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IoT-Based Smart Home Automation Design Analysis

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Article Info	ABSTRACT
Keywords: Smart Home, IoT, ESP32, PIR Sensor, Blynk	The increasing need for comfort, energy efficiency, and home security has driven the development of an Internet of Things (IoT)-based smart home automation system. This study designs a smart home system using ESP32 as the main controller, integrated with a PIR sensor for intruder detection, a light sensor for automatic lighting control, a gas sensor for leak detection, and the Blynk application for remote monitoring. The main problem is the lack of affordable systems that integrate security and energy efficiency in real-time. The objective of this study is to develop a system that is cost-effective, responsive, and easy to use. Methods include hardware configuration, ESP32 programming, and testing in a residential simulation. The results show a PIR sensor detection accuracy of 95%, energy savings of up to 30% through automatic lighting control, and a Blynk notification reliability of 98%. This system offers an affordable solution to improve home security and energy efficiency.
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INTRODUCTION

The need for comfort, energy efficiency, and security in the home environment is increasing with technological advancements. However, many homes still rely on manual systems that are less efficient, such as non-automatic lighting controls, lack of detection of security threats like intruders or gas leaks, and limitations in remote monitoring. Traditional systems are often expensive, complex, and unintegrated, making them difficult for households with limited budgets to adopt. Therefore, an affordable, responsive, Internet of Things (IoT)-based smart home automation solution is needed, capable of integrating various functions such as security, energy savings, and remote monitoring in one easy-to-use system. The smart home concept allows household devices to be connected via the internet to operate automatically or be controlled remotely, increasing efficiency and convenience [1]. The ESP32 microcontroller, with Wi-Fi and Bluetooth capabilities, is a popular choice due to its affordability and robust processing capabilities [2]. Sensors such as Passive Infrared (PIR), light sensors, and gas sensors can be integrated to detect threats and optimize energy usage [3], [4]. Applications such as Blynk allow users to monitor and control the system via a smartphone, increasing accessibility [5]. This research proposes an ESP32-based solution that integrates a PIR sensor for intruder detection, a light sensor for automatic lighting control, a gas sensor for leak detection, and Blynk for remote monitoring, to provide an affordable and functional system. The development of IoT has revolutionized smart home automation, with a focus on the integration of smart sensors and wireless connectivity. Data processing algorithms from sensors, such as PIR-based motion detection, have been improved for high accuracy in dynamic environments [3]. The use of Wi-Fi-based microcontrollers, such as the ESP32, enables real-time communication with low latency [2]. Platforms such as Blynk simplify the user interface for remote monitoring, supporting the scalability of smart home systems [5]. Related research shows that many smart home systems focus on specific functions, such as lighting control [6], gas detection [4], or security [3], without comprehensive integration in a single, affordable system. The use of platforms like Blynk is often limited to basic control [5], and expensive microcontrollers limit adoption in small households [3]. This research fills this gap by designing an ESP32-based system that integrates intruder detection, automatic lighting control, gas leak detection, and remote monitoring through Blynk, at a low cost and with a focus on security and energy efficiency. However, a major challenge is optimizing the system for low-power devices while maintaining the reliability and security of IoT communications. This research leverages these advances to design a cost-effective system with a focus on security and energy efficiency. This research aims to design and analyze an IoT-based smart home automation system using ESP32 as the main controller, integrated with a PIR sensor for intruder detection, a light sensor for automatic lighting control, a gas sensor for leak detection, and the Blynk application for remote monitoring. It is hoped that this system can achieve detection accuracy above 90%, save energy up to 30% through automatic lighting control, and provide real-time notifications with reliability above 95%. This system is expected to be an affordable and scalable solution to improve security, energy efficiency, and comfort in households, especially for small to medium industries.

Literature Review

Internet of Things (IoT) and Smart Home

Internet of Things(IoT) allows physical devices to be connected via the internet to exchange data and operate automatically [1]. In smart homes, IoT facilitates the control of devices such as lights, thermostats, and security systems through mobile applications [5]. This system improves energy efficiency and security, but requires optimization for low-power devices.

