Indonesian Journal of Electrical Engineering and Computer Science
Vol. 37, No. 3, March 2025, pp. 1487~1496
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v37.i3.pp1487-1496

Smart home advisory system based on IoT-enabled sensor network

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Article Info

Article history:

Received Mar 25, 2024
Revised Sep 8, 2024
Accepted Oct 7, 2024

Keywords:

Internet of things
Node-red
Real-time data
Sensors
Smart home advisory systems

ABSTRACT

A consistent drive to make daily living more streamlined and less complex was critical throughout the industrial revolution. Although many applications are available, the general adoption of these applications is hindered by several factors (security concerns, expensive costs, and perceived usefulness). Hence, a cost-efficient smart home system can provide significant advantages without placing unnecessary financial or operational costs on consumers. This study proposed an inexpensive internet of things (IoT) enabled smart home advisory system for promoting healthier living conditions. The system contained numerous sensors for detecting surrounding brightness, temperature, humidity, and dust levels. Consequently, the system demonstrated effective real-time updates regarding the simulated temperature (22–32 °C), humidity (11–53 %RH), light (3–100 lx), and dust (0–278 mg/m3) environments. Blynk software was also embedded as an efficient user interface for the application. Overall, the low-cost IoT-enabled smart home advisory system offered concrete benefits by allowing users to improve their living surroundings while decreasing energy usage.

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1. INTRODUCTION

The idea of a smart home has existed since the 1990s, in which interconnected devices work together and make educated choices [1]. This system offers improved household management by optimizing resources and enhancing comfort through intelligent decision-making. Given that numerous applications are regarded as insignificant novelties rather than actual improvements, this technology has been impeded by several concerns [2], [3]. Users are also further discouraged when smart home technology involving interoperability and privacy is perceived as highly complex to set up. Although smart homes have encountered these difficulties, the rise of smartphones has revived enthusiasm for smart home technologies by utilizing their extensive acceptance as convenient centers for device control [4].

The obtainability and affordability of smart home technology for a typical user have demonstrated several obstacles. Smart home implementations frequently lack substantial output and are perceived as expensive, hindering wider adoption [1]. The challenging process of acquiring knowledge and the problems related to the ability of smart home technology to work well with other devices are also additional obstacles that prevent its widespread adoption. Furthermore, acquiring personal data raises privacy concerns, contributing to customer wariness [5], [6]. These outcomes emphasize the importance of careful development to manage these issues effectively.

The increasing number of smartphones and the internet of things (IoT) expansion present hopeful opportunities for addressing these difficulties. Smartphones can be convenient centers for controlling and overseeing smart home gadgets due to their extensive usage and adaptability [7], [8]. This benefit can streamline operation and monitoring processes. The IoT also aims to link commonplace devices to the internet, which opens possibilities for inventive smart home applications. For example, home automation allows for connecting everyday objects, creating new opportunities to improve household management [9], [10]. Hence, smart home solution-based studies are necessary with the ongoing development of the IoT to develop affordable and user-focused solutions. These studies are essential for addressing obstacles to adopting smart home technology and unlocking its potential.

Various intelligent home applications are being marketed to customers, with smartphones facilitating mass access to these solutions. Nevertheless, authentic home automation systems typically necessitate substantial modifications to the existing electrical wiring in older structures or new designs in newly constructed houses [11]. These processes render the technology costly and inaccessible to the average person. Regardless of whether they are off-the-shelf or bespoke, many solutions have inherent limitations. The capacity of smart home systems to deliver significant output is another vital factor to consider [12], [13]. Several cost-effective systems depend on independent, smart hubs that primarily provide device power control, providing minimal additional benefits beyond convenience. Nevertheless, this uncomplicated nature can result in users becoming too comfortable and not adequately justifying the decision to adopt and the associated cost. Therefore, meaningful outputs, such as data-driven advice for enhancing livelihoods, are essential to improve user experience and justify investment [14].

