An IoT-based smart home prototype: Enhancing energy efficiency, water conservation, and sustainability education

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Abstract

The rapid development of the Internet of Things (IoT) has driven the emergence of smart home innovations that not only provide convenience but also contribute to energy efficiency and resource conservation. This study aims to develop an IoT-based smart home prototype using the ESP8266-12e module to control lights and solenoid valves that function as water faucets. The system operates in two modes: automatic mode, utilizing light-dependent resistors (LDRs) and ultrasonic sensors, and manual mode through a web-based control interface. The method in this study uses an experimental method consisting of a literature review, hardware and software design, implementation, and testing. The results show that the system functions reliably and remains stable within a Wi-Fi connection range of up to 21 meters. Furthermore, this prototype shows potential as a project-based learning medium in science and technology education, particularly in the context of sustainability education. By integrating the concepts of electricity and water conservation, this study contributes to increasing scientific literacy while supporting sustainable household practices.

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1. Introduction

The global challenges of energy and water sustainability have intensified with the escalating consumption of natural resources and their associated impacts on climate change (Dixit et al., 2022; Kim et al., 2021). Within this context, residential sectors represent a substantial share in electricity and water usage, thereby necessitating technological solutions that optimize resource consumption (González-Torres et al., 2022). One compelling approach is the deployment of smart home systems leveraging the Internet of Things (IoT) to control home appliances and utilities via internet connectivity (Poyyamozhi et al., 2024; Taiwo et al., 2021).

Smart home technologies not only elevate comfort and security but also influence energy savings and water conservation (Elkholy et al., 2022; Fakhar et al., 2022; Singh et al., 2025; Somefun et al., 2022). For example, ambient light sensors (LDR) can dynamically modulate lighting usage based on natural illumination, while ultrasonic-based solenoid valves can manage water flow to prevent wastage. Such integrated systems are poised to advance progress toward the United Nations' Sustainable Development Goals (SDGs) (Poyyamozhi et al., 2024).

Despite the proliferation of IoT-enabled smart home research, existing studies predominantly emphasize system performance, connectivity, or energy efficiency. Few explicitly explore the dual role of these systems as tools for sustainability education and project-based STEM learning, a gap this research aims to address. In educational settings, integrating IoT into project-based learning (PBL) frameworks has shown promise for enhancing students' scientific literacy and environmental awareness (Balyk et al., 2023; Tsybulsky & Sinai, 2022). Moreover, recent work on IoT applications in education indicates that IoT can transform traditional classroom delivery into more interactive, data-driven learning environments (Arita et al., 2025; Meylani, 2024).

Given this background, this study seeks to design and implement an IoT-based smart home prototype using the ESP8266-12e module. The system is designed to manage lighting and water tap operations both automatically (via sensors) and manually (via web interface). The novelty of this research lies in combining technical design with educational purpose: the prototype not only aims to improve energy efficiency and water conservation but also functions as a pedagogical tool for promoting sustainability literacy in STEM curricula.

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2. Method

The research procedure for developing the IoT-based smart home prototype is illustrated in Figure 1.

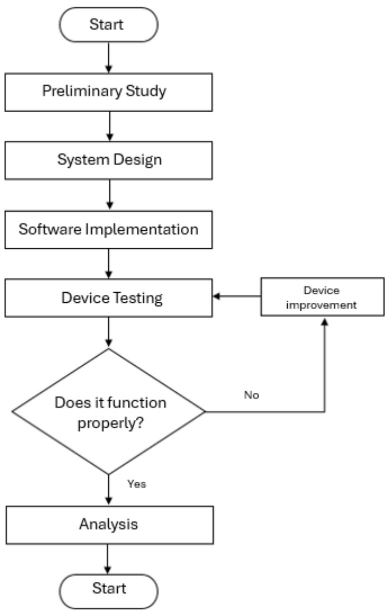


Figure 1. Research procedure flowchart

The initial stage was a preliminary study, conducted through a literature review on smart homes, the Internet of Things (IoT), and their applications in energy efficiency, water conservation, and sustainability education. This was followed by the system design stage, which comprised both hardware and software development. The hardware components included an ATmega 2560 microcontroller, an ESP8266-12e Wi-Fi module, a relay driver, an LDR sensor, an ultrasonic sensor, and actuators in the form of an incandescent lamp and a solenoid valve. For software implementation, the Arduino IDE was used to integrate the sensors, actuators, and communication module, enabling two modes of operation: automatic (sensor-based) and manual (web-based control).

