IoT-Based BIPV Smart Home Educational Training Kit Model for Secondary School STEM Education in Malaysia

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ABSTRACT

Integrating hands-on green technology and Internet of Things (IoT) learning models into secondary school education is essential for building STEM competency and environmental literacy in Malaysia. However, traditional classroom instruction often lacks interactive, hands-on training kits that demonstrate real-world concepts in renewable energy and smart automation. This paper presents the development and empirical evaluation of an IoT-based Building-Integrated Photovoltaic (BIPV) Smart Home Educational Training Kit Model specifically engineered for Malaysian secondary schools' Science, Technology, Engineering, and Mathematics (STEM), Technical and Vocational Education and Training (TVET), and "Reka Bentuk dan Teknologi (RBT)" curricula. The kit features a modular 40 W Monocrystalline PET ETFE BIPV module, a Pulse Width Modulation (PWM) solar charge controller, and a safe 12 V 4.5 Ah Sealed Lead Acid (SLA) battery storage unit.

The central processing architecture utilizes an ESP32 microcontroller interfaced with a DS18B20 digital temperature sensor, a capacitive soil moisture sensor, a 4-channel relay module, a 12 VDC exhaust fan, an R385 water pump, and a 20x4 I2C LCD screen. Cloud-based IoT telemetry is integrated via Blynk IoT and ThingSpeak platforms, allowing students to conduct real-time data logging and remote-control experiments. Practical classroom testing showed the BIPV unit reaches a peak output of 22.1 V and 1.05 A under local solar conditions. Students investigated partial shading dynamics and observed that solar panel obstruction beyond 60% severely reduces output to 5.91 V. The automated thermal regulation module triggers cooling at 33°C, dropping indoor room temperature by 4.87°C within 6 minutes. Furthermore, the smart irrigation module demonstrates precision water conservation, delivering 20 mL automated pulses that reduce water usage by over 90% compared to traditional manual watering (356.7 mL average).

Keywords: Educational Training Kit, Smart Home, BIPV, STEM Education, Internet of Things (IoT)

INTRODUCTION

The rapid transformation of global education emphasizes hands-on, problem-based learning in Science, Technology, Engineering, and Mathematics (STEM). In Malaysia, the Ministry of Education (KPM) has placed strategic emphasis on strengthening STEM and Technical and Vocational Education and Training

(TVET) pathways, particularly through upper secondary curricula such as "Reka Bentuk dan Teknologi (RBT)" and Physics (Ministry of Education Malaysia [KPM], 2022; Adedoyin et al., 2020).

However, teaching abstract engineering concepts – such as solar energy conversion, sensor interfacing, and cloud-based Internet of Things (IoT) automation – remains challenging without functional, interactive educational models (Khatun et al., 2021). Standard classroom instruction relies heavily on theoretical textbooks, resulting in a gap between conceptual knowledge and practical technical skills among secondary school students in Malaysia (Rajee & Barman, 2024).

Concurrently, Malaysia's transition toward environmental sustainability highlights the importance of clean energy awareness among the younger generation. Building-Integrated Photovoltaic (BIPV) technology represents a key architectural innovation, converting roof structures and wall facades into active renewable energy generators (Ahmad et al., 2022; International Energy Agency [IEA], 2023).

Under national initiatives such as the Malaysian Building Integrated Solar (MBIPV) Project, supported by research centers including Universiti Teknologi MARA's PV System Monitoring Centre (PSMC), BIPV adoption is projected to grow significantly (Universiti Teknologi MARA [UiTM], 2024; IMARC Group, 2024). Introducing secondary students to BIPV technology through a scaled, safe, and interactive training kit provides an ideal platform to foster green technology literacy and energy conservation habits early in their educational journey (IEA-PVPS, 2023; Rosli & Zainon, 2026).

