Democratising Engineering Education through Consumer Technology: QR Code-Based Automation Learning in Resource-Constrained Malaysian Institutions

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DOI: https://doi.org/10.47772/IJRISS.2025.91200047

Received: 11 December 2025; Accepted: 19 December 2025; Published: 31 December 2025

ABSTRACT

Educational equity in STEM fields remains a critical challenge for developing economies participating in the Fourth Industrial Revolution. This study systematically characterises QR code parameters for reliable detection in low-cost automation systems. The investigation used an ESP32-CAM-based package sorting platform representative of Malaysian educational laboratory capabilities. Multi-dimensional experimentation across code sizes (3×3 cm to 6×6 cm), scanner positioning heights (12.5 - 20.5 cm), and orientation angles (0°- 60°) established evidence-based implementation guidelines. Results from 30 experimental runs revealed that larger codes (6×6 cm) achieved 100% recognition success at optimal heights (12.5 - 16.5 cm), while smaller codes (3×3 cm, 4×4 cm) demonstrated substantially lower success rates. Educational evaluation with 31 participants showed 20% average improvement in automation concept mastery, with 61.3% reporting increased STEM interest following hands-on interaction. The QR code-based system demonstrated low implementation costs (RM 768.25/USD 62 per laboratory station) using standard office equipment and basic camera modules, making automation education accessible within typical Malaysian institutional budgets. These findings demonstrate that strategic technology selection leveraging consumer familiarity can overcome resource constraints traditionally limiting developing economy students' access to hands-on engineering education, supporting Malaysia's Industry 4.0 workforce development goals while providing frameworks applicable across ASEAN contexts.

Keywords: educational equity, automation education, QR code technology, resource-constrained institutions, STEM education

INTRODUCTION

The Digital Divide in Engineering Education

Educational equity in STEM fields remains a critical challenge for developing economies seeking to participate in the Fourth Industrial Revolution. While developed nations invest heavily in STEM infrastructure such as robotics kits and modern laboratory equipment (SEAMEO STEM-ED, 2024), Southeast Asian institutions face barriers including inadequate laboratories and lack of up-to-date educational materials (Huynh et al., 2024; Vann, 2023). This disparity threatens to widen the technology skills gap as emerging high-value jobs increasingly require STEM competencies (Jamaluddin et al., 2025), potentially excluding populations from knowledge-intensive sectors while much of the workforce remains concentrated in low-skill industries (East Asia Forum, 2025; World Economic Forum, 2025).

Malaysia exemplifies this challenge. Despite national policy commitments to Industry 4.0 readiness through the Digital Economy Blueprint and National Fourth Industrial Revolution Policy (Economic Planning Unit, 2021), technical education institutions operate within severe financial constraints limiting facility upgrades, technology adoption, and curriculum development (Ahmad & Rosnan, 2024). These budgetary limitations create barriers to implementing automation curricula, as programmes require major investments in robotics equipment, AI systems, consumables, and highly qualified trainers (Hassan, 2024).

Technology Democratisation Through Consumer Familiarity

COVID-19 accelerated QR code adoption, transforming specialised industrial tools into ubiquitous consumer interfaces. Usage increased nearly 50% during 2020-2021, normalising across diverse sectors beyond immediate pandemic applications (Tu et al., 2022, QR Code Tiger, 2025). This rapid societal adoption, with Malaysia achieving over 89% smartphone penetration by 2023, created an educational opportunity; a low-cost technology foundation for teaching complex automation concepts (Statista, 2024). Unlike traditional educational technologies, QR codes leverage students' existing smartphone competencies from daily activities like digital payments and e-commerce, providing a low-barrier entry to automation education (Low et al., 2023; Upstack Studio, 2024; Commission Factory, 2023). This widespread consumer adoption, combined with Malaysia's growing e-commerce sector, creates pedagogical opportunities connecting automation concepts to technologies students encounter daily.