Considering the increasing apprehension around residential energy usage, another crucial factor is the system's capacity to reduce energy use [15], [16]. Given the growing dependence on electrical and electronic gadgets for home comfort, there is a greater demand for affordable and efficient methods to monitor and improve energy consumption. This feature becomes particularly pertinent amid financial constraints when individuals strive to minimize energy consumption expenses. Previous studies highlighted a research gap concerning the commercial viability of a comprehensive system package that smoothly integrates software and hardware. Insufficient systems that could offer beneficial suggestions regarding the most advantageous parameter configurations for end-users were also observed. Additionally, the affordable nature of sensors was frequently disregarded in previous studies.

Forest and Shabani [17], Abraham and Li [18] introduced a sophisticated ventilation system employing intelligent damper control. Conversely, the studies only regulated one ventilation component. Other IoT-related studies by Nigam *et al*. [19] and Ladekar and Daruwala [20] provided messages to users when the air quality fell below a specific threshold. Nevertheless, these systems lacked adaptability as only the users provided alerts. Meanwhile, Kang *et al*. [21] utilized message queue telemetry transportation (MQTT) to identify a room's temperature and help suppress fires. Nonetheless, the system solely monitored the temperature alongside a smoke detection system. Another study by Kim *et al*. [22] explored the development of an IoT gateway using MQTT, which could potentially link to different sensors and actuators. In contrast, the system was still a conceptual idea and was not thoroughly tested as a final product. Meanwhile, Li and He [23] outlined an air quality system with wireless communication and sensor integration. On the contrary, the system only monitored air quality and no other vital parameters. Debele and Qian [24] described an Arduino-based automatic room temperature control system that used a DHT11 sensor, heater, and fan Nevertheless, the system significantly relied on heater and fan setups and did not possess the capacity to be monitored wirelessly. Therefore, these studies demonstrated the significance of this study in providing a low-cost IoT-enabled smart home advisory system as a solution for future applications.

Developing smart home solutions accessible to the general population requires careful consideration of cost-effectiveness and sustainability. Many current implementations are excessively costly, frequently surpassing the Malaysian Ringgit (MYR) 1000 [25]. This heavy price renders them financially inaccessible for most individuals. The intricacy of the development process and the need for additional implementation measures also contribute to the escalation of costs. Hence, creating cost-effective systems is crucial to guarantee universal acceptance and deliver significant enhancements to users' lives [26]. Even though a wide range of IoT solutions are available, they are generally expensive for most people. This phenomenon emphasizes the importance of affordable smart home systems that provide practical advantages to consumers.

This study proposed constructing a low-cost IoT-enabled smart home advisory system to solve the difficulties above. Using an IoT sensory network, the system gave users significant output, encompassing essential data, such as temperature, humidity, ambient light, and air quality. These factors were also pivotal in upholding a healthy and pleasant living environment. Thus, users could make informed decisions to enhance their environment and prevent future health problems by providing information on these variables. The system aimed to assist users in minimizing household energy use by offering guidance on optimizing the usage of energy-intensive products, such as air conditioners. Therefore, a cost-effective and sustainable manner system design was vital to achieve general acceptance. This framework could minimize superfluous intricacies, prioritize the delivery of features that efficiently cater to users' demands, reduce costs, and increase the appeal and use of the smart home system.