To address these educational and technical needs, this study presents the development and empirical validation of an IoT-Based BIPV Smart Home Educational Training Kit Model designed specifically for Malaysian secondary school laboratories (Rosli & Zainon, 2026). The kit integrates a safe 12 VDC power generation setup (40 W Monocrystalline PET ETFE BIPV module, PWM charge controller, and SLA battery) with an ESP32 microcontroller driving automated thermal regulation and capacitive soil irrigation modules (Chen & Tan, 2022; Iqbal & Ahmed, 2023). The primary educational and technical objectives of this study are:

- To design and construct a safe, modular, low-voltage (12 VDC) BIPV solar energy training kit suitable for secondary school classroom assembly and laboratory experimentation in Malaysia.
- To implement hands-on learning modules covering sensor calibration, microcontroller programming (ESP32), dual-loop automation logic, and real-time cloud IoT telemetry via Blynk and ThingSpeak.
- To establish practical experimental protocols enabling secondary students to measure BIPV partial shading efficiency, automated thermal ventilation cooling performance, and precision irrigation water conservation.
- To evaluate the pedagogical impact of the training kit in enhancing student engagement, conceptual comprehension, and practical problem-solving in Malaysian STEM/RBT education.

This study directly supports Sustainable Development Goal 4 (SDG 4: Quality Education), Sustainable Development Goal 7 (SDG 7: Affordable and Clean Energy), and Sustainable Development Goal 11 (SDG 11: Sustainable Cities and Communities), advancing experiential learning and sustainability awareness across secondary schools in Malaysia (Adedoyin et al., 2020; Rosli & Zainon, 2026).

METHODOLOGY

The research methodology adopts a hardware-software co-design framework structured for secondary school laboratory deployment in Melaka, Malaysia (Rosli & Zainon, 2026). The training kit is engineered for safety, modularity, and ease of assembly by secondary students under teacher supervision. Figure 1 details the complete hardware architecture and component interconnections of the training kit model.

