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Design and Implementation of NodeMCU ESP8266-Based Smart Home System as Residential Energy Efficiency Solution

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Abstract

The household sector accounts for approximately 42.41% of Indonesia's total electricity consumption (122,339.69 GWh in 2023), making it a strategic priority for energy efficiency efforts aligned with the Sustainable Development Goals (SDGs), particularly SDG 7, SDG 9, SDG 11, and SDG 13. This study presents the design of a NodeMCU ESP8266-based smart home system integrated with the ThingSpeak platform and an Android application built with MIT App Inventor. This system is capable of integrating three main functions, including controlling and monitoring room lights using an LDR sensor, controlling the AC along with monitoring temperature and humidity using a DHT11 sensor, and monitoring water levels using an HC-SR04 ultrasonic sensor within a single low-cost NodeMCU platform. System performance was evaluated through functional testing of each subsystem using calibrated reference instruments, with accuracy calculated by comparing measured values against theoretical reference values. The DHT11 sensor achieved 95.62% accuracy for temperature and 98.15% for humidity, while the HC-SR04 sensor achieved 97.06% accuracy. With a total component cost below IDR 1.5 million, this system demonstrates that a multi-subsystem smart home solution can be implemented affordably using locally available components, supporting residential energy efficiency and the SDGs 2030 agenda.

Keywords: Internet of Things, NodeMCU ESP8266, Smart Home, ThingSpeak, SDGs

1. INTRODUCTION

Global energy consumption continues to increase significantly, driven by population growth, urbanization, and the modernization of people's lifestyles. The building and residential sector is one of the main contributors to global energy consumption, accounting for approximately 30% of total final energy consumption [1], [2]. In Indonesia, the situation is even more critical, given the population growth from 255.58 million in 2015 to 284.44 million in 2024 [3], [4].

According to the Electricity Statistics 2023 data, the household sector contributed 122,339.69 GWh, or approximately 42.41% of the total 288,435.78 GWh of electricity sold nationally, making it the largest energy-consuming sector [5], [6]. It is also recorded that Indonesia's per capita electricity consumption in 2023 reached 1,285 kWh/capita and is targeted to increase to 1,408 kWh/capita in 2024 [7], showing a consistent upward trend. On the other hand, the average electricity selling price from PLN of IDR 1,155.47/kWh in 2023 [5] places an increasing burden on Indonesian households' energy expenditures. A more recent projection from the ASEAN Center for Energy (2024) further underscores this trend, estimating that Indonesia's residential electricity demand will continue rising through 2030 in line with urban expansion and increasing appliance ownership rates [8]

The need of household energy efficiency is crucial for achieving the global development agenda through the Sustainable Development Goals (SDGs) established by the United Nations. The SDGs involved include SDG 7 which targets global improvements in energy efficiency by 2030 [9]; SDG 9 which encourages innovative digital-based technologies to support sustainable development; SDG 11 which targets the provision of safe, inclusive, and resilient housing for urban communities by 2030 [9]; and SDG 13 which promotes the reduction of carbon emissions through efficient energy consumption. Therefore, the proposed smart home system directly contributes to these indicators by enabling real-time monitoring and remote control of energy-consuming household devices, reducing unnecessary electricity use, and providing an affordable implementation model accessible to lower-middle-income households in Indonesia.

The Internet of Things (IoT) is a technological paradigm that enables physical devices to autonomously connect, communicate, and exchange data over the internet [2]. The application of IoT in the smart home context has demonstrated a rapidly growing market. According to a report by Grand View Research (2024), the global smart home market value is projected to grow at a Compound Annual Growth Rate (CAGR) of 27% from USD 127.80 billion in 2024 to USD 537.27 billion by 2030 [2]. The Asia Pacific region is one of the fastest-growing markets, which is supported by the government for smart city development, increasing digital penetration, and urban infrastructure expansion [10]. This growth indicates that the adoption of smart home technology will become increasingly widespread in the coming decade, including in developing countries like Indonesia.