Socioeconomic Implications of Educational Technology Access

The choice of educational technology (EdTech) carries profound socioeconomic implications beyond immediate pedagogical effectiveness. Radio Frequency Identification (RFID) systems require substantial capital investment, readers ranging from RM 40 – 10,000 (USD 10 – 2,500) for educational applications, with tags costing RM 0.20 - 80 (USD 0.05 - 20) each, that effectively excludes budget-limited institutions from automation education (Lowry Solutions, 2024; RFID Card, 2025; RFIDtagworld, 2024a, 2024b). Near Field Communication (NFC) technology similarly necessitates dedicated hardware of RM 160 – 10,000 (USD 40 – 2,500), though many smartphones now include integrated NFC capability (RFIDtagworld, 2024c; Magestore, 2024). These cost barriers create a two-tier educational system; well-funded institutions in developed economies access practical automation training, while developing economy institutions remain limited to theoretical instruction.

In contrast, QR code-based educational systems can be implemented at RM 0.05 (USD 0.01) per code using existing institutional infrastructure, including standard office printers and basic camera modules under RM 45 (USD 9.45), fundamentally altering the economics of automation education. This cost differential represents a major improvement in educational accessibility, the difference between theoretical knowledge and hands-on competency development for entire student populations in budget-limited contexts.

Research Problem: Knowledge Gaps in EdTech Equity

Recent systematic reviews of EdTech in developing economies provide context for this study. Rodriguez-Segura (2022) reviewed 81 EdTech interventions across 36 low- and middle-income countries, finding that technology access alone shows limited effectiveness without complementary pedagogical support. UNESCO (2023) documented that EdTech in Southeast Asia often remains inaccessible to marginalized learners despite policy commitments. World Bank, ILO, and UNESCO (2023) identified weak institutional capacity and limited technical support as systemic barriers in TVET systems across developing economies.

However, these reviews focus predominantly on general computing technologies and mobile learning platforms. Limited research examines specialized technical training equipment, particularly low-cost automation systems suitable for resource-constrained institutions. Existing literature predominantly examines high-end automation in developed markets, leaving gaps regarding how resource-constrained institutions achieve effective educational outcomes through low-cost alternatives.

Given these accessibility barriers and demonstrated gaps in existing scholarship, four specific knowledge gaps emerge. First, research on low-cost automation training in developing economy TVET contexts remains insufficient, with existing EdTech research focused on general computing rather than specialised automation systems. Second, empirical validation of automation technology performance under budget-limited conditions typical of ASEAN institutions remains inadequate (Wickramasinghe & Wickramasinghe, 2024).

Third, practical implementation guidelines addressing limited technical support infrastructure are absent despite systemic barriers. Finally, investigation of cost-effectiveness relationships between automation training technology and learning outcomes remains limited in these contexts.

Research Purpose and Significance

To address these gaps, this study systematically characterises QR code parameters for reliable automation education in resource-constrained institutional settings. Using an ESP32-CAM-based package sorting platform representative of Malaysian educational laboratory capabilities, the investigation employs controlled experimentation across multiple parameter dimensions to establish evidence-based implementation guidelines applicable across developing economy educational contexts.

The research provides three contributions to educational equity scholarship:

1. Empirically validated technology specifications enabling effective hands-on automation education within developing economy budget constraints,

2. Practical implementation guidelines supporting technology democratisation across budget-limited institutions, and

3. A replicable methodological framework for EdTech evaluation in developing economy contexts.

METHODOLOGY

Research Design

This study employed a mixed-methods approach combining controlled laboratory testing of QR code recognition parameters with educational evaluation of learning outcomes and usability. The research was conducted at Universiti Teknikal Malaysia Melaka (UTeM) using an ESP32-CAM-based miniature automated package sorting system developed specifically for educational applications.