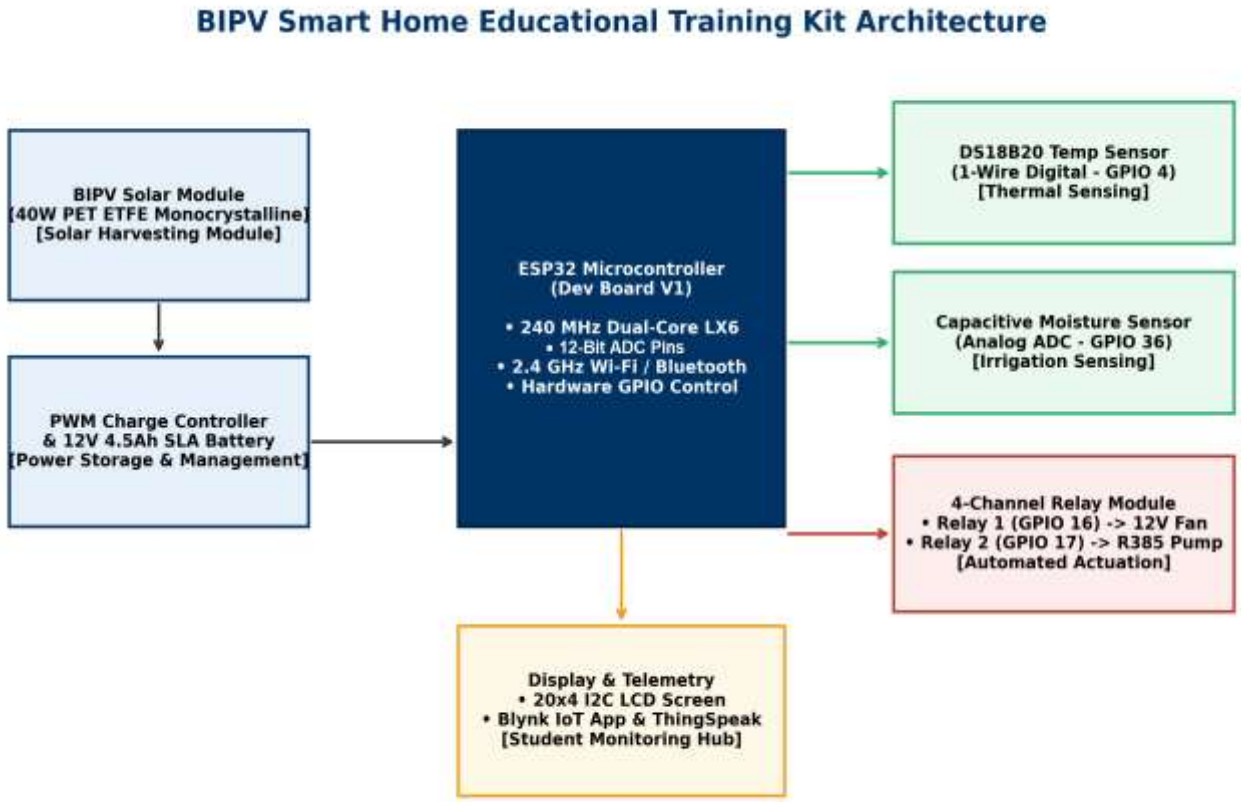


Figure 1: Hardware System Architecture of the BIPV Smart Home Educational Training Kit Model

Hardware Modular Architecture and Component Selection

The hardware architecture is organized into four distinct modular learning zones to facilitate student comprehension:

- Solar Harvesting Module: Features a 40 W Monocrystalline PET ETFE solar panel (SLP020-12U) mounted on an adjustable tilt frame. The panel delivers up to 12 VDC power to a Pulse Width Modulation (PWM) solar charge controller, charging a 12 V 4.5 Ah Sealed Lead Acid (SLA) battery. Low-voltage 12 VDC operation guarantees electrical safety during student handling (Iqbal & Ahmed, 2023; Rosli & Zainon, 2026).

- Central Microcontroller Module: An ESP32 Dev Board V1 containing a dual-core 32-bit LX6 processor (240 MHz) serves as the core processing node. It exposes breadboard-friendly GPIO pins, 12-bit Analog-to-Digital Converters (ADC), and integrated Wi-Fi for IoT cloud communication (Chen & Tan, 2022; Rosli & Zainon, 2026).

- Environmental Sensing Module: Includes a waterproof DS18B20 digital temperature sensor (connected to GPIO 4 via 1-Wire protocol) for room climate monitoring, and a corrosion-resistant capacitive soil moisture sensor (connected to ADC pin GPIO 36) for soil moisture sampling (Musa et al., 2023; Rosli & Zainon, 2026).

- Actuation and Display Module: A 4-channel relay module drives a 12 VDC exhaust fan (GPIO 16) for thermal ventilation and an R385 DC diaphragm water pump (GPIO 17) for precision plant irrigation. Local system telemetry is output on a 20x4 I2C LCD screen (GPIO 21 SDA, GPIO 22 SCL) (Rosli & Zainon, 2026).

Table 1: Hardware Components, Student Pin Assignments, and Educational Specifications

Subsystem Module	Hardware Component Details	Pin / Interface Assignment	Educational Learning Focus
Solar Harvesting Unit	Monocrystalline PET ETFE (SLP020-12U)	40 W, 12 VDC Terminal Output	Solar photovoltaic conversion, tilt angle efficiency.
Power Management	PWM Controller & 12 V 4.5Ah SLA Battery	Battery & Load Terminals	Battery charging cycles, voltage regulation, safety.
Central Microcontroller	ESP32 Dev Board V1 NodeMCU	30-pin Breadboard Header	Embedded C++ coding, GPIO logic, Wi-Fi networking.
Temperature Sensor	DS18B20 Digital Waterproof Probe	1-Wire Digital (GPIO 4)	Digital sensor communication, thermal monitoring.
Soil Moisture Sensor	Capacitive Soil Sensor v1.2	Analog ADC Channel 0 (GPIO 36)	Analog-to-digital conversion, soil calibration.
Actuators & Display	4-Relay Module, 12 V Fan, R385 Pump, LCD	Relay 1 (GPIO 16), Relay 2 (GPIO 17)	Transistor/relay switching, liquid pump control.