Despite the significant market potential, Indonesia still faces challenges in adopting smart homes due to their implementation costs. The available commercial smart homes are generally unaffordable for the majority of Indonesian households, especially the lower-middle class [11], [12], [13]. Previous research has shown that implementing an IoT-based smart home can reduce energy consumption by 15-30% [2]. However, these savings are difficult to achieve if the high initial investment costs are prohibitive for potential users. This gap between the potential benefits and accessibility of smart home technology is the primary motivation for this research.

Several previous studies have explored the implementation of a NodeMCU-based smart home system (ESP8266) to monitor and control household devices. A previous study has designed and implemented a NodeMCU-based smart home system that used a DHT11 sensor to connect temperature and humidity, and an MQ-2 sensor for air quality, with a web-based dashboard interface. The system achieved a maximum indoor WiFi range of up to 42.05 meters and demonstrated a correlation between WiFi distance and command response time [14]. Meanwhile, a study developed an IoT-based home control system using a NodeMCU ESP8266 connected to Firebase as a real-time database, allowing users to control lights, fans, and electrical sockets while maintaining temperature and humidity through a self-developed mobile application. Although both systems successfully demonstrated remote control of home devices, they only covered one or two device categories and did not integrate air monitoring utilities within a single platform [15]. On the air monitoring subsystem side, a previous study has developed an air level monitoring application on a smart home system using a NodeMCU ESP8266 and an HC-SR04 ultrasonic sensor with the MQTT protocol and the Flutter framework, which can be accessed across platforms from Android, iOS, to desktop [16]. The common limitation across these works is the absence of a unified multi-subsystem platform that simultaneously addresses lighting, air conditioning, and water management within a single, low-cost IoT architecture. This study addresses that gap by integrating all three functional subsystems into a single NodeMCU platform connected to ThingSpeak, with an Android interface built entirely using MIT App Inventor, requiring no proprietary software licenses, native programming expertise, or high-cost commercial components, making the system significantly more reproducible and cost-accessible than prior implementations.

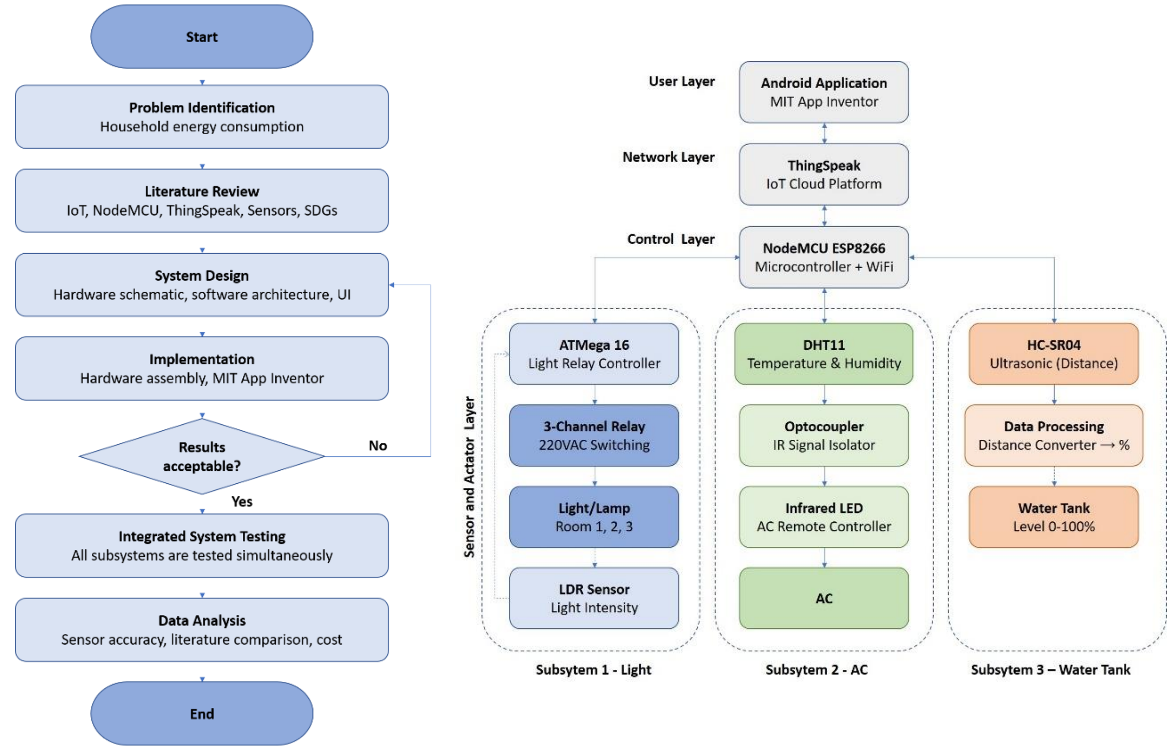
In this study, a low-cost smart home system is presented based on the NodeMCU ESP8266 with the ThingSpeak platform and an Android app interface utilizing MIT App Inventor. As previously mentioned, the NodeMCU ESP8266 was chosen because of its ability to integrate a microcontroller and a WiFi module in a small module at a very affordable price in the local market [17]This system has three basic operating subsystems that address the fundamental needs of a home: (1) controlling and monitoring room lighting using LDR sensors and relays, (2) regulating and tracking air conditioning conditions using a DHT11 sensor, and (3) monitoring water levels in the tank using an HC-SR04 ultrasonic sensor. All three subsystems are combined into a single IoT platform that can be accessed remotely through a smartphone.

