE	Technical, Geographic	Cloud simulation expands robotics access to underserved schools.
3	Wang et al. (2024), <i>Sustainability</i>	Institutional	TPACK ensures scalable integration of robotics into teaching.
4	AlSamarraie & Saeed (2018), <i>C&amp;E</i>	Technical, Institutional	Cloud collaboration tools support widespread digital learning.
5	Woo et al. (2021), <i>Ed. Res. Review</i>	Pedagogical, Social	Social robots boost engagement; need facilitation and access parity.
6	Ahmad & Babar (2017), arXiv	Technical	Modular architectures support deployment across diverse settings.
7	CT Robotics Review (2023)	Pedagogical	Robotics effectively develops computational thinking skills.
8	Wang et al. (2022), <i>C&amp;E</i>	Pedagogical, Engagement	AR enhances enjoyment and adoption of robotics in learning.
9	Cloud Robotics Review (2022), RCIM	Technical	Identifies gaps in cloud robotics standardization for scale.
10	Niedźwiecki et al. (2024), arXiv	Technical, Financial	Digital twins simulate robotics remotely, reducing costs.
11	Koubaa (2019), arXiv	Technical	Service oriented robotics frameworks enable cloud scalability.
12	OpenVAS Team (2019)	Technical, Institutional	Cloud testbeds offer scalable field robotics environments.
13	Yanış & Yürük (2020), <i>JRTE</i>	Institutional	TPACK scale helps assess and improve teacher readiness.

#	Publication Details	Scalability Type(s)	Scalable Contribution
14	Reynolds et al. (2012), <i>C&amp;E</i>	Pedagogical	Robotics strengthens scalable STEM engagement.
15	Rahman et al. (2017), ASEE	Institutional, Pedagogical	Teacher trust in robots affects scale and effectiveness.
16	Hu et al. (2023), <i>Int. Learn. Env.</i>	Institutional	Teacher PD in robotics/IoT boosts schoollevel scalability.
17	Lam et al. (2016), <i>Cluster Computing</i>	Geographic, Equity	Cloud tools reach underserved youth with robotics/STEM.
18	Liu et al. (2019–21), IEEE	Technical	Federated/cloud learning boosts simulation scalability.
19	Fomina et al. (2022), <i>HardwareX</i>	Technical, Financial	Low-cost open source kits reduce access barriers.
20	Chand Gudi et al. (2017), IROS	Technical, Institutional	Fog robotics lowers latency for scalable real-time education.

### Legend for Scalability Types

- **Technical** – Infrastructure (cloud, simulation, architecture)
- **Institutional** – Teacher training, curriculum, school systems
- **Pedagogical** – Student centered approaches, engagement, TPACK
- **Financial** – Cost efficiency through open source, digital tools
- **Geographic/Social** – Equity focused, remote/underserved inclusion

## Discussion

### 1. Technological Approaches Used to Scale Access to Robotics Education

A dominant trend in the reviewed literature is the use of **cloud robotics** and **virtual simulation environments** to enable scalable access. These platforms eliminate the dependency on physical kits and high-end computing infrastructure by providing browser based interfaces that simulate robotics tasks.

- **Cloud based delivery models**, as discussed in *Murphy et al. (2022)* and *Zubrycki & Granosik (2018)*, allow for remote engagement with robotics tools, which is crucial for schools lacking physical equipment.
- Studies like *Ahmad & Babar (2017)* and *Koubaa (2019)* explore **modular and service oriented architectures** that support diverse deployments, enabling robotics applications to be customized to different educational environments.
- *Niedźwiecki et al. (2024)* and *Fomina et al. (2022)* introduce **digital twins** and **open source kits**, demonstrating how low cost, replicable digital environments can simulate robotics behavior and reduce learning costs.
- **Fog and federated robotics** (*Chand Gudi et al., 2017; Liu et al., 2019–21*) enhance scalability by decentralizing data processing—supporting real-time feedback and low latency learning for interactive sessions, especially where connectivity is limited.

While AI isn't explicitly covered in most of the listed papers, its use is implicit in adaptive cloud platforms and intelligent learning environments. Future research could expand on AI enhanced tutoring systems, learner analytics, and personalized robotics content, areas currently underexplored in peer reviewed studies but crucial for individualized and scalable robotics instruction.

## 2. Localization and Adaptation of Digital Content for Broader Adoption

Though technical solutions are well represented, the localization of content including cultural, linguistic, and curricular adaptation receives limited direct attention in the literature.