Technical Performance Testing

Controlled laboratory testing examined QR code recognition performance across multiple parameter dimensions. The investigation comprised two complementary components:

1. **Parameter Selection:** Parameters were selected based on practical constraints in Malaysian educational contexts. Code sizes (3×3 to 6×6 cm) reflected typical size use in logistic industry and material cost considerations. Height ranges (12.5 - 20.5 cm) represented typical low-cost conveyor configurations achievable within institutional budgets. Angle variations (0° - 60°) simulated realistic misalignment scenarios in student-operated systems where precise positioning cannot be guaranteed.

2. **Experimental Design:** Thirty experimental runs tested combinations of code sizes (6×6 cm, 5×5 cm, 4×4 cm, 3×3 cm), scanner heights (20.5 cm, 18.5 cm, 16.5 cm, 14.5 cm, 12.5 cm), and orientation angles (0°, 15°, 30°, 45°, 60°). For each combination, recognition success rates (percentage of successful scans) and processing times (seconds required for recognition) were recorded.

Educational Effectiveness Evaluation

Educational evaluation employed pre-test/post-test methodology with 31 participants to assess knowledge acquisition regarding automation concepts through hands-on interaction with the QR code-based educational kit. Participants completed structured assessments measuring understanding of automation principles, system functions, and practical implementation concepts before and after kit interaction.

Usability Assessment

User feedback was collected through structured questionnaires employing 5-point Likert scales for quantitative assessment and open-ended questions for qualitative feedback. The survey addressed instructional clarity, ease of use, engagement levels, and STEM interest cultivation. Module completion rates and session retention metrics provided additional engagement indicators.

Data Analysis

Quantitative data including recognition success rates, processing times, pre-test/post-test scores, and survey responses were analysed using descriptive statistical methods appropriate to each measure. Technical performance metrics (recognition success rates and processing times) were summarised using means and percentages across experimental conditions. Educational effectiveness was assessed by calculating percentage improvement from pre-test to post-test scores for each participant, then averaging across the sample (n=31) to determine mean knowledge gains. Likert scale responses (1-5) from usability questionnaires were analysed using frequency distributions and percentages to characterise user experiences. Given the exploratory nature of this initial validation study and the small sample size, inferential statistics were not employed; instead, descriptive analysis focused on establishing preliminary effect magnitudes to inform future larger-scale investigations. Qualitative feedback was synthesised thematically to identify common usability challenges and engagement patterns.

Figure 1 shows the experimental system configuration used for all performance testing.

Figure 1 - ESP32-CAM-based QR code recognition system showing overall system architecture.

RESULTS

Technical Performance as Educational Accessibility Indicator

Controlled laboratory testing (30 experimental runs) examined QR code recognition performance across varying parameters to determine accessibility thresholds for educational implementation. Results revealed systematic relationships between code size, positioning, and recognition success rates that directly inform cost-effective educational system design.

Height and Size Parameter Analysis

Recognition success rates varied significantly based on QR code size and scanner height positioning, as illustrated in Figure 2. Larger codes (6×6 cm) achieved near-perfect detection (100%) at optimal heights (12.5 -

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

16.5 cm), while smaller codes (3×3 cm, 4×4 cm) demonstrated substantially lower success rates, particularly at greater heights.