The primary scientific contributions of this study include integrating three smart home subsystems into a single IoT platform, developing an innovative interface based on an Android Application, and employing inexpensive components that significantly reduce implementation costs compared to existing commercial solutions.

2. MATERIALS AND METHODS

2.1. System Architecture

This research was conducted in five sequential stages. The first stage involved a literature review to identify the research gap and determine appropriate components and platforms. The second stage comprised system design, including hardware circuit schematic design, software architecture planning, and Android application wireframing. The third stage was hardware and software implementation, covering assembly of the NodeMCU-based circuit, firmware development using Arduino IDE, and Android application development using MIT App Inventor. The fourth stage was system integration and testing, where each subsystem was tested individually using calibrated reference instruments, followed by integrated system testing. The fifth stage involved data analysis and documentation of results. Figure 1a presents the research flowchart illustrating the research stage process.



(a) (b)

Figure 1. (a) Stage flowchart, and (b) Smart Home System Block Diagram

The designed smart home system consists of four main layers, including sensor and actuator layer, control layer (NodeMCU ESP8266), network layer (ThingSpeak), and user layer (Android Application). Figure 1b shows the overall system block diagram. Data from sensors connected to the NodeMCU was sent to the ThingSpeak server every 250 ms via a WiFi connection. An Android application developed with MIT App Inventor reads and sends data to ThingSpeak. Users can monitor and control all home devices from anywhere as long as they are connected to the internet.

2.2. Component Specifications

A smart home is a residential environment equipped with interconnected devices that can be monitored and controlled remotely through internet-connected systems [18]. The Internet of Things (IoT) paradigm enables this interconnection by allowing physical devices to autonomously collect, exchange, and act upon data over the internet [19]. In the context of this study, IoT enables all three subsystems to communicate through a unified cloud platform accessible via smartphone. NodeMCU is an open-source IoT development platform based on the ESP8266EX chip, which integrates a 32-bit Tensilica L106 processor operating at 80 MHz with an onboard IEEE 802.11 b/g/n WiFi module [20]. Its compact form factor and low cost make it particularly suitable for multi-subsystem smart home implementations. ThingSpeak is an open IoT analytics platform developed by MathWorks that allows devices to collect, store, analyse, and visualise sensor data in real time through a simple REST API. In this study, ThingSpeak serves as the cloud intermediary between the NodeMCU hardware and the Android application.

The DHT11 is a digital temperature and humidity sensor with a measurement range of 0–50°C (±2°C accuracy) and 20–90% RH (±5% RH accuracy). It uses a single-wire serial interface and is widely adopted in IoT applications due to its low cost and ease of integration. The HC-SR04 operates by emitting a 40 kHz ultrasonic pulse and measuring the time elapsed before the echo is received. Its measurement range spans 2 cm to 4 m with ±3 mm accuracy. MIT App Inventor is a block-based visual programming environment for developing Android applications without requiring native programming expertise. It was selected in this study to demonstrate that a functional smart home interface can be built without proprietary IDEs or licensing costs, supporting the accessibility objective of this research. Table 1 summarises the main components used in the system, along with their specifications and roles.