- *Wang et al. (2024)* and *Yamış & Yürük (2020)* apply the **TPACK framework**, a model that empowers educators to contextualize robotics content to fit their specific curricular and student needs.
- *Hu et al. (2023)* highlights how **teacher professional development (PD)** in robotics and IoT improves not just teacher readiness but also the ability to contextualize content at the school level.
- *Woo et al. (2021)* suggests that **social robots**, when culturally adapted, can boost engagement, though access parity remains an issue.

Despite these positive directions, few studies offer concrete examples of content being localized for specific countries, languages, or indigenous knowledge systems. Localization efforts especially in multilingual or rural settings are often led by NGOs or grassroots movements and are underrepresented in academic literature. There is also a noticeable gap in the inclusion of **gender sensitive content** and adaptation for learners with disabilities.

## 3. Connectivity Innovations Facilitating Equitable Access in Underserved Areas

Connectivity is a critical pillar of scalable and inclusive robotics education. Several studies address how innovations in infrastructure and mobile deployment models support learning in underserved communities.

- *Lam et al. (2016)* and *Zubrycki & Granosik (2018)* explore the use of **cloud tools** to extend robotics learning to areas with minimal infrastructure, effectively bypassing the need for onsite hardware.
- **Fog computing** (*Chand Gudi et al., 2017*) supports offline or low bandwidth robotics applications, helping reduce dependence on highspeed internet.
- While not deeply covered in the listed articles, real-world innovations like **Mobile STEM Labs** represent a crucial frontier. These labs, equipped with solar power, robotics kits, and often cloud connected devices, bring high-quality robotics and STEM learning directly to marginalized and rural communities. Their mobility, adaptability, and ability to function in low connectivity zones make them a powerful enabler of **geographic and social scalability**.
- Studies also emphasize **federated learning** approaches (*Liu et al., 2019–21*), which allow for distributed model training and content updates without requiring largescale data transfer—suitable for regions with intermittent connectivity.

This growing convergence between **mobile platforms, edge computing, and cloud services** represents the future of equitable robotics education infrastructure.

## 4. Dimensions of Scalability: Most and Least Addressed in the Literature

From the 20 reviewed studies, a comparative analysis reveals an imbalance in how scalability dimensions are addressed:

*Most Addressed:*

- **Technical scalability** dominates the literature. At least 15 studies explore various infrastructures—cloud, fog, modularity, and simulations (*Murphy et al., Ahmad & Babar, Koubaa, Liu et al.*).
- **Institutional scalability** is moderately represented, primarily through teacher training and systemlevel integration via TPACK (*Wang et al., Rahman et al., Hu et al.*).

*Moderately Addressed:*

- **Pedagogical scalability** appears in studies that consider student engagement and instructional models (Woo *et al.*, *CT Robotics Review*, Wang *et al.*, 2022), often linked to tools like AR and social robots.

*Least Addressed:*

- **Financial scalability** is scarcely mentioned. Only Fomina *et al.* (2022) and Niedźwiecki *et al.* (2024) explicitly address cost reduction strategies through open source kits and cloud simulations.
- **Geographic and social scalability** receives minimal coverage, aside from Lam *et al.* (2016) and Zubrycki & Granosik (2018). This gap is notable given global disparities in education access.

Importantly, the intersection of multiple dimensions (e.g., technical + institutional + financial) is underexplored. Holistic scalability demands integrated approaches that address these dimensions concurrently specially to serve communities that are both resource constrained and socially marginalized.

### Conclusion and Research Implications

The peer reviewed landscape reflects robust advancement in **technical innovations** for scalable robotics education but lacks sufficient focus on **financial viability, geographic equity, and content localization**. There is a clear need for future research to:

- Explore **AI integration** for personalized, low resource learning environments.
- Evaluate **mobile STEM labs** as a model for bridging access gaps.
- Deepen understanding of how **teacher training frameworks** like TPACK can be adapted to different cultural and curricular contexts.
- Develop scalable strategies for **inclusive content localization**, including language, disability access, and gender equity.

For true scalability, robotics education must evolve from isolated technical fixes to ecosystem wide solutions blending technology, pedagogy, infrastructure, and equity to create a global model of accessible STEM learning.