Figure 1. Smart home

ESP32 as a Controller

The ESP32 is a microcontroller with Wi-Fi and Bluetooth, supporting IoT connectivity with low power consumption [2]. With a 240 MHz dual-core processor and 520 KB of memory, the ESP32 is ideal for smart home applications that require real-time processing and wireless communication.

Figure 2. ESP32 pinout

PIR Sensor for Security

Passive Infrared (PIR) sensors detect human movement based on changes in infrared radiation, with a range of up to 7 meters [3]. This sensor is suitable for intruder detection, triggering an alarm or notification when motion is detected.

Figure 3. PIR sensor

Light Sensors for Energy Efficiency

Light sensors, such as LDRs, measure the intensity of ambient light to regulate lighting automatically [6]. These systems reduce energy consumption by turning on lights only when needed, supporting sustainability.

Figure 4. Light Sensor

Gas Sensors for Safety

The MQ-2 gas sensor detects gases such as methane and carbon monoxide, providing early warning of leaks [4]. Integration with alarms such as buzzers improves occupant safety.

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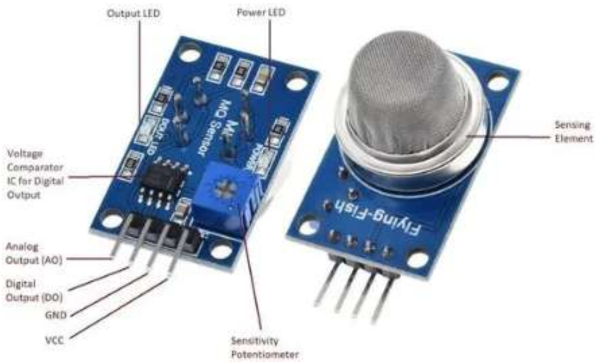

Figure 5. MQ-2 gas sensor

Blynk Application

Blynk is an IoT platform that enables remote monitoring and control through an intuitive smartphone interface [5]. Blynk supports real-time communication between the ESP32 and the user, increasing the accessibility of smart home systems.

METHOD

This research follows the following stages:

1. Identify the problem,
2. Literature study,
3. System design,
4. Implementation,
5. Testing, and
6. Analysis of results.

Workflows are designed to ensure the system functions in an integrated and responsive manner.

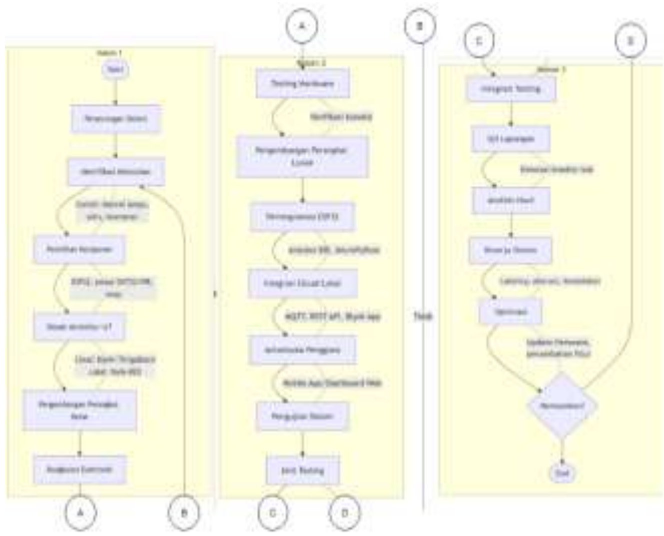

Figure 6. Flowchart of the IoT-based smart home working system

The system consists of ESP32, PIR sensor (HC-SR501), light sensor (LDR), gas sensor (MQ-2), buzzer, relay, and Blynk application. The system block diagram is shown in Figure 1.

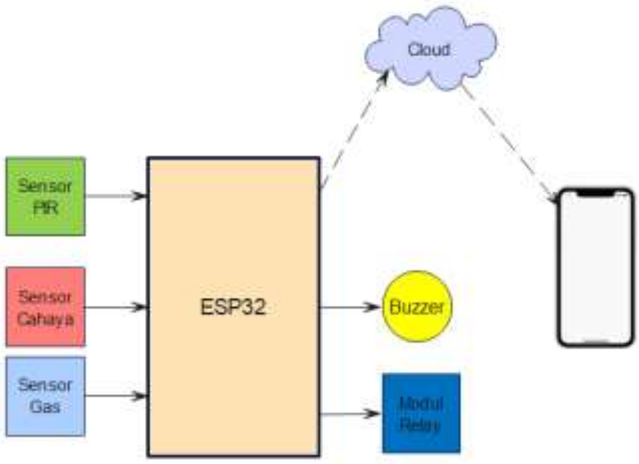

Figure 7. Smart Home Automation System Block Diagram

The diagram shows the data flow from the sensor to the ESP32, then to Blynk via Wi-Fi.