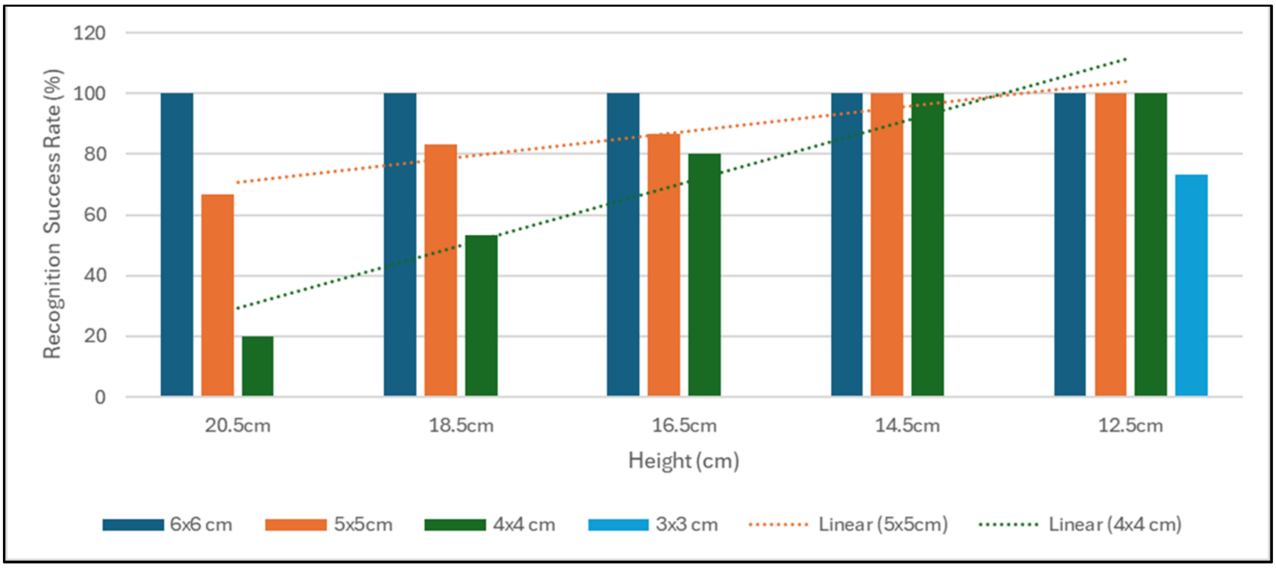

Figure 2 - Recognition success rates (%) across five scanner heights for four QR code sizes.

6×6 cm codes require only standard office printers, while optimal heights (12.5-16.5 cm) accommodate low-cost conveyor designs.

Average recognition processing times demonstrated modest variation across parameter combinations (Figure 3), ranging from 4.21 to 4.57 seconds.