2. METHOD

This study highlighted a smart environmental sensing device tailored for indoor settings (living rooms, bedrooms, or kitchens). The device detected and measured numerous real-time characteristics such as temperature, humidity, light, and dust levels. This system also consisted of two physical components: i) a comfort system containing all the sensors with a microcontroller and ii) a smartphone application that displayed data and sent alarms based on the processed data. Notably, the comfort system comprised a temperature (Bosch BME280, temperature operation range = -40 °C to 85 °C, 0.01 °C resolution) with humidity sensor (relative humidity = 0% to 100%, 0.008 %RH resolution), an air quality sensor (Sharp GP2Y1010AU0F), and an ambient light sensor (Vishay TEMT6000X01, wavelength range = 390 nm to 700 nm). The dust density (ρ_{dust}) in this study is also measured using the (1):

$$\rho_{dust} = (0.17 \times v_{sensor} - 0.1) \times 1000 \quad (1)$$

where v_{sensor} is the voltage measured from the sensor. The smartphone application was available for download on iPhone Operating System (iOS) and Android smartphones, offering real-time alerts when readings deviated from optimal conditions. The smartphone and the comfort system were connected via wireless fidelity (WI-FI). International norms and standards also established optimal circumstances, allowing users to modify and maintain a stable environment. Figure 1 depicts the proposed system architecture in this study.

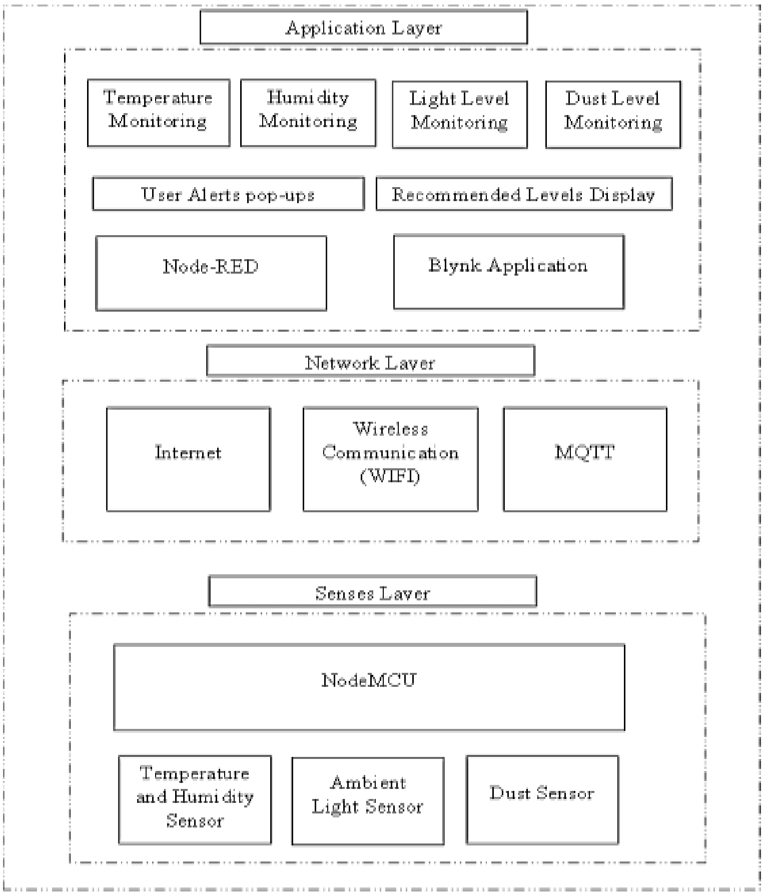

Figure 1. The proposed system architecture in this study

The system architecture has three layers: sensory, network, and application. Initially, the sensory layer detected environmental stimuli (temperature, humidity, light, and dust) in transmitting data to the microcontroller [Node MicroController Unit (NodeMCU) Lua V3 ESP8266] for analysis before relaying it to the network layer. The network layer then served as an intermediary, establishing a connection between the sensor and the application layer through wireless technology (Wi-Fi protocol and MQTT as the messaging protocol). Finally, the application layer presented information to users, utilizing developer tools (Node-RED and the Blynk application) to enable the construction of logical processes and data transmission. The viewing portion provided real-time monitoring services for temperature, humidity, light, and dust levels during the system's operation. Moreover, the program delivered alerts through smartphone pop-up notifications for the environmental data and exhibited suggested parameter levels for the present activity level. Figure 2 illustrates the Node-RED programming tool. The data obtained in this study was transmitted to Node-RED. This tool formulated the initial logic for the system before transferring the output to the user via their smartphone using a smartphone application. Meanwhile, the MQTT protocol operated on a publish-subscribe model. The MQTT broker oversaw data reception, analyzed it, and published it to interested clients via topics. The computed data was transmitted to the mobile application for user visualization as shown in Figure 3. This process was aided by blynk.io, which enabled smooth mobile integration with IoT networks and supported integration with Node-RED.