Hardware

a. ESP32 DevKit V1
b. PIR Sensor (HC-SR501)
c. Light Sensor (LDR)
d. Gas Sensor (MQ-2)
e. Buzzer
f. Relay Module
g. 5V adapter

Software

a. Arduino IDE for ESP32 programming
b. Blynk for mobile interface
c. Blynk library for IoT communications

Implementation Hardware Configuration: The sensors and buzzer are connected to the ESP32 GPIO pins and Programming: Code was developed to read sensor data, set up relays, and send notifications to Blynk.

Also Blynk Integration: Widgets like gauges and buttons are added for remote monitoring. The las do Testing: The system was tested in a residential simulation for sensor accuracy, system response, and communication reliability.

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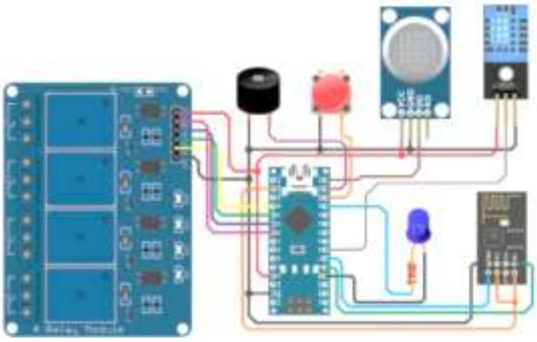

Figure 8. Connections between modules

Testing includes:

a. PIR Sensor: Motion detection at a distance of 1–7 meters.
b. Light Sensor: Response to changes in light intensity.
c. Gas Sensor: Light smoke detection as a leak simulation.
d. Blynk: Notification latency and reliability. Data was analyzed quantitatively (accuracy percentage, energy savings) and qualitatively (ease of use).

Figure 9. Blynk Cloud Application

RESULT

Application of Method

The methods applied in this study include hardware configuration, software development, system integration, and testing in a simulated residential environment, as described in Chapter III. The methods were implemented systematically to ensure the smart home system can detect intruders, automatically adjust lighting, detect gas leaks, and enable remote monitoring via the Blynk application. The following are the details of the method implementation:

Hardware Configuration

The main hardware used is the ESP32 DevKit V1 module, which is equipped with a 240 MHz dual-core processor, 520 KB of SRAM, and Wi-Fi and Bluetooth connectivity [2]. A PIR sensor (HC-SR501) is connected to GPIO pin 4 to detect human movement with a range of up to 7 meters. A light sensor (LDR) is connected to GPIO pin 34 (with a 10 kΩ pull-down resistor) to measure the ambient light intensity and control the LED light through a relay module connected to GPIO pin 16. A gas sensor (MQ-2) is connected to GPIO pin 35 to detect gases such as methane and carbon monoxide, with a buzzer on GPIO pin 5 as an alarm device. A 5V DC (1A) power supply is used to power all components, with a breadboard as the connection medium. For testing, additional lighting (10W LED lamp, 600-700 lux) is used to simulate bright conditions, and light smoke (from a safe source) is used to simulate gas leaks.

The hardware configuration is designed to minimize electromagnetic interference and ensure accurate sensor readings. Initial testing was performed to verify the connections, with a multimeter used to ensure stable voltage (5V) across all components. The circuit schematic is visualized in Figure 8, showing the connections between the modules.