Table 1. Smart Home System Component Specifications

Component	Function	Main Spesification	Role
NodeMCU ESP8266	Microcontroller/ WiFi	3.3V, 80MHz, GPIO 17-pin	System brain and Wifi connection

Component	Function	Main Spesification	Role
DHT11	Temperature and Humidity Sensor	0-50°C, ±2°C; 20-90% RH	Monitors room air conditions
LDR Sensor	Light intensity	500Ω - 200kΩ	Detects light status
HC-SR04 Sensor	Ultrasonic range	2 cm - 4 m, ±3 mm	Monitors tank water level
ATMega 16	AVR Microcontroller	16KB Flash, 8-bit, 16MHz	Relay controller
3-channel Relay	Electronic Switch	5V coil, 220VAC/10A	Switching lights for 3 rooms
Optocoupler	Opto-isolator	IF: 10mA, VISO: 5kV	Isolates AC remote control
MIT App Inventor	Application Platform	Android	User Interface

2.3. Light Controller Subsystem Design

The light controller subsystem consists of an LDR sensor, a 3-channel relay, and an ATMega 16 as a secondary light controller that receives instructions from the NodeMCU via UART serial communication at a baud rate of 9600 bps. In the lighting control system, users can control the lights on and off through a smartphone, allowing them to control the relay (on/off), which functions as a light switch. The light control logic uses a simple protocol, while the NodeMCU sends a command byte (11 = light 1 ON, 10 = light 1 OFF, 21 = light 2 ON, etc.) to the ATMega 16, the corresponding output port will be activated.

The 220VAC electricity supply was stepped down to 12VDC using a step-down transformer, then regulated to 5VDC by a 7805 regulator IC to supply the entire electronic circuit. The relay was controlled by a digital signal from the ATMega 16, with an optocoupler acting as an isolator between the control circuit and the power circuit to ensure system safety.

2.4. AC Controller Subsystem Design

The AC control utilises the principle of an infrared remote control digitally controlled by the NodeMCU. A DHT11 sensor was utilised to detect room temperature and humidity, which was connected to pin D2 of the NodeMCU and takes temperature and humidity readings every 15 seconds. The reading data was uploaded to fields 2 (temperature) and 3 (humidity) on the ThingSpeak monitor channel, then displayed via smartphone.

The AC's power state can also be managed by adjusting the temperature up or down. The AC on/off and temperature control were performed via three digital signals from the NodeMCU (pin D7 for ON/OFF, pin D5 for PLUS, pin D6 for MINUS), each connected to an optocoupler that activates the AC remote's infrared LED circuit. In this way, the NodeMCU can electronically mimic the functions of a real AC remote.

2.5. Water Tank Monitoring Subsystem Design

The water level is detected using the HC-SR04 ultrasonic sensor, which emits ultrasonic waves and then receives them back through a receiver. The time difference between the transmission and reception of these waves represents the distance to the object being measured. The HC-SR04 ultrasonic sensor was mounted above the water tank with the Trigger pin at D0 and the Echo pin at D1 of the NodeMCU. The system sends a 10µs trigger pulse and then measures the duration of the returning echo pulse.

The sensor output undergoes a discrete quantization process, whereby raw depth measurements are mapped to multiples of 4 cm and subsequently normalized into percentage values relative to the tank's maximum capacity. Given a reference tank height of 40 cm, a measured water depth of 36 cm corresponds to full capacity (100%), while depths ranging from 32 cm up to 36 cm yield a reading of 90%. This stepwise conversion continues at uniform 4 cm intervals across the entire measurement range. The resulting percentage values, rather than absolute depth figures, are transmitted to and rendered on the user's smartphone interface.