The testing stage is carried out in two phases, namely unit testing and overall system testing. In unit testing, individual components were validated using appropriate instruments. For the LDR sensor, a calibrated lux meter (LX-101A) was employed to measure illumination levels and verify sensor readings. For the ultrasonic sensor, a standardized ruler and repeated distance measurements (10 trials at each distance) were used to validate accuracy, with error tolerance set at ±2 cm. For voltage measurements, a digital multimeter (Sanwa CD800a) was used to verify stable power delivery at 5 V and 3.3 V supply rails. In system testing, performance was evaluated for automatic and manual modes. The indicators included:

a. Accuracy of LDR response compared to lux meter readings (acceptable error ≤ ±5%).

b. Accuracy of ultrasonic readings compared to ruler measurements (acceptable error ≤ ±5%).

c. Wi-Fi connectivity success rate across multiple trials (percentage of successful connections).

d. System response delay (measured from sensor detection to actuator response), with a target of <1 second.

e. System reliability, assessed through repeated on/off cycles (20 repetitions) for lamps and solenoid valves.

f. Each test was repeated at least five times, and mean values and standard deviations were calculated to improve reliability.

Finally, in addition to the technical evaluation, the system was assessed for sustainability and educational aspects. In this regard, the prototype is also designed for integration into project-based learning (PBL) activities for students, enabling them to engage in hardware assembly, Arduino programming, sensor calibration, and experimental evaluation of energy and water efficiency. This pedagogical design allows the prototype to serve not only as a functional household solution but also as an educational medium to enhance STEM competencies and sustainability literacy.

2.1. System Design

2.1.1. System Block Diagram

A system consists of inputs, processes, and outputs that together define its intended functions. These components are represented in a block diagram, which is designed to simplify the understanding of the system's functionality and workflow. The block diagram of the IoT-based smart home prototype is presented in Figure 2.

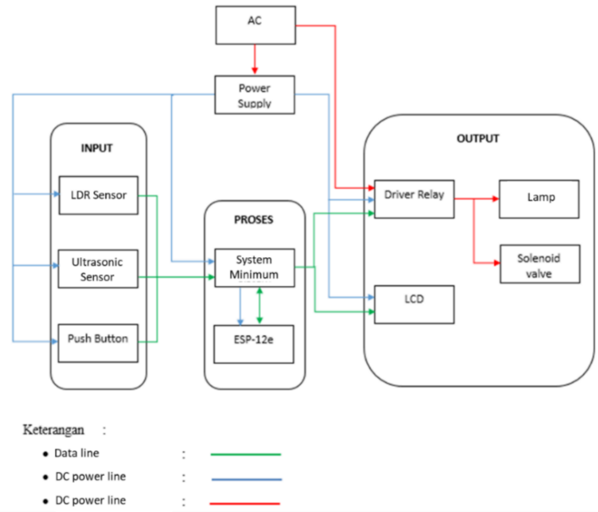


Figure 2. System Block Diagram

This block diagram illustrates the operational flow of the IoT-based smart home system. The system receives power from an AC source, which is converted into DC by the power supply. The input section consists of an LDR sensor to detect light intensity, a water level sensor to monitor water height, and push buttons for manual control. Data from these inputs are transmitted to the processing section, which includes a microcontroller-based minimum system integrated with the ESP-12e module, serving as the main controller and internet communication interface.

The processed signals are then sent to the output section through a relay driver to control lamps and a solenoid valve, while system status information is displayed on an LCD. The diagram also shows the data paths (green lines), DC power lines (blue lines), and AC power lines (red lines), ensuring proper connectivity and energy flow between components.