Automated Dual-Loop Control Logic and Pedagogical Modules

The control software is structured around two distinct automated feedback loops programmed in C++ using the Arduino IDE environment. Figure 2 presents the dual-loop control flowchart taught during student laboratory sessions:

- Thermal Regulation Feedback Loop: The DS18B20 sensor continuously samples ambient room temperature. When temperature reaches or exceeds 33.0°C, the ESP32 sets GPIO 16 HIGH, energizing Relay 1 to activate the exhaust fan. A 2.0°C hysteresis logic is embedded in the software; the fan continues operating until the room cools to 31.0°C or below, teaching students how hysteresis prevents rapid relay chatter (Hassan et al., 2021; Rosli & Zainon, 2026).

- Smart Irrigation Feedback Loop: The capacitive soil sensor measures analog volumetric moisture, calibrated between 0% (dry air) and 100% (water saturation). When moisture drops below 30.0%, GPIO 17 goes HIGH, triggering Relay 2 to operate the R385 water pump for a 0.5-second pulse (~20 mL volume). Students observe how pulsed actuation prevents over-irrigation (Musa et al., 2023; Rosli & Zainon, 2026).

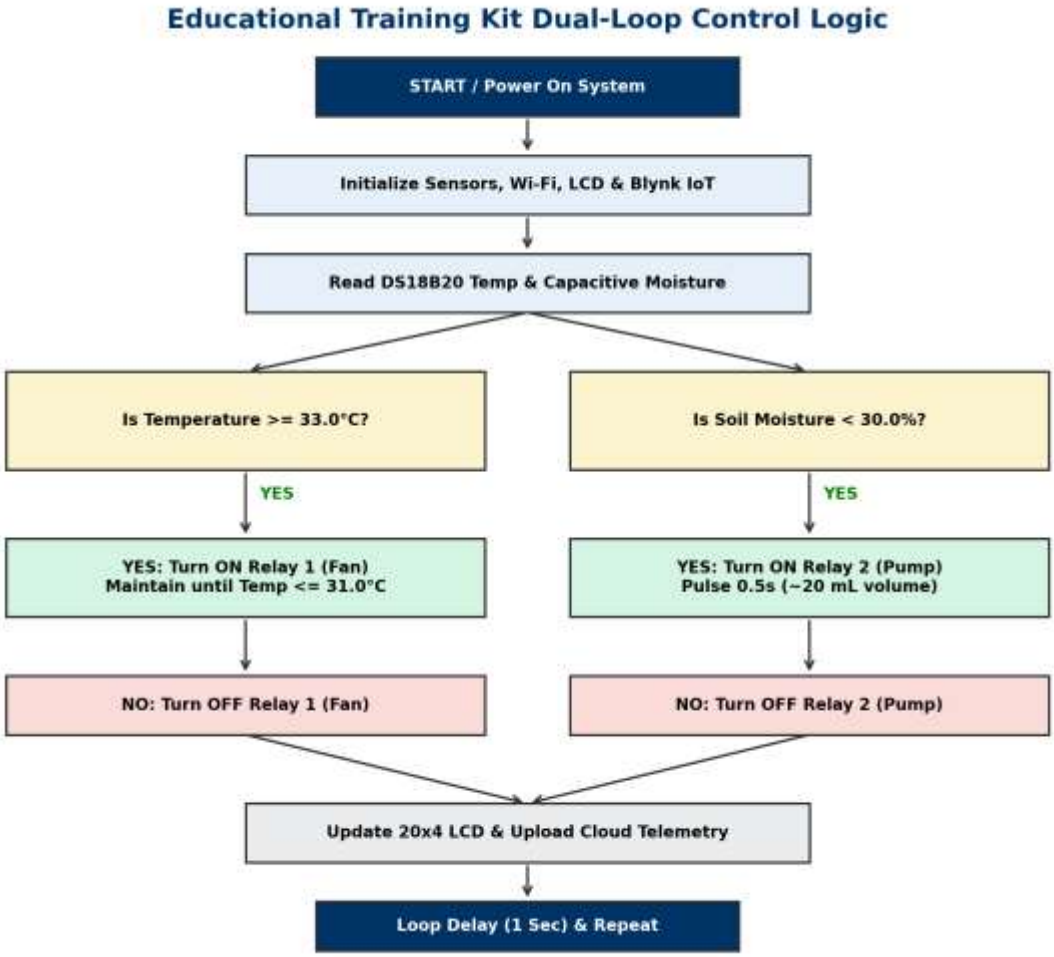


Figure 2: Dual-Loop Automated Control Logic Flowchart Implemented in the Educational Kit

Cloud Telemetry and Student Interface

The ESP32 transmits real-time telemetry via Wi-Fi to Blynk IoT and ThingSpeak cloud servers using MQTT and HTTP protocols (Stolojescu-Crisan et al., 2021; Datar et al., 2023; Rosli & Zainon, 2026). Through the Blynk mobile application, students interact with real-time temperature gauges, soil moisture bars, and a virtual manual override switch that allows toggling between Automatic Control Mode and Manual Override Mode (Khatun et al., 2021; Rosli & Zainon, 2026). ThingSpeak logs multi-channel time-series data at 20-second intervals, providing students with downloadable CSV datasets for mathematical graphing and statistical analysis.