2.6. Android Application Development

The user interface was developed using MIT App Inventor, a block-based visual programming environment that enables Android application development without in-depth programming knowledge. The application has several main screens: (1) the Main Menu with navigation to each subsystem, (2) the Light Controller Screen with status indicators and ON/OFF buttons for three rooms, (3) the Air Conditioner Controller Screen with real-time temperature/humidity display and control buttons, and (4) the Water Tank Screen with graphical water level visualization. Application data updates are performed through the WebViewer and Clock components in App Inventor at 250 ms for light and AC control data, and 15 seconds for DHT11 and HC-SR04 sensor data, to comply with ThingSpeak's rate limits.

3. RESULTS AND DISCUSSION

3.1. Hardware Implementation

The smart home system was successfully implemented in the form of a house model representing three functional areas: the main room (lights), the bedroom (air conditioning), and the utility area (water tank). The entire electronic circuit was assembled on a PCB stripboard and housed in a separate control box, as shown in Figure 2.

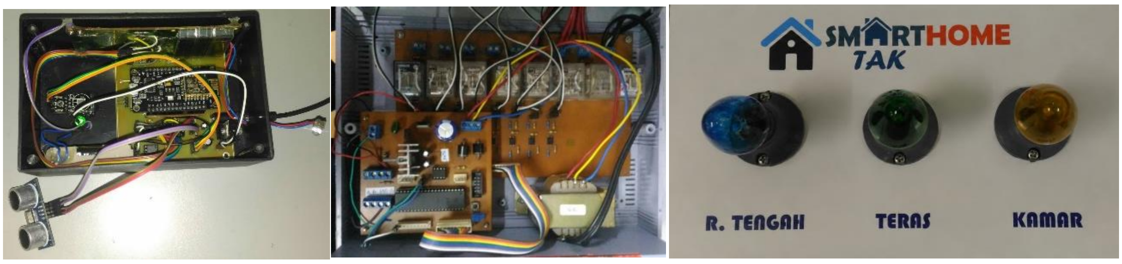


Figure 2. Smart Home System Hardware

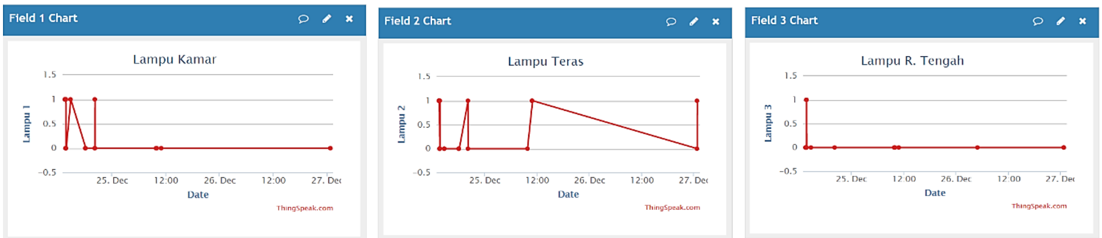
3.2. Monitoring and Control Results via ThingSpeak Platform

All data sent by the NodeMCU ESP8266 to the ThingSpeak platform was successfully visualised in real-time as a time-series graph for each configured channel field.

3.2.1 Lamp Status Monitoring Subsystem

Figure 3a-c shows the ThingSpeak response of light subsystem in three difference room: Field 1 (Bedroom Light), Field 2 (Porch Light), and Field 3 (Living Room Light). The graphs record the binary logic status of the lamps with values of 1 (ON) and 0 (OFF). Monitoring results during the testing period indicate that the system successfully responded to control commands from the Android app and accurately recorded them in ThingSpeak.

The Bedroom Light (Field 1) exhibited intense switching activity on December 25th, with several short ON-OFF cycles, then remained OFF for the remainder of the monitoring period. The Porch Light (Field 2) exhibits a more varied usage pattern. It activates on December 25th, then reactivates continuously from 12:00 AM on December 26th until nearly December 27th. The Living Room Light (Field 3) exhibited only one short ON cycle at the beginning of the test on December 25th, then remained consistently OFF. This data demonstrates that the light status recording mechanism operates reliably, with every change in relay condition accurately recorded on the ThingSpeak server without any missing data.