2.1.2. Software Design

In this IoT-based smart home prototype, two programs were developed: one for the minimum system and another for the ESP module. The programming flowcharts are presented in Figure 3 and Figure 4.

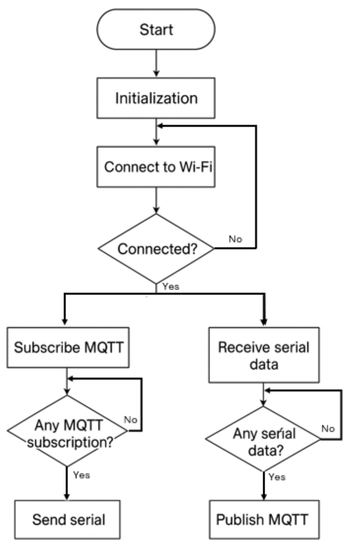


Figure 3. ESP Programming Flowchart

Figure 3 illustrates the communication process between the IoT device and the MQTT server. The system begins with initialization and then attempts to connect to the Wi-Fi network. If the connection fails, the system continues to retry until successful. Once connected, the system executes two main processes. First, it subscribes to the MQTT server, and if a message is received, the data are transmitted via serial communication. This process allows the system to interpret and execute manual control commands.

Second, the system receives data through the serial interface; if data are available, the information is published to the MQTT server. This process represents how sensor readings are captured and transmitted to the server. Through this mechanism, two-way communication is established between the device and the server, enabling real-time data exchange.