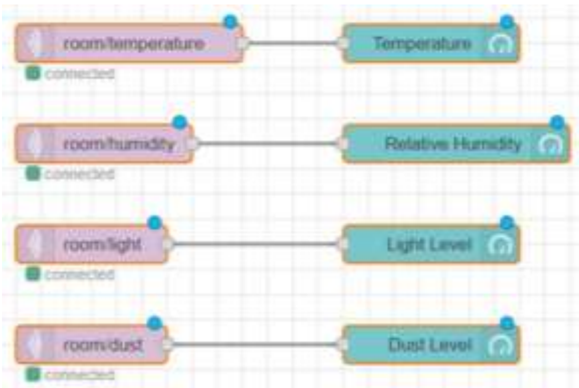

Figure 2. The general node-RED flow in this study

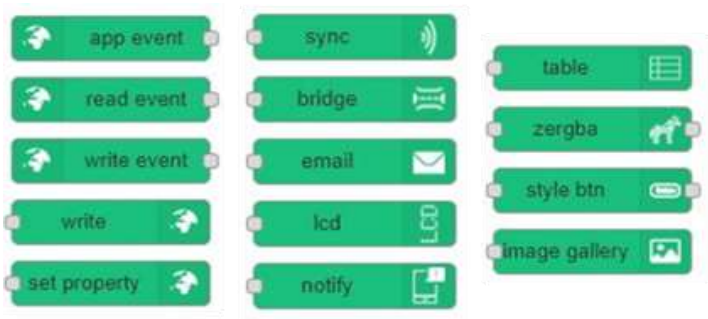

Figure 3. The blynk node within node-red in this study

3. RESULTS AND DISCUSSION

3.1. Hardware prototype framework

Figure 4 presents hardware prototype framework. The hardware prototype comprised a nodeMCU baseboard, a sensor-printed circuit board (PCB), and a 3D-printed enclosure to house the entire system as shown in Figure 4(a). Particularly, the nodeMCU baseboard featured a direct current (DC) barrel jack, which enabled it to connect to a DC adapter that converted the main power supply to the appropriate DC voltage for operating the device. The subsequent component was the PCB for the sensor array. This board utilized a donut-shaped design to facilitate the process of creating prototypes. The sensor circuit and associated electronics were also attached to the donut-shaped board. Essential components, such as the sensors and the

ADC module, were not directly glued onto the board to achieve modularity in the design and facilitate the prototype process. These components were connected using the header pins visible in the schematics. The header reduced effortless substitution of the elements while enabling the reuse of the identical PCB in case of any component-related problems. Moreover, the 3D-printed enclosure was another cheap factor as shown in Figure 4(b) [27], [28]. Consequently, this design saved expenses and enhanced the ease of access.