(a) (b) (c)

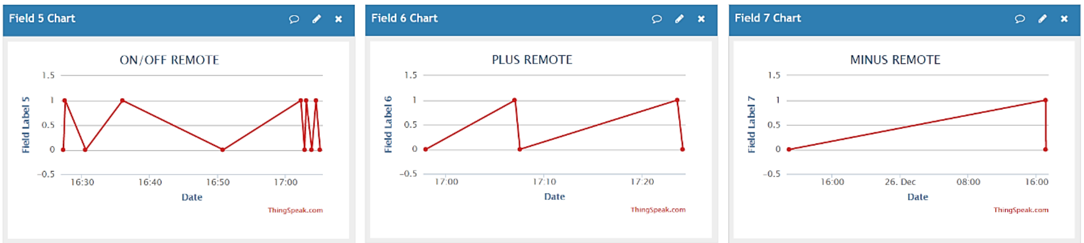
Figure 3. ThingSpeak Response to Light Subsystem in three different rooms: (a) Bedroom Light, (b) Porch Light, and (c) Living Room Light

3.2.2 AC Control Subsystem

As illustrated in Figure 4a-c, the AC unit is controlled by three independent control signals monitored in Field 5 (ON/OFF Remote), Field 6 (Plus Remote), and Field 7 (Minus Remote). All three of these signals are basically commands sent from the Android app to the NodeMCU, which then re-sent by an optocoupler/infrared LED circuit to the AC unit.

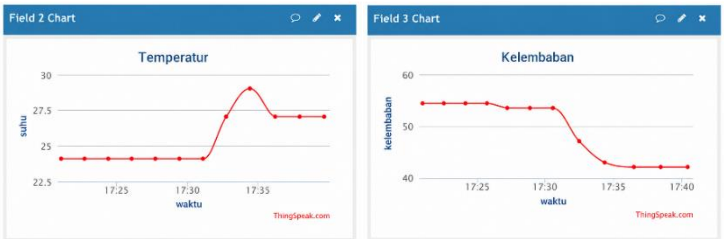
The Field 5 graph shows fairly frequent ON/OFF switching activity between 4:25 PM and 5:05 PM, with a consistent signal response each time a command is issued from the app. Field 6 (Plus Remote) displays a pattern of gradually increasing values between 5:00 PM and 5:25 PM, indicating a series of sequential temperature increase commands. Field 7 (Minus Remote) shows a similar pattern over a longer time span (from December 26th to 4:00 PM the following day), reflecting periodic temperature decrease commands. Recording the three control signals in ThingSpeak successfully validates that the designed IoT-based AC control architecture can be applied to practical cases and serves as an alternative to traditional AC remote controls.

The temperature (Field 2) and humidity (Field 3) graphs from the DHT11 sensor record changes in environmental conditions in real time between 5:20 PM and 5:40 PM, as shown in Figure 5a-b. At baseline (5:20–5:30 PM), the room temperature was stable at 24°C with a humidity of around 53–54% RH, representing the room's conditions before the AC was turned on. After the ON command was sent via the app, the temperature graph showed a temporary increase to nearly 29°C at 5:33–5:34 PM. This is a normal response of the AC unit, which requires time for the compressor to warm up before starting to cool the room. Afterwards, the temperature dropped again and stabilised at around 26–27°C. Conversely, the humidity graph showed a consistent decrease from 53% to around 42% RH as the AC cooled the room, which is expected physical behaviour considering the AC also functions as a dehumidifier.



(a) (b) (c)

Figure 4. ThingSpeak Response to AC Subsystem: (a) On/Off Remote, (b) Plus Remote, and (c) Minus Remote



(a) (b)

Figure 5. ThingSpeak Response to AC Subsystem: (a) Temperature, and (b) Humidity

These two graphs validate the system's ability to monitor the environmental conditions of an air-conditioned room in real time and continuously. The measured temperature and humidity changes are consistent with the operating characteristics of typical AC units, thus providing confidence that the integration of the DHT11 sensor with the ThingSpeak platform is running correctly and can be relied upon as a basis for automated AC control decisions in future system developments.