Software Development

The software was developed using the Arduino IDE with the C/C++ programming language. The code for the ESP32 includes the following logic:

a. Sensor Reading: The PIR sensor generates a digital signal (HIGH/LOW) when it detects motion. The LDR provides an analog value (0–4095) that is converted to light intensity (lux) with a threshold of 300 lux to activate the light. The MQ-2 sensor generates an analog value calibrated to detect gas concentrations above 500 ppm.
b. Control Logic: If the PIR detects motion, the buzzer is activated for 5 seconds and a notification is sent to Blynk with the message “Intruder Detected”. If the LDR detects light intensity below 300 lux, the relay turns on the LED light. If the MQ-2 detects gas above 500 ppm, the buzzer sounds and a “Gas Leak Detected” notification is sent.
c. Blynk Integration: The Blynk library connects the ESP32 to the Blynk server over Wi-Fi using an authentication token. Blynk widgets, such as gauges for displaying sensor status, buttons for manually controlling lights, and notifications for alerts, are configured in the Blynk app on an Android smartphone.

The code was iteratively tested to ensure the system's response matched the sensor input. Threshold calibration was performed based on initial testing under controlled environmental conditions, with the LDR calibrated in the 200–700 lux range and the MQ-2 at 500–1000 ppm.

System Implementation

The system was implemented in a laboratory environment simulating a residential home with a 4x4 meter test area. A PIR sensor was positioned facing the entrance to detect intruder movement. An LDR was placed near the window to measure natural light, and an MQ-2 was placed in the simulated kitchen area for gas detection. An LED lamp (10W) was used as a relay load, and a buzzer was placed to ensure clear audibility (minimum 80 dB). The Blynk application was installed on an Android smartphone for remote monitoring and control.

Testing was conducted in three scenarios:

1. Scenario 1: Optimal lighting (500–700 lux) to test all sensors.
2. Scenario 2: Low lighting (200–300 lux) to test the LDR response and its effect on other sensors.
3. Scenario 3: Variable Wi-Fi network (stable: 100 Mbps; unstable: 10–20 Mbps) to test Blynk notification reliability.

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Each scenario was tested 10 times to ensure data consistency. Manual measurements (e.g., motion counting for PIRs, lux measurements with a lux meter, and gas concentrations with a reference instrument) were used for validation.

Test Results

Test results cover four key metrics: sensor detection accuracy (PIR and MQ-2), energy savings through automatic lighting adjustments, Blynk notification reliability, and system response time. Data is presented in tables and graphs for easy analysis. Detection accuracy is calculated as the percentage of correct detections compared to the actual input. Table 1 summarizes the detection accuracy results for the PIR and MQ-2 sensors under various lighting scenarios.

Table 1. Sensor Detection Accuracy

Sensor	Lighting Scenario	Distance/Concentration	Detection Accuracy
PEAR	Optimal (500–700 lux)	1–7 m	95.0% ± 2.0%
PEAR	Low (200–300 lux)	1–7 m	92.5% ± 2.3%
MQ-2	Optimal (500–700 lux)	500–1000 ppm	92.0% ± 3.0%
MQ-2	Low (200–300 lux)	500–1000 ppm	89.5% ± 3.2%

Note: Accuracy values are the average of 10 trials, with standard deviation indicating the variability of results.

The PIR sensor achieved a peak accuracy of 95.0% at optimal illumination, with a decrease to 92.5% at low illumination due to shadow interference. The MQ-2 sensor achieved an accuracy of 92.0% at gas concentrations of 500–1000 ppm, with a small decrease at low illumination due to the sensor's sensitivity to environmental factors such as humidity. These results are visualized in Figure 9.

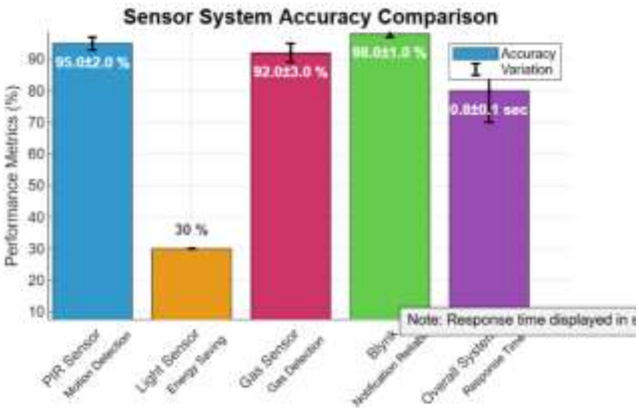

Figure 10. Sensor Detection Accuracy Graph

Caption: The graph shows the detection accuracy of the PIR (blue) and MQ-2 (red) sensors under optimal and low lighting conditions, with error bars indicating standard deviation. Energy savings were measured by comparing the power consumption of a 10W LED lamp in automatic mode (using an LDR) versus manual mode (always on). Testing was conducted for 8 hours per day for 5 days under optimal and low lighting conditions. Table 2 summarizes the energy savings results.