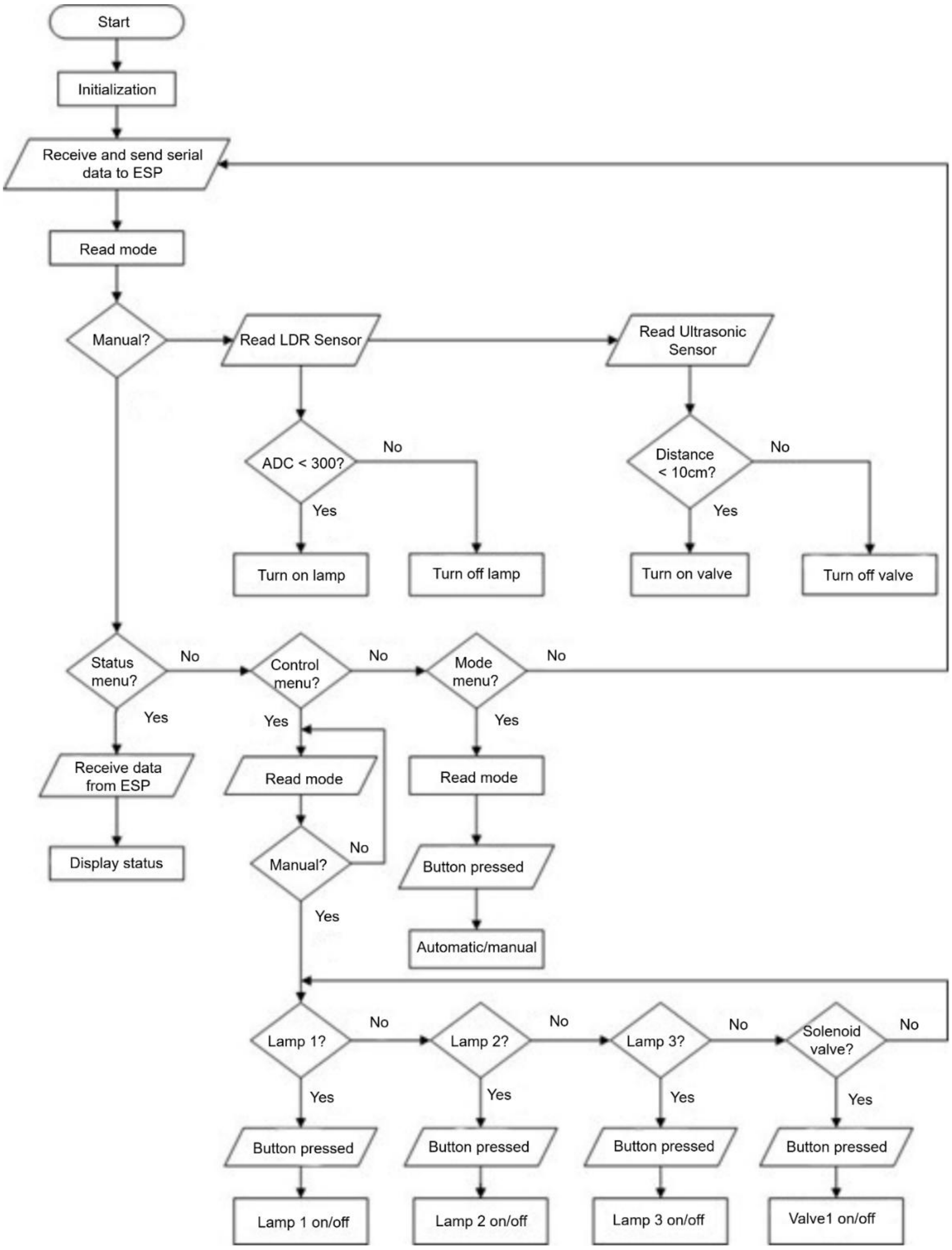


Figure 4. System Programming Flowchart

The flowchart in Figure 4 explains the control mechanism of the IoT-based smart home system, which operates in two main modes: automatic and manual. The process begins with initialization, followed by serial communication between the microcontroller and the ESP module to ensure system synchronization.

In automatic mode, the system performs a decision-making process based on sensor data. The LDR sensor adaptively controls lighting, turning the lamps on when the light intensity is low and off when it is high. The ultrasonic sensor manages the solenoid valve by detecting the water level: if the water distance is below a threshold (10 cm), the solenoid valve closes; otherwise, it opens. This automation supports both energy efficiency and water conservation.

In manual mode, users intervene directly through control or status menus. In the control menu, users can select specific devices (lamp or solenoid valve) and switch them on or off via physical buttons. The status menu provides feedback on the system's condition, transmitted from the ESP module.

Overall, this flowchart illustrates a hybrid system that integrates automatic sensor-based control with manual override via user input. Such a design provides high flexibility, allowing the system to operate autonomously under normal conditions while still granting full user control when necessary. This approach not only supports efficient household automation but also facilitates user-centered control, thereby enhancing comfort and system reliability.

3. Results and Discussion

3.1. Result

3.1.1. System Overview

The IoT-based smart home prototype represents a miniature model of a smart home capable of operating automatically through sensors and being controllable remotely via a web interface. The prototype consists of two rooms, each equipped with one lamp, along with an additional lamp outside the rooms. In addition to lighting control, the system is also designed to manage one solenoid valve functioning as a water tap. The physical appearance of the prototype is shown in Figure 5.

Figure 5. IoT-Based Smart Home Prototype

The system uses a minimum system based on the ATmega 2560 microcontroller and is integrated with a Wi-Fi module for internet connectivity, enabling remote control through a web interface. The specifications of the prototype are as follows:

a. Dimensions: 62 cm × 42 cm × 31 cm

b. Minimum system with ATmega 2560 microcontroller operating at 5 V DC

c. ESP8266-12e Wi-Fi module operating at 3.3 V DC

d. Relay driver operating at 5 V DC

e. Incandescent lamps operating at 220 V AC

f. Solenoid valve operating at 220 V AC

3.1.2. Testing Methodology

The prototype was tested in two phases: component-level testing and overall system performance testing. Each test was repeated 10 times, and mean values with standard deviations were calculated to ensure reliability.

Component Testing

The minimum system was tested at 5 V input and 3.3 V for the ESP module. Results are presented in Table 1.