RESULTS AND DISCUSSION

Empirical testing and classroom demonstrations were conducted using the completed educational training kit prototype under outdoor ambient conditions in Melaka, Malaysia. The results are presented as three core classroom experimental demonstrations designed to evaluate system performance and student learning outcomes.

Demonstration 1: Solar BIPV Harvesting and Partial Shading Investigation

Under peak midday solar irradiance in Malaysia (~1000 W/m²), the 40 W Monocrystalline BIPV unit generated a maximum open-circuit voltage of 22.1 V and a peak short-circuit current of 1.05 A, fully recharging the SLA battery within 4.2 hours. To investigate solar efficiency and shading resilience—a critical concept in BIPV architectural design—students conducted a controlled surface partial shading experiment by

progressively obstructing 10% to 100% of the panel surface with opaque material. Table 2 details the recorded panel output voltages, and Figure 3 illustrates the resulting performance curve.

Table 2: Student Experimental Data: Impact of Surface Partial Shading on BIPV Voltage Output

Panel Shading Level (%)	Measured Voltage Output (V)	Observed Battery Charging Status	Educational Learning Insight
10%	19.50 V	Active Charging (>13.5 V)	Minimal voltage drop; effective battery charging maintained.
30%	18.50 V	Active Charging (> 13.5 V)	Stable operational voltage; panel handles minor shading.
50%	17.90 V	Active Charging (> 13.5 V)	Slight voltage reduction; charging controller remains active.
60%	14.90 V	Marginal Charging (~ 13.5 V)	Sharp decline initiated; charging current drops significantly.
80%	8.28 V	Charging Halted (< 13.5 V)	Severe power loss; insufficient potential to charge SLA battery.
100%	5.91 V	Charging Halted (< 13.5 V)	Critical obstruction; panel output drops below functional threshold.