3.2.3 Water Level Monitoring Subsystem

The water level graph in Field 1 of the tank channel records data from the HC-SR04 ultrasonic sensor during the time period from 5:20 PM to 5:40 PM, as shown in Figure 6. Data is displayed as a percentage (%) on a scale of 0–100%. The graph shows that before 5:20 PM, the water level was at full (100%), then dropped drastically to near 0% around 5:20 PM and 5:27 PM, simulating a nearly empty water tank. Then the value increased significantly to about 70–80% as taken during the time period of 5:28 PM–5:30 PM, and then stabilised at around 75–80% until the end of the test session at 5:40 PM. This varying behaviour is indicative of a water tank refilling process, which was successfully detected and monitored in real time by the system. The stable values at the end of the session indicate that the HC-SR04 sensor was able to provide consistent readings without excessive fluctuations, which could indicate measurement noise.

Figure 6. ThingSpeak Response to Water Tank Level Subsystem

3.2.4 Test Results

Testing was conducted on each subsystem independently prior to integrated system testing. For the DHT11 sensor, a total of 10 measurement observations were recorded for each parameter (temperature and humidity) and compared against a calibrated reference thermometer and hygrometer. For the HC-SR04 sensor, 10 distance measurements at varying water levels were compared against a precision ruler. LDR sensor status detection (ON/OFF) was tested across 5 repeated trials for each condition. The test results are summarised in Table 2. The accuracy for each parameter was calculated using Equation (1).

$$\%\text{Accuracy} = 100 - \left(\frac{\text{Measured Value} - \text{Theoretical Value}}{\text{Theoretical Value}} \text{x}100\right) \quad (1)$$

Table 2. System Test Results using Reference Data

Parameters	Theoretical Value	Measured Value	Accuracy
DHT 11 Sensor – Temperature	25.1°C	24°C	95.62%
DHT 11 Sensor – Humidity	54%	53%	98.15%
DHT 11 Sensor – Increasing temperature	Up	Up	100%
DHT 11 Sensor – Decreasing temperature	Down	Down	100%
HC-SR04 Sensor – Water Level	27.2 cm	28 cm	97.06%
LDR Sensor – Light Status (ON)	ON	ON	100%
LDR Sensor – Light Status (OFF)	OFF	OFF	100%

According to the test results, the developed smart home system demonstrated adequate performance for residential control needs. The DHT11 sensor demonstrated accuracies of 95.62% and 98.15% for temperature and humidity measurements, respectively. The HC-SR04 ultrasonic sensor can also measure water levels with good accuracy. Measurement interference can occur due to water-surface turbulence during pump operation, but this can be addressed by using a moving-average technique in subsequent implementations. The ultrasonic sensor's accuracy is approximately 97.06%. In addition, the LDR sensor demonstrates accurate on-off light conditions.

The developed system offers the advantage of integrating three subsystems into a single NodeMCU platform, reducing implementation costs. The total cost of the system components is estimated to be less than Rp 1.5 million, which is much more affordable than commercial smart home solutions, which generally cost up to millions of rupiah.

3.3. Software Implementation

Figure 7a-d illustrates the application display of the main menu, light controller, AC controller, and water tank monitor. In the light controller display, the condition of the lights in several rooms can be monitored. In addition, users can control the lights in several rooms using the ON/OFF button, as shown in Figure 7b. However, the lights transition from off to on still have a few-second delay due to a system update. On the AC controller display, the current temperature and humidity can be displayed. The AC temperature can be increased or decreased using the Up/Down buttons. The green button indicates the on or off AC conditions, as shown in Figure 7c. Moreover, this system also has a notification when the temperature exceeds 50°C, with an “Extreme Temperature” prompt. In the Water Tank display, users can monitor the water tank level, as shown in Figure 7d.