Table 1. Minimum System Voltage Testing

Trial	Minimum System Voltage	
	5 volt	3,3 volt
1	5.10	3.30
2	4.98	3.28
3	5.00	3.25
4	5.19	3.27
5	5.08	3.29
6	5.05	3.26
7	5.11	3.30
8	4.99	3.27
9	5.12	3.28
10	5.06	3.29
Mean ± SD	5.07 ± 0.06	3.28 ± 0.02

The results indicate that both 5 V and 3.3 V supplies were stable, with deviation <1.2%. This confirms that the minimum system operates within acceptable tolerance ranges. The ESP8266 module was tested for Wi-Fi connectivity up to 22 meters. Results are shown in Table 2.

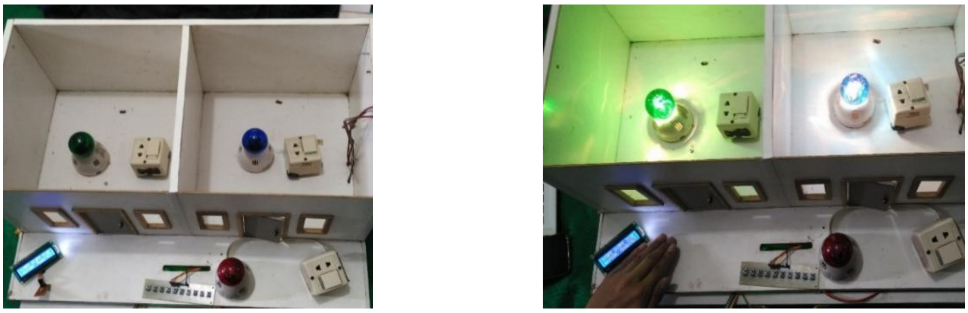
Table 2. ESP Module Connectivity Test

Distance (m)	Success Rate (%)	Avg. Response Delay (s)
2	100	0.45 ± 0.05
10	100	0.52 ± 0.07
16	90	0.61 ± 0.08
20	80	0.75 ± 0.12
22	0	–

Connectivity was highly reliable up to 16 m, slightly decreased at 20 m (80%), and dropped completely at 22 m. Average communication delay remained <0.8 s, suitable for real-time control.

System Testing

After the testing results of each part of the system showed good performance, the next step was to test the system as a whole, both in automatic and manual modes. The automatic system testing was carried out on the lighting system as well as the water filling system by testing the sensors used. In the automatic lighting system, the LDR sensor was tested under conditions where it was uncovered and covered, so that it did not receive light. This was intended as a simulation of day and night. The testing of the automatic lighting system can be seen in Figure 6 and Table 3.



(a) (b)

Figure 6. Automatic Lamp Control Testing (a) Sensor Exposed to Light (b) Sensor Covered

The LDR sensor consistently detected illumination changes with high accuracy. Lamps turned ON when lux <25 and OFF when lux >100, with a response delay <0.6 s. This mechanism can reduce lighting usage by an estimated 20–30% daily, depending on natural lighting availability.

Table 3. LDR Automatic Control Test

Condition	Lux (mean ± SD)	Lamp Status	Response Delay (s)	Accuracy (%)
Exposed	128 ± 4	OFF	0.48 ± 0.06	100
Covered	21 ± 2	ON	0.55 ± 0.07	100

The subsequent test was conducted on the automatic water tap controlled by an ultrasonic sensor. The sensor was positioned above the water reservoir to measure the distance between the sensor and the water surface. When the sensor detected a distance greater than 10 cm, the tap was activated, whereas when the detected distance was less than 10 cm, the tap was automatically deactivated, as presented in the Table 4.

Table 4. Ultrasonic Automatic Control Test

Reference Distance (cm)	Sensor Reading (mean ± SD)	Error (%)	Valve Status	Response Delay (s)	Accuracy (%)
50	49.5 ± 0.7	-1.0	ON	0.62 ± 0.08	100
20	20.2 ± 0.5	+1.0	ON	0.58 ± 0.07	100
11	11.1 ± 0.4	+0.9	ON	0.60 ± 0.05	100
10	10.0 ± 0.3	0.0	OFF	0.65 ± 0.06	100

Ultrasonic readings were accurate within ±1% error. The valve consistently opened when water level was low (>10 cm) and closed at ≤10 cm.