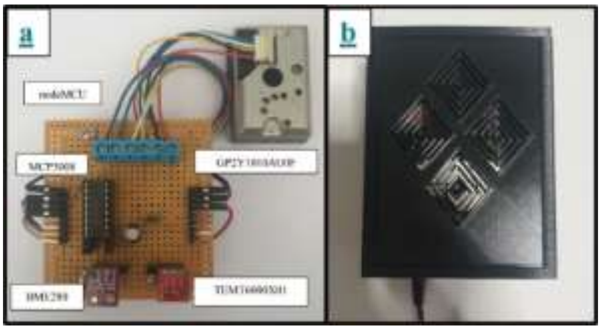

Figure 4. Hardware prototype framework (a) PCB and (b) the 3D printed enclosure

3.2. Sensor calibration and testing

3.2.1. Temperature and humidity sensor

The BME280 sensor utilized in the study was a digital sensor that enabled precise data acquisition and owned a high level of tolerance against noise. This sensor was also previously calibrated at the factory. Nonetheless, prototype testing was conducted to verify the sensor's functionality in the intended environment. Table 1 tabulates the sensor statuses at room temperature (32 °C), in a room equipped with an air conditioning unit set to 26 °C, and in a cooler (24 °C). Overall, the results indicated that the sensor could undergo all the tests without any influence on the operation result as shown in Figure 5. The sensor also influenced the cooler system's low %RH condition. This outcome implied that integrating the temperature and humidity sensor was feasible in the smart home advisory system.

Table 1. Summary of the BME280 sensor readings in various environments

Environment	Temperature (°C)			Humidity (%RH)		
Room temperature	1	2	Avg.	1	2	Avg.
	31.76	31.77	31.77	50.67	50.78	50.71
Air-conditioned room	1	2	Avg.	1	2	Avg.
	25.97	25.95	25.96	53.00	53.00	53.00.
Cooler	1	2	Avg.	1	2	Avg.
	23.95	22.83	23.39	11.94	12.26	12.10

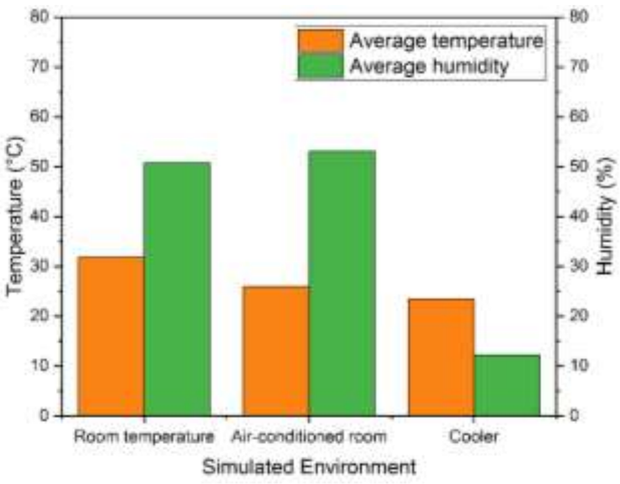

Figure 5. The average temperature and humidity detected by the BME280 sensor

3.2.2. Light sensor

The TEMT6000X01 sensor generated an analog signal as its output. Generally, analog signals are highly susceptible to the influence of noise in their environment. Therefore, the sensor was calibrated by comparing its readings to the built-in ambient light sensor on a smartphone using a specialized photometer application. Table 2 lists the comparison between the TEMT6000X01 sensor and smartphone light meter. The light sensor demonstrated average light intensities of 4.71 lx and 66.75 lx under dim and light bright environments, respectively. Alternatively, the smartphone meter presented average light intensities of 3.81 lx and 88.06 lx under dim and bright light environments, respectively. Despite minor discrepancies, the readings obtained from the smartphone meter and the TEMT6000X01 were similar over 16 trials as shown in Figure 6. These variances were attributed to the fact that the smartphone meter was equipped with an exact sensor calibrated using specialized equipment [29]. Consequently, integrating the light sensor was feasible in the smart home advisory system.

