

From Theory to Practice: Designing a STEM-Based IoT Hydroponic Module for Enhanced Student Learning

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Abstract

This paper presents the design and implementation of a Solar-Powered IoT Hydroponic Module developed as an educational training module aimed at deepening students' understanding of STEM principles while connecting these concepts to the United Nations Sustainable Development Goals (SDGs). The program employed a feedback-driven, mixed-methods approach—combining direct performance assessment with structured participant reflections and surveys—to validate both technical proficiency and engagement. This paper presents the design, implementation, and immediate outcomes of the module, while a separate paper at this conference, titled 'Multi-Stakeholder Feedback Analysis of a Solar-Powered IoT Hydroponic STEM Module: Impact, Perceptions, and Optimization,' provides an in-depth analysis of the multi-stakeholder feedback. The module's primary objective was to deliver a structured, hands-on learning experience centered on an IoT-enabled hydroponic module powered by renewable energy, thereby promoting STEM education alongside awareness of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Using a systematic and replicable methodology, the program integrated ESP32 microcontrollers, environmental sensors, solar energy components, and cloud-based monitoring platforms to create an accessible agricultural solution tailored for educational settings. Supported by the 2024 IEEE Region 10 Educational Activities Development Grant, the module was delivered through structured workshops involving secondary school and polytechnic students. Participants gained practical experience in hardware assembly, sensor integration, programming, and real-time data visualization using platforms such as ThingSpeak. A comprehensive assessment strategy combining direct performance evaluations with reflective feedback validated both technical proficiency and student engagement with IoT technologies, with over 90% of students rating their overall workshop experience as "Excellent" or "Good". The findings demonstrate that contextually relevant, experiential learning significantly enhances students' technical skills and fosters positive attitudes toward emerging technologies. The module's structure and methodology offer a practical framework that can be adapted for broader adoption in national TVET programs and diverse educational settings, making it a valuable resource for educators committed to integrating technology and sustainability in their curricula.

Keywords: *STEM education, ESP32 microcontroller, IoT in Education, Hydroponics, Renewable energy, Sustainable agriculture, hands-on learning.*

1.0 Introduction

The imperative for sustainable agricultural practices has never been greater, driven by the confluence of climate change, resource depletion, and escalating energy demands. Within this context, the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), underscore the critical need for innovative, efficient, and resilient agricultural solutions. The integration of renewable energy and Internet of Things (IoT) technologies into agriculture represents a promising avenue for addressing these challenges through enhanced resource management, optimized crop yields, and real-time monitoring and automation. Despite the acknowledged importance of Science, Technology, Engineering, and Mathematics (STEM) disciplines in fostering such innovation, attracting and retaining students in these fields remains a persistent challenge. Perceptions of STEM careers as demanding, requiring extensive theoretical knowledge, and lacking immediate practical relevance can deter potential entrants. Moreover, the often-abstract nature of traditional STEM curricula and the scarcity of relatable role models can further exacerbate this issue, particularly among underrepresented groups. To mitigate these challenges, educational strategies must prioritize experiential learning opportunities that bridge the gap between theoretical concepts and tangible, real-world applications (Chen et al., 2020a). By providing students with practical, hands-on engagement with emerging technologies such as

IoT and renewable energy, educators can enhance comprehension, cultivate problem-solving skills, and demonstrate the direct relevance of STEM to pressing global issues.

This paper details the systematic design and development of a scalable STEM-based training module Solar-Powered IoT Hydroponic Module centred on solar-powered IoT solutions for sustainable hydroponic farming. Supported by the 2024 IEEE Region 10 Educational Activities Development Grant, this initiative seeks to provide secondary school and polytechnic students with practical, hands-on experience in applying IoT and renewable energy principles to address real-world agricultural challenges (Rao & Elias-Medina, 2024). The module's design emphasizes a structured approach to hardware selection, software integration, and system architecture, enabling students to not only acquire technical skills but also develop a deeper understanding of the potential for STEM to contribute to a more sustainable and technologically advanced future for agriculture.

2.0 Literature Review

Agriculture today faces pressing sustainability challenges, including climate variability, water scarcity, and rising energy demands. Hydroponic farming offers a promising, sustainable solution by using less water and improving crop yields. Effective deployment of IoT-enabled hydroponic systems hinges on continuous monitoring of environmental factors—a gap well addressed by IoT automation platforms that enhance both productivity and resource efficiency (Thiagarajah et al., 2024).