In addition to the automatic system testing, tests were also carried out on the manual system. Tests were conducted by controlling lamps and taps via a web interface, with system feedback displayed on the LCD. As shown in Figure 7 and Figure 8, the manual testing demonstrated that the system was able to function properly.

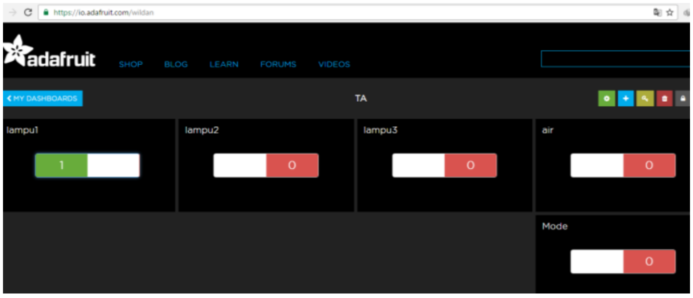


Figure 7. Website display when Lamp 1 is turned on

(a) (b)

Figure 8. Prototype condition (a) and LCD display (b) when Lamp 1 is turned on through the website

The water tap in the manual system was also tested by activating the tap through the website, as shown in Figure 9 and Figure 10.

Figure 9. Website display when the water tap is activated.

Figure 10. System LCD display when the tap is activated.

The manual mode testing demonstrated that all devices (three lamps and one solenoid valve) were able to respond to ON/OFF commands via the web interface with a 100% success rate across 10 trials each (Table 5). The average response delay was 0.61 seconds ± 0.11 seconds, consistent with the 20-trial test, though the slightly higher standard deviation reflects greater variability due to fewer repetitions. Lamps exhibited faster response times (0.59–0.62 s), while the solenoid valve had a marginally longer delay (0.65 s), attributable to its mechanical actuation. Overall, the results confirm the robustness of the manual control system, even with reduced testing repetitions.

Table 5. Manual Mode Testing Results (n=10 per device)

Device Controlled	Command Type	Number of Trials	Success Rate (%)	Average Response Delay (s)
Lamp 1	ON / OFF	10	100	0.59 ± 0.10
Lamp 2	ON / OFF	10	100	0.62 ± 0.11
Lamp 3	ON / OFF	10	100	0.60 ± 0.09
Solenoid Valve	ON / OFF	10	100	0.65 ± 0.12
Overall	–	40 (total)	100	0.61 ± 0.11

3.2. Discussion

Based on the experimental results, four principal aspects are discussed: (1) technical reliability and connectivity, (2) energy efficiency, (3) water conservation, and (4) educational and sustainability-literacy implications.

3.2.1. Technical Reliability and Connectivity

The ESP8266 module in this study maintained stable Wi-Fi connectivity up to approximately 20 meters, with disconnection observed at 22 meters. Such behavior is consistent with broader literature showing that wireless link quality in smart-home deployments is strongly influenced by physical obstacles, radio interference, antenna design, and network configuration; these factors can produce variable effective ranges and latency that directly affect real-time automation functions (Poyyamozhi et al., 2024; Zhong & Nie 2024). For practical deployments, these constraints imply that network planning is necessary to ensure reliable automatic control and mitigate the risk of missed actuations due to transient connectivity loss (Poyyamozhi et al., 2024; Ntafalias et al., 2024).

The reliability of this connection is crucial for the functioning of the automatic mode, as delays or connection failures may cause the lamp or valve to fail to respond in a timely manner, thereby reducing the potential for energy or water savings.