Table 2. Comparison summary between the TEMT6000X01 sensor and smartphone light meter

No	TEMT6000X01		Smartphone meter	
	Dimly Lit (lx)	Brightly Lit (lx)	Dimly Lit (lx)	Brightly Lit (lx)
1	4.51	70.90	3	70
2	4.51	62.52	4	80
3	5.16	57.36	3	77
4	4.51	60.59	4	89
5	4.51	66.39	5	91
6	4.51	71.54	3	92
7	4.51	74.12	4	76
8	5.16	72.83	5	98
9	4.51	66.39	3	100
10	5.16	56.72	4	89
11	4.51	58.01	5	90
12	3.87	62.52	3	91
13	4.51	67.03	4	101
14	5.16	72.83	5	95
15	5.16	74.77	3	82
16	5.16	73.48	3	88
Avg.	4.71	66.75	3.81	88.06

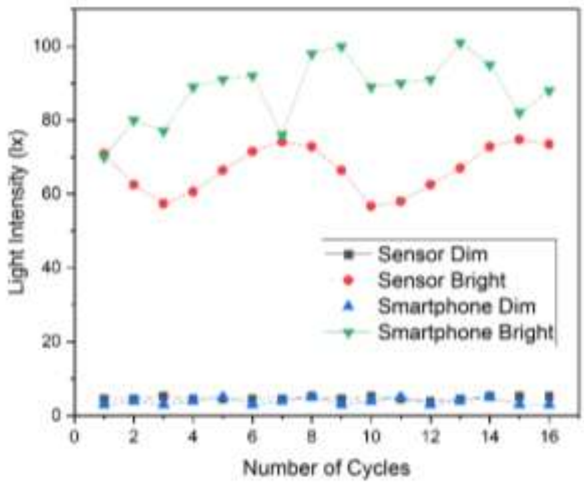

Figure 6. The light intensity values of the BME280 and smartphone sensors under 16 cycles

3.2.3. Air quality indicator

The Sharp GP2Y1010AU0F sensor was an optical dust sensor that generated an analog output. Nevertheless, the sensor necessitated calibration and testing to guarantee that the sensor operated with the specified precision. Table 3 summarizes the sensor capabilities in smoke and non-smoke conditions. The sensor was evaluated and simulated in a burning mosquito coil. The readings were consistent across a few trials as shown in Figure 7. This simulation replicated a climate characterized by a significant concentration of particulate matter in the atmosphere. The absence of smoke in the surroundings also demonstrated its inherent value, which could be used as a reference point for measurement. This air quality sensor was feasible in the smart home advisory system.

Table 3. Comparison summary of the Sharp GP2Y1010AU0F sensor in smoke and non-smoke conditions

No	Parameter	Non-smoke condition	Smoke condition
1	Signal Value	101.60	630
	Voltage (V)	0.33	2.22
	ρ_{dust} (mg/m^3)	0	278.02
2	Signal Value	101	690
	Voltage (V)	0.33	2.22
	ρ_{dust} (mg/m^3)	0	278.02
3	Signal Value	103.60	690
	Voltage (V)	0.33	2.22
	ρ_{dust} (mg/m^3)	0	278.02
4	Signal Value	99	377
	Voltage (V)	0.32	1.21
	ρ_{dust} (mg/m^3)	0	106.54
5	Signal Value	105.00	550
	Voltage (V)	0.34	1.84
	ρ_{dust} (mg/m^3)	0	210.00

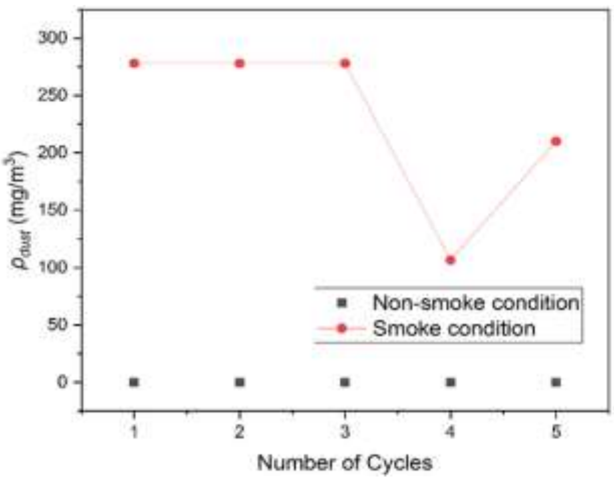

Figure 7. The ρ_{dust} values in non-smoke and smoke-simulated conditions obtained from the Sharp GP2Y1010AU0F sensor