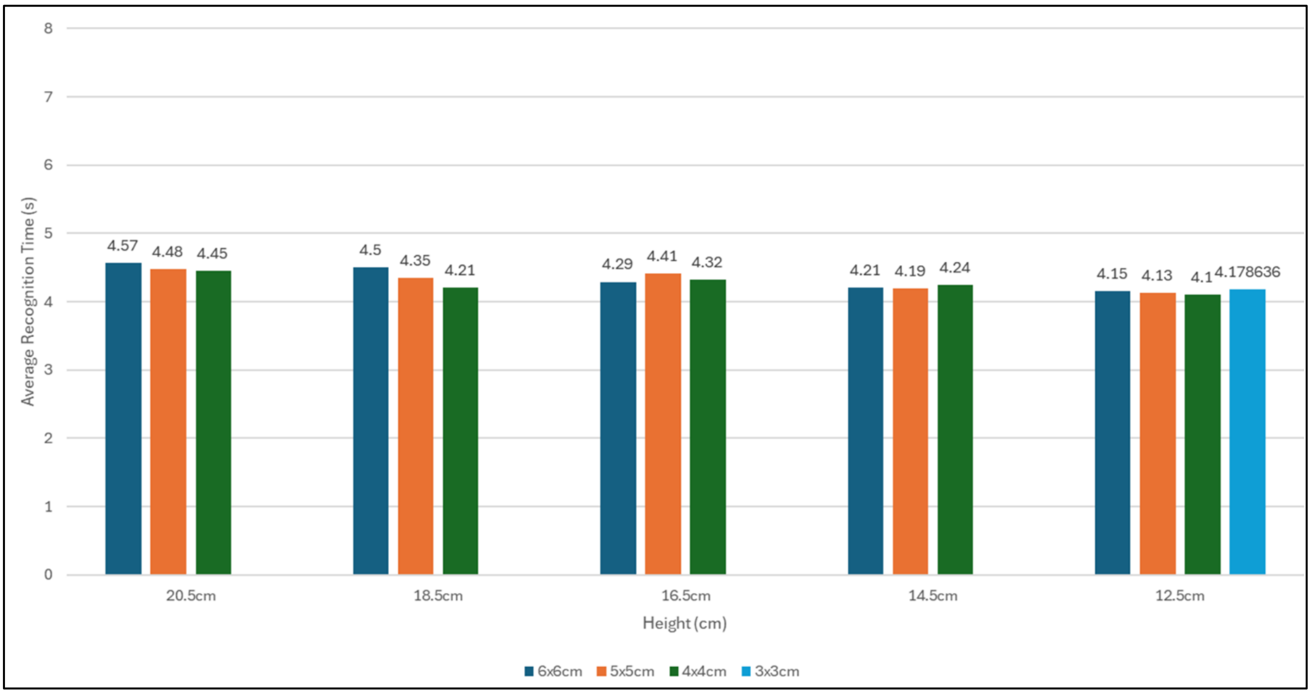

Figure 3 - Average recognition time across scanner heights for different QR code sizes.

Orientation Angle Robustness

Testing across orientation angles (0°, 15°, 30°, 45°, 60°) revealed differential robustness by code size, with implications for operational reliability in student-operated educational environments (Figure 4).

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

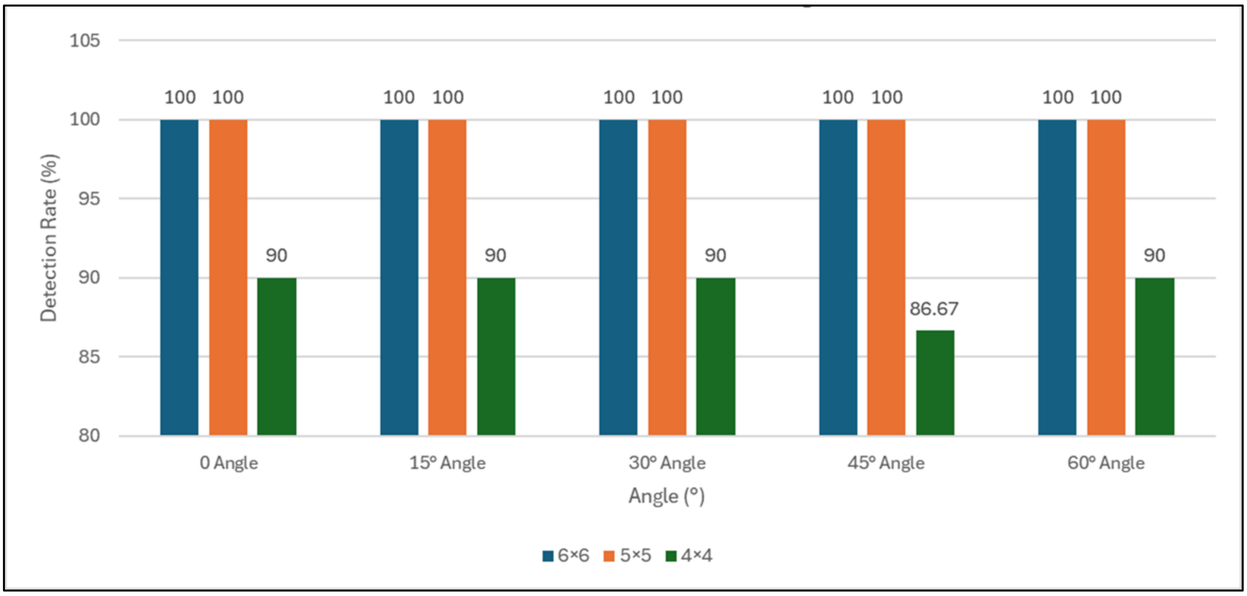

Figure 4 - Detection rates for three QR code sizes across five orientation angles.

These technical performance results establish that educational systems using low-cost hardware can achieve reliable performance (≥90% success) when designed within validated parameter ranges: codes ≥5×5 cm at heights ≤16.5 cm.

Educational Effectiveness and Learning Outcomes

Evaluation with 31 participants employed pre-test/post-test methodology to assess knowledge acquisition regarding automation concepts through hands-on interaction with the QR code-based educational kit.