In preparing the next generation to meet these challenges, STEM education plays a crucial role. Research consistently shows that hands-on, interdisciplinary learning experiences involving IoT technologies significantly boost student engagement and deepen understanding by integrating electronics, programming, data analytics, and sustainability principles (Chen et al., 2020). Embedding Sustainable Development Goals (SDGs) particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) within STEM curricula raises awareness of global sustainability issues and motivates students to apply STEM knowledge meaningfully to environmental and energy challenges (Maidatsi et al., 2022).

To scaffold this complex learning, the educational program adopts a four-layer IoT architecture depicted in **Figure 1**, which mirrors real-world IoT system design and facilitates systematic student learning. The Sensing Layer involves environmental sensors such as the DHT11 and water-level sensors that gather vital data. This data is wirelessly transmitted by the Network Layer, powered by the ESP32 microcontroller. The Service Layer utilizes the ThingSpeak cloud platform to enable real-time data visualization and remote monitoring, permitting students to observe system performance dynamically. Finally, the Interface Layer offers interactive feedback mechanisms, including LEDs, LCDs, and buzzers, fostering hands-on engagement and immediate system interaction. This layered approach helps learners progressively understand each component's role from data acquisition to user feedback thereby reinforcing both conceptual and practical knowledge in IoT systems (Maidatsi et al., 2022b).

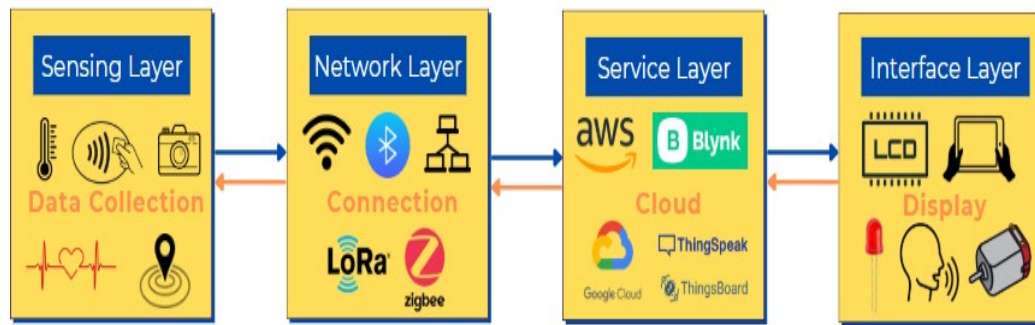


Figure 1: Proposed 4-Layer IoT Architecture System for Data Collection, Communication, Processing, and Display

From a pedagogical perspective, active learning strategies blending problem-based, project-based, and hands-on experiences have proven highly effective in STEM education, especially when integrated with IoT technologies. For instance, postgraduate IoT courses using phased instructional methodologies achieved marked improvements in student grades, participation, and concept retention. Gamification efforts in undergraduate settings similarly boosted motivation from 30.5% to 92.2%. Additionally, IoT kits deployed in hybrid learning environments (remote and in-person) raised student engagement from 60% to 85% (Sánchez et al., 2020). These findings highlight the value of authentic, real-world challenges paired with continuous formative feedback in STEM curricula, fostering vital skills such as problem solving, critical thinking, and collaboration—core outcomes aligned with the system architecture and instructional design of this study.

3.0 Hardware Components

The primary components for the Solar-Powered IoT Hydroponic Module were carefully selected based on their relevance to current agricultural IoT applications, ease of use in educational settings, and compatibility with renewable energy solutions (Tarigan et al., 2023). In summary, Table 1 demonstrates that each component was intentionally selected not only for technical relevance but also to ensure the module can be easily scaled, adapted, and replicated across a wide range of educational and agricultural settings, as recommended by (Tarigan et al. 2023).

Table 1: IoT Hardware Components Used in the Solar-Powered IoT Hydroponic Module

Component	Description
ESP32 Microcontroller (NodeMCU-ESP32)	The ESP32 was chosen due to its built-in Wi-Fi connectivity, low power consumption, and ease of programming using the Arduino IDE, making it ideal for educational IoT projects.
Environmental Sensors (DHT11 and Water Level Sensor)	The DHT11 sensor was selected to measure temperature and humidity accurately, vital parameters for hydroponic farming. The water level sensor was chosen to monitor water availability precisely, essential for automating hydroponic irrigation (Tarigan et al., 2023)
Solar Energy Module (Solar Panels and Charge Controller)	A solar panel with appropriate specifications was integrated to power the system sustainably. A solar charge controller regulated energy distribution, ensuring stable and efficient power delivery.
Actuators and Indicators (LEDs, LCD Display, Buzzers)	LEDs and LCD displays provided visual feedback for monitoring sensor data, while buzzers delivered auditory alerts, offering students practical experience in electronic circuit outputs.