3.2.2. Efficiency Energi

The LDR-based lighting control implemented in the prototype illustrates a low-complexity approach to reducing unnecessary lighting usage. Empirical studies and systematic reviews indicate that sensor-driven automation (occupancy sensing, daylight harvesting, scheduling) and IoT-enabled control can deliver measurable electricity savings in residential and building contexts, with reported reductions ranging from single-digit percentages up to substantially higher gains when combined with analytics and user feedback loops (Kanso et al., 2024; Rao et al., 2025; Chiradeja et al., 2023). Importantly, the realized savings depend on deployment scale, end-user behavior, and whether the system includes active feedback/recommendation features that encourage energy-conserving habits (El Mezouari, 2022; Ntafalias et al., 2024). Hence, while the prototype demonstrates technical feasibility for lighting energy reduction, wider field trials with metered consumption and behavioral interventions are recommended to quantify actual energy savings.

3.2.3. Water Conservation

The ultrasonic sensor and solenoid valve arrangement successfully automated stop/start of water flow based on detected level thresholds. This mechanism reflects practices used in smart water and irrigation systems, where automated valve control, leak detection, and level monitoring reduce overflow and unnecessary run-time (Singh et al., 2025; Mujoo et al., 2021). Literature on smart water applications reports substantial percentage reductions in wastage when control is automated and complemented by monitoring/alerts though magnitudes vary widely by context (domestic vs. agricultural) and by how comprehensively the system monitors flows (sensor density, presence of flow meters) (Obaideen et al., 2022; Nsoh et al., 2024; Pagano et al., 2025). For household application, integrating flow metering and usage dashboards would enable precise estimation of water savings and support learning-oriented visualizations for educational use.

3.2.4. Comparison with related studies.

The prototype aligns with reported trends where IoT platforms yield operational efficiency gains in building systems and domestic contexts (Poyyamozhi et al., 2024; Ntafalias et al., 2024). Studies that combine monitoring, automated control, and user recommendations show higher savings than automation alone, highlighting the value of hybrid approaches that couple control with information and nudges (Rao et al., 2025; Machorro-Cano et al., 2023). Thus, the prototype's hybrid design (automatic, manual override. web feedback) is consistent with best practices in the literature and positions it well for augmentation with analytics and UX features to maximize resource savings.

3.2.5. Educational and Sustainability Literacy Aspects

Beyond technical performance, the prototype's role as a hands-on, project-based learning (PBL) tool is strongly supported by recent education research. IoT-based PBL interventions consistently report improvements in students' science process skills, systems thinking, and sustainability awareness (Balyk et al., 2023; Meylani, 2024). Instructors using IoT prototypes for experiential activities also observe increased engagement and better contextual understanding of resource management issues (Arita et al., 2025; Tsybulsky & Sinai, 2022). Consequently, the prototype can be framed not only as a resource-saving device but also as an educational artefact that supports inquiry, data literacy, and sustainability competences.

4. Conclusion

This study successfully designed and developed an IoT-based smart home prototype using the ESP8266-12e module and the ATmega 2560 microcontroller, capable of controlling lamps and a water tap both automatically and manually through the internet. The system demonstrated reliable performance, with stable operation and effective Wi-Fi connectivity up to 20 meters. In addition, the use of an LDR sensor for lamp control and an ultrasonic sensor for water tap management highlights the potential of the system to enhance household energy efficiency and water conservation. Beyond technical achievements, the prototype has significant value as a project-based STEM learning medium. By engaging students in hardware assembly, coding, and experimental evaluation, the system provides opportunities to develop scientific literacy, problem-solving skills, and sustainability awareness in practical educational contexts.

Limitations. This study was conducted on a small-scale prototype with limited devices and basic sensors, and Wi-Fi connectivity was tested only in controlled conditions. The system has not yet been validated under real household environments or with larger loads, which may affect scalability and performance. Future Work. Future research will focus on integrating artificial intelligence for adaptive decision-making, incorporating real-time energy and water consumption monitoring, and expanding connectivity with IoT platforms. Further trials will also be conducted in educational settings, such as schools and polytechnics, to assess the effectiveness of the prototype as a project-based learning tool for sustainability education.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

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

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