Knowledge Acquisition Metrics

Quantitative assessment revealed substantial knowledge gains across all measured dimensions, as summarised in Table 1.

Table 1 - Educational Effectiveness Metrics.

Metric	Target	Achieved	Performance
Pre-to-Post Test Improvement	20%	20%	Met target
Functional Explanation Accuracy	90%	90%	Met target
Module Completion Rate	85%	85%	Met target
Basic Comprehension Time	≤30 min	≤30 min	Met target

These learning gains occurred within single 30-minute interaction sessions, suggesting efficient knowledge transfer through familiar technology interfaces.

STEM Interest Cultivation

User engagement metrics demonstrated notably high interaction levels with significant implications for STEM pipeline development. Table 2 shows the percentage of participant responses regarding increased STEM interest following kit interaction.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

Table 2 - User Engagement and Interest Indicators.

Indicator	Result	Significance
Increased STEM Interest	61.3%	High impact on disciplinary motivation
Would Recommend to Others	48.4%	Moderate endorsement rate
Session Retention Rate	80%	Strong sustained engagement

The hands-on nature of the kit allowed active engagement with automation systems. The 61.3% increase in STEM interest represents a particularly significant finding for workforce development.

Usability and Accessibility Perceptions

User feedback (*n* = 31) revealed generally positive usability experiences whilst highlighting areas for refinement in EdTech design for diverse user populations.

Instructional Clarity and Ease of Use

Table 3 presents the results of user responses regarding instructional clarity, revealing that whilst nearly half found instructions completely clear, significant portions experienced varying levels of difficulty.

Table 3 - Usability Performance Indicators.

Usability Dimension	Measurement	Result
Instructions Clarity	% rating 4-5	48.4%
Task Completion Time	Target: ≤10 min	Met for majority
Task Success Rate	Target: ≥90%	Met for majority
Hardware Durability Satisfaction	Qualitative	Positive feedback

Table 4 shows specific components presenting usability challenges.

Table 4 - Component-Specific Usability Challenges (Qualitative Feedback).

Component	Reported Challenge	Frequency
Motor system	Less intuitive operation	Moderate
Scanning system	Understanding automation concepts	Moderate
QR code reading	Barcode scanning difficulties	Low
Overall assembly	Setup complexity	Low

Engagement Quality

Participant engagement with the educational kit demonstrated high levels across multiple indicators, as shown in Table 5. This is based on engagement ratings (5-point scale) for hands-on activities. Results: 48.4% rated engagement level 4 (high), 32.3% rated 5 (very high), with minimal low-engagement responses.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XII December 2025

Table 5 - Engagement Distribution.

Engagement Rating	Response %	Cumulative %
5 (Very High)	32.3%	32.3%
4 (High)	48.4%	80.7%
3 (Moderate)	19.4%	100%
2 (Low)	0%	100%
1 (Very Low)	0%	100%

The absence of low-engagement responses (ratings 1-2) indicates consistent user interest, whilst the 80.7% reporting high-to-very-high engagement suggests effective pedagogical design for maintaining learner attention and motivation.

DISCUSSION

These technical performance, educational effectiveness, and usability findings inform several key implications for EdTech equity in resource-constrained contexts.

Implications for EdTech Selection and Educational Equity

Technical performance data reveal critical implications for EdTech selection in budget-limited contexts. Low-cost ESP32-CAM systems (RM 768.25 per station) achieved 100% recognition rates with appropriately sized codes (6×6 cm, 5×5 cm), suggesting that educational quality need not require high-cost specialised equipment (Rodriguez-Segura, 2022). These findings suggest that for foundational automation education, consumer-grade technologies provide adequate functionality when implemented within validated parameter ranges. The 85% module completion rate and 61.3% STEM interest increase demonstrate that resource-constrained contexts can achieve quality outcomes through strategic technology selection combined with thoughtful pedagogical design.