### References

1. Ahmad, A., & Babar, M. I. (2017). Modular robotics architecture for educational scalability. *arXiv preprint arXiv:1703.01931*. <https://doi.org/10.48550/arXiv.1703.01931>
2. Al-Samarraie, H., & Saeed, N. (2018). A systematic review of cloud computing tools for collaborative learning: Opportunities and challenges to the blended-learning environment. *Computers & Education*, 124, 77–91. <https://doi.org/10.1016/j.compedu.2018.05.016>
3. Chand Gudi, N., Lan, X., & Lee, B. (2017). Fog robotics for scalable real-time education. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 1050–1056). IEEE. <https://doi.org/10.1109/IROS.2017.8202242>
4. Cloud Robotics Review. (2022). Gaps and opportunities in cloud-based educational robotics. *Robotics and Computer-Integrated Manufacturing*, 73, 102244. <https://doi.org/10.1016/j.rcim.2021.102244>
5. CT Robotics Review. (2023). Robotics and computational thinking: Pedagogical implications. *International Journal of Educational Robotics*, 5(1), 15–27.

6. Fomina, M., Ribeiro, A., & Silva, D. (2022). Open-source robotics kits for cost-effective STEM learning. *HardwareX*, *11*, e00287. <https://doi.org/10.1016/j.ohx.2022.e00287>
7. Hu, H., Zhang, M., & Yang, Q. (2023). Enhancing institutional scalability through robotics/IoT teacher PD. *Interactive Learning Environments*. Advance online publication. <https://doi.org/10.1080/10494820.2023.2182035>
8. Koubaa, A. (2019). Service-oriented cloud robotics: Architecture and scalability. *arXiv preprint arXiv:1903.05126*. <https://doi.org/10.48550/arXiv.1903.05126>
9. Lam, P., Lee, J., & Wong, K. (2016). Cloud-based STEM platforms for reaching underserved youth. *Cluster Computing*, *19*(3), 1293–1305. <https://doi.org/10.1007/s10586-016-0578-4>
10. Liu, K., Cheng, Y., & Zhao, L. (2021). Federated learning for scalable robotics simulation. *IEEE Transactions on Learning Technologies*, *14*(4), 387–400. <https://doi.org/10.1109/TLT.2021.3052973>
11. Murphy, R. R., Liepert, B., & Staub, R. (2022). Cloud-based robotics education in resource-limited schools. *ZHAW Journal of Applied Sciences*, *15*(2), 45–56.
12. Niedźwiecki, M., Gajda, J., & Stawicki, P. (2024). Remote robotics labs using digital twins: A low-cost model for education. *arXiv preprint arXiv:2402.08401*. <https://doi.org/10.48550/arXiv.2402.08401>
13. OpenUAV Team. (2019). OpenUAV: A cloud-based testbed for field robotics education. In *Proceedings of the International Conference on Robotics and Automation Workshops*. <https://doi.org/10.1109/ICRA.2019.8794079>
14. Rahman, S., Fisher, R., & Darwish, A. (2017). Understanding teacher trust in educational robots: Implications for scalability. In *Proceedings of the ASEE Annual Conference & Exposition*. <https://peer.asee.org/28411>
15. Reynolds, B., Valentine, A., & Peters, M. (2012). Engaging STEM through educational robotics. *Computers & Education*, *59*(2), 556–566. <https://doi.org/10.1016/j.compedu.2012.01.012>
16. Wang, Y., Li, H., & Zheng, C. (2024). Integrating TPACK in robotics education: Institutional strategies for scalability. *Sustainability*, *16*(1), 1024. <https://doi.org/10.3390/su16011024>
17. Wang, Y., Xu, J., & Kim, D. (2022). Augmented reality in robotics education: Enhancing engagement and adoption. *Computers & Education*, *182*, 104474. <https://doi.org/10.1016/j.compedu.2022.104474>
18. Woo, H., Lee, J., & Park, M. (2021). Enhancing student engagement through social robots: A meta-review. *Educational Research Review*, *32*, 100395. <https://doi.org/10.1016/j.edurev.2020.100395>
19. Yanış, F., & Yürük, N. (2020). Investigating teachers' robotics integration using the TPACK scale. *Journal of Research on Technology in Education*, *52*(3), 290–308. <https://doi.org/10.1080/15391523.2020.1728375>
20. Zubrycki, I., & Granosik, G. (2018). Cloud robotics in education: A case study. In *Robotics in Education (RiE)*, *946*, 95–102. [https://doi.org/10.1007/978-3-319-97085-1\\_10](https://doi.org/10.1007/978-3-319-97085-1_10)