3.1 Software and IoT Platform

For coding and software development, Arduino IDE was utilized due to its accessibility and simplicity in educational environments. The IoT platform Thingspeak was selected for cloud data visualization because of its straightforward integration with the ESP32, ease of data monitoring, and suitability for educational applications involving real-time IoT data.

3.2 System Architecture and Design

The Solar-Powered IoT Hydroponic Module consisted of interconnected modules:

- **Input Module:** Environmental sensors (temperature, humidity, water level sensors) capturing real-time data.
- **Processing Module:** ESP32 microcontroller receiving sensor data, performing initial data processing, and transmitting data to the IoT platform.
- **Output Module:** LEDs, LCD displays, and buzzers providing immediate feedback and status updates.
- **Energy Module:** Solar panels and a charge controller supplying sustainable power to the entire system.

The overall functional architecture illustrating the interaction between these components and various system elements is presented in **Figure 2**. Circuit schematics and diagrams were developed to visually guide participants through assembly and component integration.

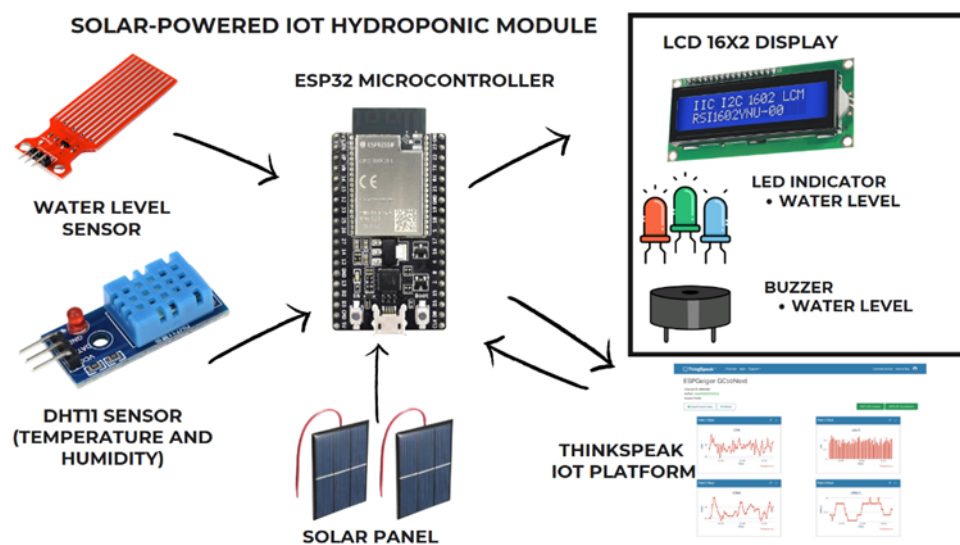


Figure 2: System Architecture and Components of Solar-Powered IoT Hydroponic Module

3.3 Facilitator and Participant Profile

The workshop was supported by a dedicated team of nearly 10 facilitators from Malaysian Polytechnics with backgrounds in electrical engineering, alongside 5 lecturers holding doctoral degrees from Universiti Malaysia Terengganu. This diverse and experienced team provided both technical expertise and academic guidance, ensuring that participants received comprehensive support throughout the program. Approximately 20 secondary school students participated in the one-day workshop, engaging in hands-on activities designed to develop their STEM and IoT competencies. Throughout the program, facilitators closely monitored and oversaw the participants' progress at each stage, providing

real-time feedback and assistance. This continuous supervision was critical in verifying the accuracy and completeness of each participant's work, which was systematically documented using a verification form. The verification form served as an essential tool to authenticate the participants' achievements and skill acquisition, ensuring that learning objectives were met effectively. By embedding facilitator oversight into the program structure, the workshop not only enhanced the quality of learning but also reinforced accountability and motivation among participants. This approach aligns with Malaysia's STEM and TVET educational frameworks, emphasizing hands-on, project-based learning supported by expert mentorship to cultivate both technical skills and scientific values such as curiosity and perseverance.