However, performance degradation with smaller codes (3×3 cm: 20-73% success) illustrates important boundary conditions. Educational systems must balance cost reduction against functional reliability; highly cost-optimised implementations risking unreliable operation may undermine effectiveness through student frustration.

The usability challenges highlight that technology cost reduction alone proves insufficient for equity. Accessible hardware must accompany accessible pedagogy; clear instructions, scaffolded learning progressions, and support for diverse user needs. The finding that only 48.4% found instructions completely clear highlights persistent challenges in EdTech design for diverse user populations serving students with varying prior knowledge and learning styles.

Learning Outcomes and Hands-On Engagement

The educational evaluation revealed important patterns in knowledge acquisition and learner engagement. The 20% knowledge improvement and 90% functional explanation competency achieved in 30-minute sessions suggest that hands-on interaction with familiar technologies facilitates efficient automation concept acquisition, though long-term retention remains to be evaluated. Familiar interfaces may reduce cognitive load, enabling students to focus on automation principles rather than technology operation.

The 61.3% increase in STEM interest represents a particularly significant finding for developing economy equity concerns. Given Malaysia's Industry 4.0 workforce development goals, educational interventions that substantially increase student interest in technical disciplines address critical pipeline challenges. The hands-on engagement model, allowing active manipulation rather than passive observation, appears particularly effective for sparking disciplinary curiosity, potentially influencing long-term educational and career trajectories.

However, the 48.4% recommendation rate suggests room for enhancement. This may reflect the usability challenges noted in feedback, particularly regarding instructional clarity. Addressing these pedagogical gaps could strengthen the kit's effectiveness.

Usability and Inclusive Design Considerations

The reported struggles with motor systems and scanning components suggest that 'user-friendly' consumer technology familiarity does not automatically extend to understanding underlying automation principles. This gap represents a critical pedagogical challenge; leveraging consumer technology recognition while building deeper engineering comprehension requires deliberate instructional design beyond hardware provision.

The qualitative feedback about automation concept difficulties indicates that the kit successfully challenges users intellectually while potentially requiring enhanced pedagogical scaffolding. Balancing intellectual challenge (necessary for meaningful learning) with frustration avoidance (necessary for sustained engagement) represents an ongoing design tension in EdTech development.

Methodological Limitations and Boundary Conditions

The evaluation sample (n = 31 participants) represents an important limitation constraining the generalisability of learning outcome claims. This sample size, whilst providing preliminary evidence for substantial knowledge gains (20% average improvement) and STEM interest cultivation (61.3% increase), is insufficient to establish robust statistical power or ensure representation across diverse student populations. The findings should be interpreted as initial validation requiring replication with larger, more diverse samples across multiple Malaysian institutions before confident generalisation. Future research employing sample sizes of $n > 100$ across varied institutional contexts is essential to confirm these preliminary educational effectiveness patterns. Additionally, the single-institution context may not represent broader Malaysian educational diversity, particularly regarding student demographics, prior technical exposure, and institutional resources.

The study examined one specific low-cost technology (QR code/ESP32-CAM systems) for foundational automation concepts. Generalisability to other consumer technologies, other engineering topics, or advanced specialisation remains uncertain. The observed learning outcomes apply specifically to introductory automation concepts; whether foundational education using low-cost technologies adequately prepares students for advanced specialisation requiring industry-standard equipment warrants longitudinal investigation.

Furthermore, the evaluation measured immediate learning outcomes (post-test) and short-term engagement (module completion) without examining long-term knowledge retention or sustained STEM interest. The durability of observed effects, critical for educational investment decisions, requires follow-up assessment.

Several additional limitations warrant consideration. First, this study evaluated QR code systems without direct comparison to RFID, NFC, or barcode alternatives, limiting conclusions about relative cost-effectiveness. Second, the 30-minute evaluation captured immediate learning outcomes but not long-term knowledge retention. Third, STEM interest increases were self-reported without validated psychometric instruments, potentially inflating estimates. Finally, the single-institution context may not represent the full diversity of Malaysian educational settings, particularly regarding student demographics, prior technical exposure, and available resources.