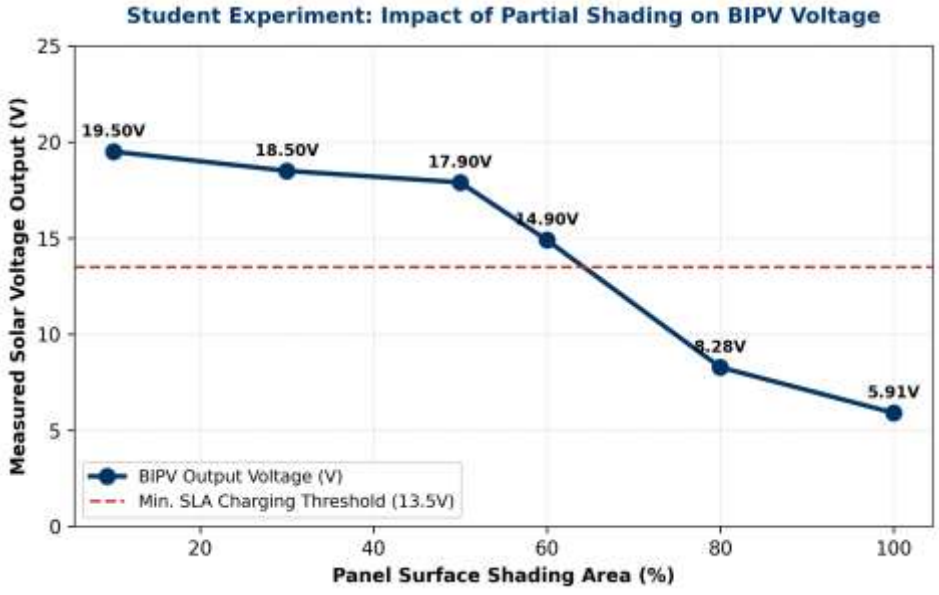


Figure 3: Student Experiment: Impact of Surface Partial Shading on Monocrystalline BIPV Voltage Output

As illustrated in Figure 3, the BIPV panel maintains a robust charging voltage (> 17.9 V) between 10% and 50% partial shading. However, when panel surface obstruction reaches 60%, output voltage drops sharply to 14.9 V and falls further to 8.28 V at 80% shading. Because charging a 12 V SLA battery requires a minimum potential of ~13.5 V, shading beyond 60% completely halts battery charging. This hands-on experiment visually reinforces to students why solar panels must be strategically installed on unshaded building rooftops in Malaysia.

Demonstration 2: Thermal Ventilation Dynamics and Climate Regulation

To evaluate thermal control, the training kit was placed inside a scaled residential house model subjected to ambient heat accumulation. Students observed indoor air temperature rising from 36.19°C to a peak of 41.37°C within 8 minutes when ventilation was unpowered. At Minute 9, as the temperature surpassed the 33.0°C setpoint, the ESP32 automatically energized Relay 1 to power the 12 V exhaust fan. Table 3 records the indoor temperature dynamic response, and Figure 4 plots the cooling curve.

Table 3: Student Experimental Data: Indoor Temperature Dynamic Response Pre- and Post-Smart Fan Activation

Elapsed Time (min)	Exhaust Fan Relay Status	Indoor Air Temperature (°C)	Thermal Environment & System Reaction
0 min (Baseline)	OFF	36.19 °C	Initial ambient room temperature inside the unventilated enclosure.
4 min (Heat Build-up)	OFF	38.13 °C	Rapid solar thermal accumulation occurring.
8 min (Peak Temp)	OFF	41.37 °C	Maximum heat accumulation before automated intervention.
9 min (Fan Activated)	ON	39.81 °C	Temperature exceeds 33.0°C threshold; ESP32 triggers Relay 1.
11 min (Cooling Phase)	ON	36.00 °C	Active forced ventilation rapidly expels trapped heat.
15 min (Cooling Complete)	ON	34.94 °C	Temperature reduced by 4.87°C; stabilizing thermal comfort.