4.0 Result and Method

The workshop was conducted on 10–11 August 2024 at Universiti Malaysia Terengganu, bringing together twenty high-achieving secondary school students from Kuala Terengganu. As depicted in **Figure 3**, the program followed a structured sequence of phases, each designed to progressively develop participants' technical and analytical competencies. Throughout the workshop, students engaged in a series of hands-on, STEM-focused IoT activities, with results presented in alignment with these distinct stages of learning and implementation.



Figure 3: Structure of the program, outlining schedule and objective



Figure 4: Participant successfully planting seed into Hydroponic

The training begins with students transferring young seedlings from the nursery into hydroponic containers prepared with non-toxic plastic materials and supportive growing media such as sponge or cocopeat. This hands-on activity introduces essential plant care techniques, including handling root systems delicately and ensuring proper placement in a soil-less system. Once transplanted, students move on to preparing the nutrient solution using two types of liquid fertilizer—Fertilizer A (containing calcium nitrate and iron) and Fertilizer B (containing potassium nitrate, magnesium sulfate, and micronutrients). They learn to measure and mix these nutrients in correct ratios, then use TDS and EC meters to monitor the concentration, ensuring optimal nutrient availability for plant growth. This integrated process emphasizes precision, environmental awareness, and foundational skills in hydroponic farming, setting the stage for IoT-based monitoring in later modules. This hands-on activity effectively grounded theoretical principles in practical agricultural skills, fostering early engagement and enthusiasm among students, consistent with best practices highlighted by (Chen et al., 2020b).

In the subsequent Controlling Output lesson, participants gained essential experience with ESP32 microcontroller functionalities, GPIO architecture, and circuit assembly, reinforced by practical programming exercises using Arduino IDE. Facilitators verified correct component

wiring, ensuring technical competence and accurate code execution—important steps in Embedded system development and closely aligned with successful approaches described by (Thiagarajah et al., 2024). This verification process ensured not only task accuracy but also reinforced foundational skills crucial for advanced IoT applications.

EVALUATION FORM
Skills Competency for Advanced IoT Applications

Name of Participant : _____

LESSON	JOB DESCRIPTION	REMARK	VERIFY BY FACILITATOR
CONTROLLING OUTPUT	1 - LED		
	a. Connect the jumper wire from the anode red LED to D25 at the ESP-32		
	b. Connect the jumper wire from the cathode red LED to GND at the ESP-32		
	c. Run the code		
	d. Observation and Result	Red LED blink in 2s : Yes/No	
	e. Connect the jumper wire from the anode green LED to D26 at the ESP-32		
	f. Connect the jumper wire from the cathode green LED to GND at the ESP-32		
	g. Modify the code		
	h. Observation and Result	Green LED blink in 2s : Yes/No	
	2 - BUZZER		
i. Connect the jumper wire from the positive pin BUZZER to D27 at the ESP-32			
j. Connect the jumper wire from the negative BUZZER to GND at the ESP-32			
k. Modify the code			
l. Observation and Result	BUZZER turn ON and OFF in 2s : Yes/No		

Figure 5: Evaluation Form Solar-Powered IoT Hydroponic Module

Each step was verified and signed off by facilitators such as shown in **Figure 5**, confirming that all students completed the task confidently and accurately. This hands-on approach not only strengthened foundational skills in microcontroller interfacing and circuit assembly but also enhanced students' proficiency in using the Arduino IDE, preparing them for more advanced IoT applications within the IoT Hydroponic Module.

Table 2: Learning Outcome and activities for Controlling Output

Skill Area	Activity Description	Tools / Components
GPIO Pin Familiarity	Wiring LEDs (LED Red to D25, green LED to D26) and buzzer to D27	ESP32, LEDs, buzzer, jumper wires
ESP32 Architecture	Assigning sensor (DHT11 to D33, water level sensor to D32) and LCD display (SCL to D22, SDA to D21) to specific pins	ESP32, sensors, LCD display
Circuit Assembly	Connecting circuit on PCB or breadboard with proper connections and grounding	Breadboard, PCB and components
Arduino IDE Usage	Writing, compiling and uploading code to Blink LEDs, active the buzzers and read sensor data	Arduino IDE, USB cable
Verification Process	Facilitator lead and observe with verification and sign off to ensure task completion	Facilitators, evaluation checklist



Figure 6: Workshop participants wiring the IoT Solar-Powered IoT Hydroponic Module