3.3. Application user interface

The user interface was created via blynk.io, which is a platform specifically tailored for IoT applications as shown in Figure 8. When the application was opened, users were presented with a summary page that provided an overview of the monitored parameters. The application comprised five primary pages: summary as shown in Figure 8(a), temperature as shown in Figure 8(b), humidity as shown in Figure 8(c), light level as shown in Figure 8(d), and air quality as shown in Figure 8(e). Every page presented pertinent information and suggestions for the corresponding parameter. The application interface incorporated four separate gauges that displayed real-time temperature measurements in °C, ambient light level in lx, relative humidity as %, and air quality in mg/m$_3$. Overall, users could easily browse between these pages using the tabs at the top of the interface.

The interface was designed to give users comprehensive information and well-informed recommendations based on their chosen parameters. The top portion of each page had a gauge that displayed the current measurement of the parameter. In contrast, the bottom portion gave recommendations that matched the chosen parameter. Therefore, users could use this advice to make well-informed judgments about their surroundings. The application also incorporated a notification function to promptly inform users of anomalous readings identified in the monitored parameters as shown in Figure 9. These notifications leveraged the smartphone's inherent notification functionality, guaranteeing that users received timely updates even when the application was not actively used. Users received notifications when any recorded metrics surpassed predetermined thresholds, ensuring timely alerts and prompting necessary action.

Figure 8. The customized user application involves the: (a) summary page, (b) temperature, (c) light level, and (d) %RH readings

Figure 9. The customized user application involves notification alerts when anomalies are detected

3.4. Discussion

The findings of this study indicated that an affordable smart house advisory system containing IoT capabilities was essential to address specific challenges (cost and complexity) impeding the general acceptance of smart home technology. Thus, an economical and easily implementable solution could aid in the accessibility of smart home technology for the general population. This process could then promote healthier living conditions and more efficient energy usage. This study also reinforced the current trajectory in smart home technology research regarding the significance of cost-effectiveness and user-friendliness. Although previous studies examined several facets of smart home systems, a significant number of these studies primarily investigated impractical designs for the typical consumer [17], [18], [22], [24]. Therefore, this study improved existing methods by including affordable components and leveraging commonly used technologies like MQTT and Node-RED.

Subsequent investigations can expand on these discoveries by examining the integration of other sensors to develop a more comprehensive home monitoring system, such as gas detection, motion sensing, or sound monitoring. Additional efforts should also be undertaken to enhance the algorithms employed by the system for proposing energy-saving measures, potentially integrating machine learning techniques to anticipate user behavior and optimize energy consumption more efficiently [11]. Overall, this study illustrated that smart home systems could be accessible to more individuals by utilizing affordable IoT technology and prioritizing practical user requirements, promoting more sustainable and healthier living conditions. The results indicated that creating a cost-effective, user-friendly, and efficient smart home system with a substantial impact was feasible.

4. CONCLUSION

This study successfully developed a low-cost smart home monitoring system that provides valuable feedback on environmental conditions. The system effectively addressed current limitations by integrating real-time temperature, humidity, light, and air quality tracking sensors. Thus, utilizing technologies like MQTT and Node-Red contributed to cost reduction and efficiency in system development. 3D printing was also employed to protect the IoT system without significant cost increases. Consequently, the overall practicality of the research ensured commercial viability, potentially driving the adoption of such technologies and further reducing costs. This study filled a gap in the literature by developing a comprehensive, low-cost environmental monitoring system leveraging various technologies.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial sponsorship from Telekom Research and Development (TM R&D) Sdn Bhd, under TM R&D Research Fund (Grant No: RDTC/231080, Project ID: MMUE/230009). TM R&D Research Fund funded the APC.

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