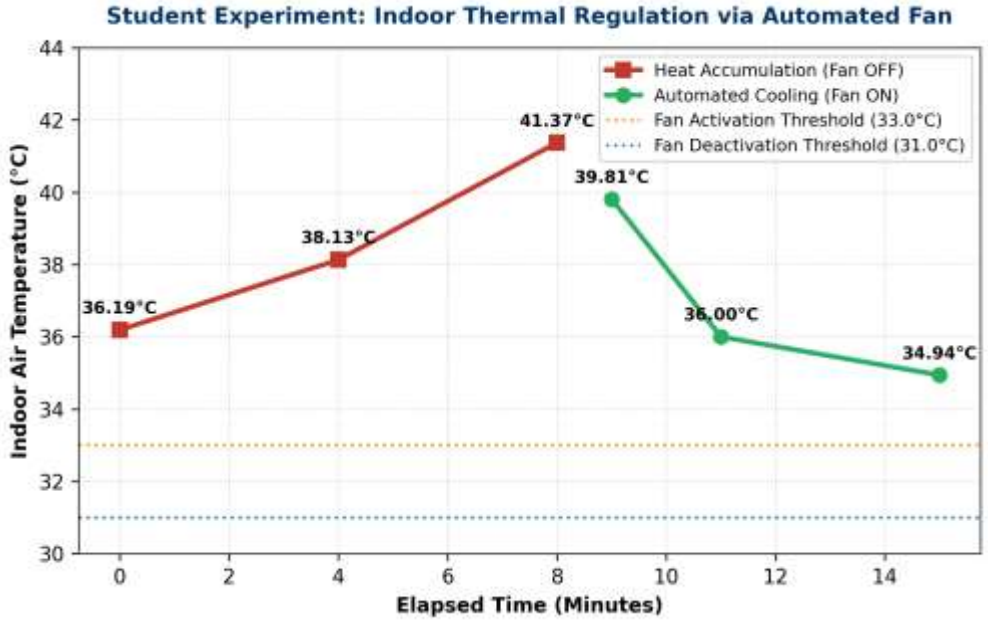


Figure 4: Student Experiment: Indoor Ambient Temperature Dynamic Response Pre- and Post-Smart Fan Activation

Figure 4 clearly demonstrates the cooling curve following automated fan activation. Within 6 minutes of forced ventilation (Minutes 9 to 15), indoor room temperature dropped from 39.81°C to 34.94°C, representing a net temperature reduction of 4.87°C. Students observe how sensor-driven feedback loops regulate indoor microclimates efficiently without requiring continuous manual control or high-power air conditioning.

Demonstration 3: Smart Irrigation and Resource Conservation Benchmark

To evaluate water conservation, the automated capacitive smart irrigation kit was benchmarked against traditional manual watering performed by secondary school students. Three student participants watered identical soil containers based on visual estimation, while the smart system delivered automated 0.5-second water pulses (~20 mL) triggered strictly when soil moisture fell below 30.0%. Table 4 summarizes the applied water volumes, and Figure 5 displays the comparative benchmark.

Table 4: Student Experimental Data: Water Volume Consumption: Manual Irrigation vs. Smart Automated System

Irrigation Method / Participant	Applied Water Volume (mL)	Soil Water Saturation Impact	Resource Efficiency Assessment
Manual - Student Participant 1	350 mL	Over-saturated soil; noticeable bottom drainage.	Excessive manual application.
Manual - Student Participant 2	420 mL	Severe waterlogging; heavy surface runoff.	High water waste via visual estimation.
Manual - Student Participant 3	300 mL	Moderate over-saturation; minor runoff.	Inconsistent manual volume.

Manual Average	356.7 mL	Sustained over-watering baseline.	Baseline manual water consumption.
Smart Irrigation System Kit	20 mL (per activation)	Optimal moisture retention; zero runoff.	>90% water saving achieved.