CONCLUSIONS

Principal Findings and Theoretical Contributions

This research demonstrates that consumer-grade technologies, when strategically selected and appropriately implemented, can deliver educationally effective automation learning experiences within budget constraints typical of Malaysian technical institutions. Three principal findings emerge:

First, EdTech value derives from the intersection of technical functionality, cost constraints, and learner familiarity, challenging technology-centric evaluation approaches prioritising sophistication over accessibility. The demonstration that RM 768.25 systems achieve effective learning outcomes suggests cost-effectiveness as a legitimate design criterion rather than inevitable compromise.

Second, consumer technology adoption patterns create time-limited educational opportunities. The widespread QR code familiarity resulting from pandemic-driven digital payment adoption represents population-level technological competency that reduces learning curves and cognitive barriers to engineering education.

Third, hands-on engagement with familiar technologies demonstrates effectiveness for STEM interest cultivation. The 61.3% interest increase following brief hands-on interaction suggests that strategic interventions addressing cognitive and engagement barriers can meaningfully influence educational and career trajectories even with modest resource investments.

Practical Implications

Institutions should strategically select technologies optimising cost-functionality-familiarity intersections, permitting validated low-cost alternatives for broad-access training whilst reserving specialised equipment for advanced specialisation. Procurement policies should distinguish foundational from advanced equipment needs, permitting validated low-cost alternatives for broad-access training whilst reserving specialised equipment for advanced specialisation.

Contributions to Scholarship

This research advances equity scholarship through empirical demonstration that strategic technology selection can overcome resource constraints traditionally limiting developing economy students' access to hands-on engineering education. The findings challenge two assumptions; that educational quality correlates with technology cost, and that developing economy education must await budget increases for quality improvement.

These contributions suggest theoretical directions for EdTech research in developing economies: frameworks emphasising accessibility, cultural familiarity, and sustainability alongside technical performance dimensions often marginalised in developed economy research.

Future Research Directions

This study opens multiple research avenues addressing remaining uncertainties:

1. **Longitudinal Outcomes**: Systematic investigation of whether foundational low-cost education adequately prepares students for advanced specialisation.

2. **Comparative Effectiveness**: Cross-institutional studies examining learning outcome equivalence across different technology cost points with controlled pedagogical variables. Current findings demonstrate low-cost technology effectiveness but do not directly compare to high-cost alternatives with equivalent pedagogical support.

3. **ASEAN Contextualization**: Comparative studies across Southeast Asian contexts identifying which findings represent generalisable developing economy patterns versus Malaysian-specific conditions. Such research would establish regional applicability and identify context-dependent adaptation requirements.

Closing Perspective

Strategic technology selection can leverage societal adoption patterns to advance educational equity. QR codes, transformed from specialised tools to ubiquitous interfaces, now offer budget-limited Malaysian institutions pathways to hands-on automation education previously economically inaccessible. However, this opportunity remains time limited as consumer technology evolves continuously. Educational institutions and policymakers must act deliberately to capture current opportunities whilst building frameworks for identifying future consumer technology transitions. Engineering education accessibility requires neither major budget increases nor equipment philanthropy, merely strategic technology selection, evidence-based implementation, and commitment to equity as achievable within existing resource constraints

ACKNOWLEDGEMENT

Authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for the technical and financial support to carry out this research work.

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Ethical Considerations

Ethical Approval

This research involving human subjects was conducted in accordance with the ethical standards of Universiti Teknikal Malaysia Melaka (UTeM). Informed consent was obtained from all participants prior to their involvement in the study. Participation was voluntary, and participants were informed of their right to withdraw at any time without penalty.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

The datasets generated and analysed during the current study, including technical performance measurements, educational evaluation results, and survey responses, are available from the corresponding author upon reasonable request. Raw data cannot be made publicly available due to institutional policies regarding research data management and participant privacy considerations. Summary statistics and aggregate findings are presented in full within this manuscript.