Participants successfully integrated environmental sensors—specifically the DHT11 temperature and humidity sensors and water-level sensors—into their circuits. Facilitators verified correct connections and supervised the uploading of code that facilitated real-time data acquisition, directly validating sensor functionality. This robust integration of sensor technology with ESP32 aligns with IoT best practices documented by Tarigan et al. (2023), reinforcing practical learning outcomes. According to the evaluation form, nearly all students completed this task successfully, requiring only minor assistance with LCD configuration. The accurate output readings of temperature, humidity, and water level validated the proper functioning of the sensors and demonstrated students' understanding of sensor data acquisition. As detailed in **Table 3**, the learning outcomes and activity breakdown for reading sensor values confirm that participants not only mastered the technical steps but also deepened their ability to interpret real-time environmental data—an essential skill in IoT-based agricultural monitoring. By systematically mapping, designing, and assessing sensor activities against the outcomes in **Table 3**, the program ensures a clear, measurable, and effective alignment that supports both student learning and robust educational reporting. This task reinforced the importance of precise wiring and programming in IoT environmental monitoring, while strengthening participants' competence and confidence in handling sensor data within an IoT framework.

Table 3: Learning Outcome and breakdown activities for Reading Sensor Value

Skill Area	Activity Description	Tools / Components
Sensor Wiring	Connecting DHT11 sensor (VCC, GND, signal to D33), water-level sensor (to D32) and LCD display (SCL to D22, SDA to D21) with correct power and ground	ESP32, DHT11, Water-level sensor, LCD, jumper wires
Pin Verification	Facilitator verification of correct pin assignment and stable connection	Facilitators, evaluation checklist
Code Uploading	Programming the ESP32 to read sensor data and display it on the serial monitor and LCD	Arduino IDE, ESP32
Data Display	Confirming temperature, humidity, and water level values appear correctly on output devices	Serial monitor, LCD display
Troubleshooting Support	Minor facilitator assistance provided mainly for LCD configuration issues	Facilitators
Task Completion Verification	Facilitators signed off on successful task completion based on correct wiring and output validation	Facilitators, evaluation form

In this task, participants learned to transmit real-time environmental data from their sensors to the cloud using the ThingSpeak platform. After setting up a new channel and incorporating the required API keys into their Arduino code, students successfully uploaded temperature, humidity, and water level data from their hydroponic systems. Facilitators verified the live appearance of this data on the ThingSpeak dashboard, confirming that the task requirements were met. As illustrated in **Figure 7**, participants were able to visually confirm their success by observing dynamic charts that updated in real time with their sensor readings. This experience represented a pivotal moment where theoretical knowledge translated into practical application, enabling students to see their physical sensor data reflected in an online IoT interface. The visualization reinforced their understanding of wireless communication and cloud-based monitoring (Varela-Aldás et al., 2025) key components in modern precision agriculture.

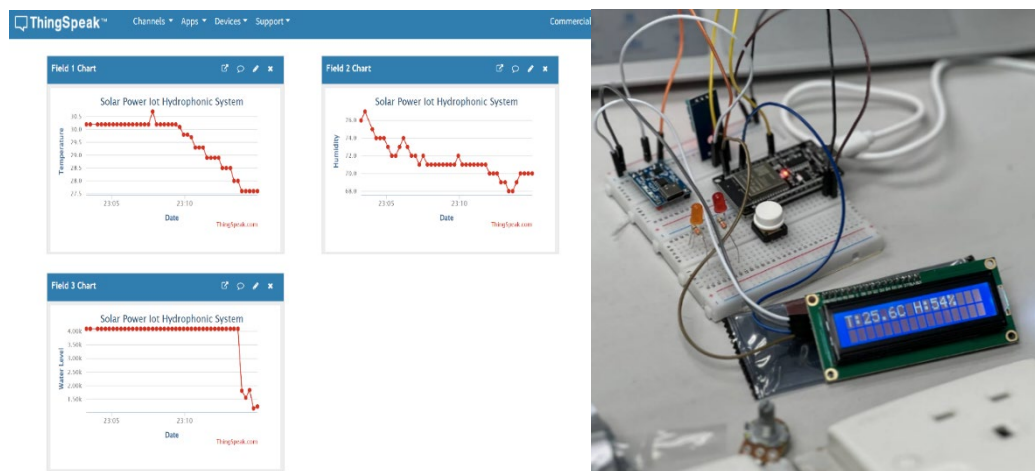


Figure 7: ThingSpeak dashboard displaying live temperature, humidity, and water level readings from participants' ESP32 systems.