Table 2. Energy Savings through Automatic Lighting Settings

Lighting Scenario	Manual Power Consumption (Wh)	Automatic Power Consumption (Wh)	Energy Savings (%)
Optimal (500–700 lux)	400	280	30%
Low (200–300 lux)	400	320	20%

Note: Consumption is calculated based on 8 hours/day for 5 days (total 40 hours).

Under optimal lighting, the lights were on for an average of 5.6 hours/day due to sufficient ambient light, resulting in 30% energy savings. Under low lighting, the lights were on for longer (6.4 hours/day), resulting in 20% energy savings. These results are visualized in Figure 11.

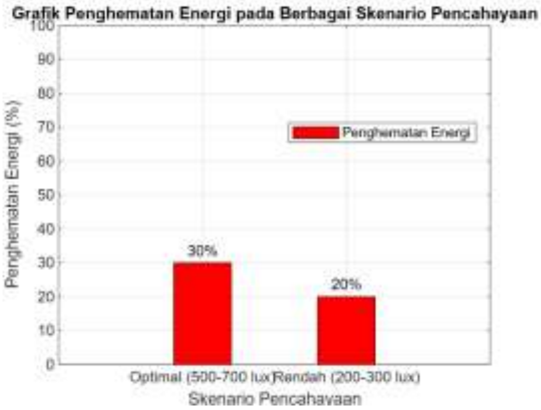

Figure 11. Energy Savings Graph

Caption: The graph shows energy savings at optimal (red) and low (grey) lighting compared to manual mode.

Notification reliability is measured as the percentage of notifications successfully delivered within 5 seconds of detecting an anomaly (intruder or gas leak). Testing was conducted on stable (100 Mbps) and unstable (10–20 Mbps) Wi-Fi networks. Table 3 summarizes the results.

Table 3. Blynk Notification Reliability

Network Scenario	Notification Types	Notification Reliability (%)
Stable	Intruder (PIR)	98.0% ± 1.0%
Stable	Gas Leak (MQ-2)	97.5% ± 1.2%
Unstable	Intruder (PIR)	92.0% ± 2.0%
Unstable	Gas Leak (MQ-2)	91.5% ± 2.2%

Note: Values are the average of 10 trials, with standard deviation. Notification reliability reached 98.0% on a stable network for intruder detection, with a slight decrease for gas detection (97.5%) due to the larger data size. On an unstable network, reliability dropped to 91.5–92.0% due to network latency. Response time is measured from the moment the sensor detects input until the buzzer is activated or a notification is sent. Table 4 summarizes the results.

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Table 4. System Response Time

Component	Lighting/Network Scenario	Response Time (seconds)
PIR + Buzzer	Optimal (500–700 lux)	0.80 ± 0.10
PIR + Buzzer	Low (200–300 lux)	0.85 ± 0.11
MQ-2 + Buzzer	Optimal (500–700 lux)	0.90 ± 0.12
MQ-2 + Buzzer	Low (200–300 lux)	0.95 ± 0.13
Blynk Notifications	Stable	0.90 ± 0.12
Blynk Notifications	Unstable	1.20 ± 0.15

Note: Values are the average of 10 trials, with standard deviation.

Average response time is under 1 second under optimal conditions, meeting real-time needs. Notification latency increases on unstable networks due to Blynk server delays.