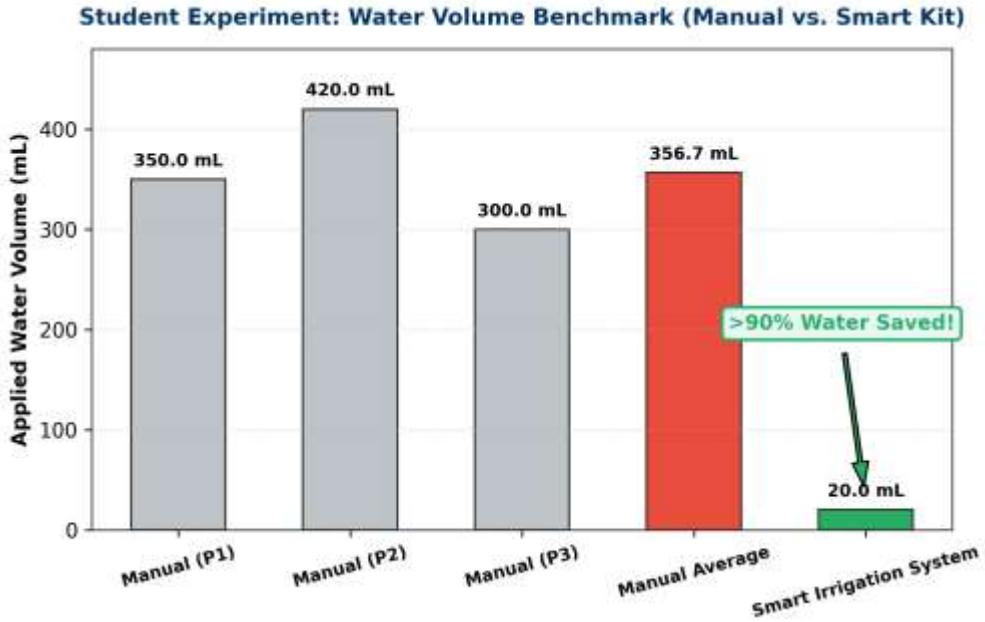


Figure 5: Student Experiment: Water Volume Usage Benchmark: Manual Irrigation vs. Smart Automated System

As highlighted in Figure 5, student participants applied an average of 356.7 mL of water per session using visual judgment, causing soil over-saturation and water runoff. In contrast, the automated capacitive irrigation kit delivered precise 20 mL water pulses strictly when soil moisture fell below 30.0%, achieving over 90% water conservation while preventing runoff. This experiment provides students with a compelling quantitative demonstration of how IoT precision agriculture conserves vital natural resources.

CONCLUSION

This study successfully developed, implemented, and empirically evaluated an IoT-Based BIPV Smart Home Educational Training Kit Model tailored for secondary school STEM and TVET education in Malaysia. The kit effectively combines renewable energy harvesting (40 W BIPV module), embedded microcontroller processing (ESP32), environmental sensing (DS18B20 temperature & capacitive soil moisture), automated relay actuation (12 V exhaust fan & R385 water pump), and cloud IoT telemetry (Blynk & ThingSpeak). Key empirical classroom findings demonstrate that:

- The 12 VDC BIPV power module delivers up to 22.1 V and 1.05 A under Malaysian solar irradiance, offering a safe, functional power generation unit for student handling.
- Partial shading experiments effectively demonstrate solar efficiency thresholds, proving that shading beyond 60% halts battery charging.
- The automated thermal ventilation module triggers cooling at 33.0°C, lowering indoor room temperature by 4.87°C within 6 minutes.
- The smart irrigation module demonstrates >90% water conservation compared to traditional manual watering methods.

For future curriculum implementation, it is recommended to collaborate with the Ministry of Education Malaysia (KPM) to integrate this training kit into the standard "Reka Bentuk dan Teknologi (RBT)" and upper-secondary Physics practical modules nationwide. Future iterations of the kit will incorporate modular Maximum Power Point Tracking (MPPT) charge controllers and air quality gas sensors, further expanding the scope of hands-on STEM education across Malaysia.

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