Finally, participants successfully integrated renewable energy into their IoT Hydroponic Module by connecting solar panels and charge controllers, enabling sustainable power supply. Facilitators carefully verified these connections and ensured system functionality, emphasizing the real-world relevance of sustainable energy solutions, a key focus in contemporary sustainable agriculture efforts (Maidatsi et al., 2022). This hands-on experience with renewable energy not only deepened students' technical understanding but also heightened their engagement by illustrating the meaningful intersection of STEM competencies and environmental stewardship. Overall, the workshop's structured, practical tasks, combined with continuous facilitator guidance and real-time validation, fostered strong technical skill development. This approach, supported by comprehensive verification methods, ensured that learning outcomes were effectively achieved and reflected best practices in STEM education assessment (Abichandani et al., 2022).

All 20 participants successfully completed each module task, as verified by facilitator checklists. Post-workshop surveys indicated that 90% of students rated their experience as "Excellent" and 10% as "Good." Additionally, 80% reported increased confidence in using IoT platforms. These results are summarized in **Table 4**.

Table 4: Quantitative Summary of Participant Outcomes

Metric	Result
Number of Participants	20
Task Completion Rate	100%
“Excellent” Satisfaction	90%
“Good” Satisfaction	10%
Increased IoT Confidence	80%

5.0 Discussion

The Solar-Powered IoT Hydroponic Module offered students a structured, hands-on journey from basic component integration to the creation of a fully functional, IoT-enabled, solar-powered agricultural system. Through practical activities—such as circuit wiring, sensor calibration, data collection, and cloud-based visualization—students developed a strong understanding of embedded systems and IoT architecture, while directly applying STEM concepts to real-world agricultural challenges.

Facilitators played a crucial role, guiding students and verifying each stage of the process using structured checklists and project rubrics. This direct assessment confirmed that participants consistently demonstrated technical proficiency and effective problem-solving, with system outputs—like sensor data and real-time dashboard updates—validating their competence. Indirect assessments, including participant reflections and Likert-scale surveys, revealed increased enthusiasm for technology, greater confidence in tackling complex tasks, and a deeper appreciation for sustainable innovation.

These results align with recent research showing that iterative, experiential IoT modules enhance student engagement, knowledge retention, and willingness to adopt new technologies when learning is contextualized within relevant fields such as agriculture (Chen et al., 2020; Sánchez et al., 2020; Varela-Aldás et al., 2025). Notably, our dual-mode assessment approach—combining skill verification with attitudinal feedback—ensures a holistic evaluation of both technical and personal growth, as advocated in best practices for STEM-IoT education (Abichandani et al., 2022).

In summary, the IoT Hydroponic Module stands as a replicable and robust framework for introducing IoT concepts within STEM education. Its accessible, hands-on approach and use of open-source components make it adaptable for integration into national TVET curricula and secondary schools across diverse regions (Thiagarajah et al., 2024). By providing scalable training resources, the program supports broader institutional adoption and inspires further STEM initiatives aligned with sustainability goals (Scotini & Abdullah, 2022).

6.0 Conclusion

This study highlights the successful implementation of a carefully designed educational IoT Hydroponic Module that introduces students to the interdisciplinary field of IoT and smart agriculture through a solar-powered hydroponic system. By guiding participants through a series of hands-on activities—from sensor integration and cloud data streaming to solar energy system setup—the program effectively equipped students with critical technical skills while simultaneously fostering problem-solving and analytical thinking.

The assessment strategy employed a balanced combination of direct performance evaluations and reflective feedback tools, providing a comprehensive picture of both students' technical mastery and their attitudinal development. This dual approach aligns with the framework proposed by Abichandani et al. (2022), which underscores the value of triangulating observable competencies with learners' perceptions to fully capture educational impact. Moreover, the findings support those of Varela-Aldás et al. (2025), demonstrating that

contextually relevant IoT training—especially when utilizing accessible platforms like ESP32 and ThingSpeak—can significantly enhance technology acceptance and engagement across diverse learner groups.

Consistent with the work of Thiagarajah et al. (2024) and others, this program exemplifies how IoT-based STEM initiatives can simultaneously build technical expertise and deepen environmental consciousness, particularly when anchored in sustainability goals such as SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Looking ahead, this module offers significant potential for broader institutionalization and replication across national TVET programs and diverse educational settings, serving as a scalable model for fostering SDG-aligned STEM competencies among various age groups. Additionally, longitudinal studies tracking participants' academic and career trajectories would provide valuable insights into the lasting influence of such experiential learning modules. In sum, this paper contributes to the growing body of evidence that structured, hands-on IoT education represents a powerful and impactful approach to preparing students for the challenges and opportunities of 21st-century STEM fields.

Acknowledgements

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