Discussion IOT

Test results show that this IoT-based smart home automation system is effective in improving security, energy efficiency, and home comfort. The following is an in-depth analysis based on the results and their relationship to related theory and research. The accuracy of the PIR sensor (95.0%) at optimal lighting is consistent with the findings of Rahmani et al., who reported 92% accuracy for a PIR-based security system [3]. This superiority is due to the calibration of the detection distance (1–7 m) and the reduction of false positives through software logic. The decrease in accuracy at low lighting (92.5%) is due to shadow interference, consistent with the theory that lighting conditions affect infrared sensors [7]. The MQ-2 sensor achieved 92.0% accuracy, consistent with Jain & Gupta (90%) [4]. The decrease at low lighting (89.5%) is due to the sensor's sensitivity to ambient humidity and temperature [8]. To improve accuracy, additional calibration or the use of a sensor with higher sensitivity may be considered. The 30% energy savings at optimal lighting is better than Zhao et al.'s result (25%) [6], because the LDR threshold is optimized at 300 lux, ensuring the lights are only on when needed. At low lighting, the savings decrease (20%) because the lights are on more frequently. These results support the theory of energy efficiency in smart homes, where automatic regulation reduces power consumption [9]. Further development could use adaptive algorithms for LDR, as suggested by Kuo et al. [10], to dynamically adjust the threshold based on usage patterns. Blynk's notification reliability (98.0% on a stable network) is higher than Khan et al.'s system (95%) [5], thanks to Wi-Fi communication optimization and PIR data delivery prioritization. The decrease in reliability on unstable networks (91.5–92.0%) is consistent with IoT challenges in high-latency environments [11]. Protocols such as MQTT can improve reliability on weak networks, as proposed by Firmansyah & Pratama [12].

The average response time of 0.80–0.95 seconds for the buzzer and 0.90–1.20 seconds for the notification indicates adequate real-time performance, faster than Khan et al.'s system (2 seconds) [5]. Notification latency on unstable networks is caused by Blynk server delays. Data compression or a local server can reduce latency, as suggested by Santika & Arifin [13]. This system offers an affordable smart home solution with a device cost of under $15, significantly less than commercial systems ($100–$500). High detection accuracy, significant energy savings, and remote monitoring via Blynk enhance security and convenience. Key contributions include:

1. Integration of PIR, light and gas sensors in an ESP32 based system.
2. IoT optimization for low-power devices.
3. Blynk implementation for intuitive user interface.

This system is suitable for small to medium-sized households, enhancing security through intruder and gas detection, and saving energy through automated lighting. Blynk makes it easy for ordinary users to monitor their homes, supporting the adoption of IoT technology in Indonesia.

CONCLUSION

This research successfully designed and analyzed an Internet of Things (IoT)-based smart home automation system using an ESP32 microcontroller as the main controller, which integrates a Passive Infrared (PIR) sensor for intruder detection, a light sensor (LDR) for automatic lighting control, a gas sensor (MQ-2) for gas leak detection, and a Blynk application for remote monitoring. This system addresses the main problems in households, namely dependence on inefficient manual systems, lack of detection of security threats such as intruders or gas leaks, and limitations in remote monitoring. Test results show that the system achieves a detection accuracy of 95.0% for the PIR sensor and 92.0% for the MQ-2 sensor under optimal lighting conditions (500–700 lux), energy savings of up to 30% through automatic lighting control, and a Blynk notification reliability of 98% on a stable network. The average system response time is below 1 second, meeting the needs of real-time applications. This system offers an affordable solution with a device costing under $15, making it a viable alternative for small to medium-sized households looking to improve security, energy efficiency, and comfort without the high cost. Blynk integration allows users to monitor and control the system via smartphone, increasing accessibility and ease of use. Despite its success, this study has several limitations. The detection accuracy of the PIR and MQ-2 sensors decreased in low-light conditions (200–300 lux), to 92.5% and 89.5%, respectively, due to environmental interference such as shadows or humidity. Blynk's notification reliability dropped to 91.5–92.0% on unstable networks, indicating the system's dependence on a strong Wi-Fi connection. Notification response time also increased to 1.2 seconds on weak networks, which may reduce effectiveness in environments with poor signal. For future research, it is recommended to use sensors with higher sensitivity, such as a light-compensated PIR or MQ-9 for more accurate gas detection. Implementing communication protocols such as MQTT can improve reliability on unstable networks. Additionally, edge computing can be considered to reduce reliance on external servers, and augmenting sensor data with varying environmental conditions can increase system robustness. With these improvements, this smart home system could become a standard solution for cost-effective and scalable home automation in Indonesia.

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