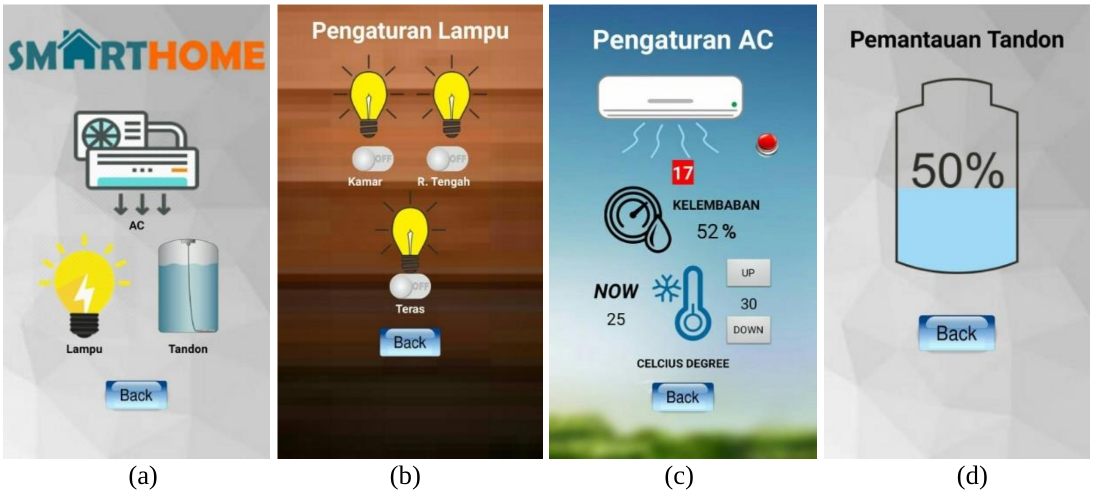


Figure 7. Application Display (a) Main Menu, (b) Light Controller, (c) AC controller, and (d) Water Tank Monitor.

3.4. Discussion

The experimental results demonstrate that the proposed smart home system achieves satisfactory performance across all three subsystems. The DHT11 sensor accuracy of 95.62% for temperature and 98.15%

for humidity. The minor temperature error (approximately 1.1°C deviation) falls within the sensor's rated tolerance of ±2°C, confirming that the sensor operates within its specified parameters. The HC-SR04 sensor accuracy of 97.06% aligns with the theoretical accuracy. The deviation observed in HC-SR04 measurements is attributed to minor surface turbulence during the water refilling simulation, which temporarily disrupted the ultrasonic echo path. This can be mitigated in future implementations through a moving average filter applied to raw distance readings before percentage conversion.

From a cost perspective, the total component cost of below IDR 1.5 million represents a significant advantage over commercial smart home solutions, which typically range from IDR 3 million to tens of millions of rupiah for equivalent functionality. The use of ThingSpeak as a free cloud platform and MIT App Inventor as a no-cost development environment further reinforces the cost accessibility of the proposed system. However, several limitations must be acknowledged. The system's complete dependence on WiFi connectivity means that any network disruption renders all remote control and monitoring functions unavailable. Additionally, the free tier of ThingSpeak imposes a 15-second minimum update interval on certain channels, which limits the temporal resolution of sensor data logging. The current implementation also does not include any security mechanisms such as user authentication or encrypted data transmission, which would be essential for real-world deployment. Future work should address these limitations by implementing a local (offline) fallback mode using direct ESP-NOW or Bluetooth communication between the NodeMCU and the smartphone, incorporating TLS-based data encryption for ThingSpeak communications, and expanding the sensor suite to include gas detection (MQ-2) and motion sensing (PIR) for comprehensive home security integration.

4. CONCLUSION

This study successfully designed and implemented a low-cost NodeMCU ESP8266-based smart home system integrating three functional subsystems: room lighting control, air conditioning control, and water tank level monitoring, through the ThingSpeak IoT platform and an MIT App Inventor-based Android interface. The DHT11 sensor achieved accuracies of 95.62% for temperature and 98.15% for humidity, while the HC-SR04 ultrasonic sensor achieved 97.06% accuracy, confirming that the system meets the performance requirements for residential monitoring applications. With a total component cost below IDR 1.5 million, the proposed system demonstrates that a multi-subsystem smart home solution can be implemented affordably using locally available components, contributing to more inclusive residential energy efficiency and supporting the SDGs 2030 agenda. The primary limitation of this system is its dependence on a stable internet connection and the ThingSpeak free-tier rate limit, which restricts real-time responsiveness for certain subsystems. Future research should explore offline operation modes, enhanced security protocols, and the integration of additional sensors to expand system functionality toward a more comprehensive smart home solution.

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