A Didactic Approach to the Design and Development of an IoT-Based Smart Aquaponic System for Sustainable Development Goals (SDG)

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ABSTRACT

This study presents a didactic approach to the design and development of an Internet of Things (IoT)-based smart aquaponic system for small-scale urban agriculture. The system integrates an ESP32 microcontroller, soil moisture sensor, temperature and humidity sensor, relay-controlled water pump, and Blynk IoT platform for real-time monitoring and automated irrigation. A hysteresis-based control strategy was implemented for activating the pump when soil moisture falls below 35% and deactivating it at 55% to reduce unnecessary switching and water consumption. Experimental validation demonstrated successful sensor acquisition, actuator response, Wi-Fi connectivity and remote data monitoring. The prototype was developed at a relatively low cost while maintaining a modular and scalable architecture. Through closed-loop water circulation, demand-driven irrigation, and efficient resource utilization, the developed system demonstrates potential for sustainable urban food production while supporting Sustainable Development Goals 7 (Affordable and Clean Energy) and Sustainable Development Goals 13 (Climate Action).

Keyword: Aquaponics; Internet of Things (IoT); Smart Agriculture; Automated Irrigation; Sustainable Development Goals (SDGs).

INTRODUCTION

Aquaponics is increasingly recognized as an environmentally friendly approach to food production that integrates aquaculture and hydroponics into a single interconnected ecosystem [1], [2], [3]. In this symbiotic system, wastewater generated from fish cultivation is biologically processed and utilized as a nutrient source for plant growth. The plants absorb essential nutrients from the water, while the treated water is subsequently recirculated back into the fish tank [3], [4]. This closed-loop approach enables the simultaneous production of aquatic life and crops while promoting efficient resource utilization.

One of the major advantages of aquaponics is its potential to significantly reduce water consumption compared with conventional agricultural practices. Water losses within a recirculating aquaponic system mainly occur through evaporation and plant transpiration, thereby reducing the requirement for continuous water replacement. Moreover, fish waste can be converted into nutrients that support plant growth and reducing the dependency on chemical fertilizers. The integrated nature of aquaponics also minimizes the need for synthetic pesticides and promotes a more environmentally sustainable approach to food production [2], [5].

Despite these environmental and economic advantages, maintaining an aquaponic system remains challenging because the ecosystem requires continuous monitoring and appropriate control to maintain a suitable balance between fish, water quality, aquatic organisms, microorganisms, and plant growth [6]. Parameters such as temperature, humidity, soil moisture, water conditions [7], and feeding schedules must be appropriately managed to ensure the healthy growth of both aquatic life and crops. The challenges associated with aquaponics are further intensified by global concerns related to food security, rapid population growth, urbanization, and the limited availability of agricultural land. As modern urban areas continue to experience increasing spatial and water constraints, conventional large-scale agricultural practices are becoming

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increasingly difficult to implement. Consequently, compact, space-efficient, and automated food production systems are becoming increasingly important, particularly for small-scale urban applications such as residential homes, apartments, and balconies.

Traditional small-scale aquaponic systems often rely heavily on manual human intervention for routine activities such as environmental monitoring, water management, and fish feeding [8]. This dependency can introduce operational inefficiencies because manual processes may be time consuming, inconsistent, and susceptible to human error. For instance, inconsistent fish feeding may result in overfeeding or underfeeding. Overfeeding can lead to the accumulation and decomposition of uneaten feed, contributing to the generation of nitrogenous waste and deterioration of water quality [9]. On the other hand, insufficient feeding may negatively affect fish health and growth. The accumulation of fish waste and uneaten feed can increase the concentration of ammonia and other harmful nitrogen compounds, potentially disrupting the balance of the aquaponic ecosystem if not properly managed.

The advancement of the Internet of Things (IoT) offers significant potential to address these challenges through real-time monitoring, data acquisition, and automated control [1], [10]. By integrating sensors, actuators, and communication technologies, an IoT-based aquaponic system can continuously monitor important environmental parameters and support automated responses when predetermined operating conditions are reached. Such automation can reduce dependence on continuous human intervention while improving operational consistency and accessibility [1].

Therefore, this study presents the design and development of an IoT-based smart aquaponic system designed for small-scale applications. The proposed system integrates an IoT sensor network to monitor environmental parameters, including soil moisture, humidity, and temperature in real time. The system is also developed using a compact vertical structure that enables the simultaneous cultivation of plants and aquatic life within limited spaces. In addition, the aquaponic ecosystem utilizes a closed-loop water circulation process in which fish waste contributes nutrients for plant growth while water is continuously recycled throughout the system. Through the integration of IoT technology, automation, and a space-efficient physical design, the proposed system aims to provide a practical, sustainable, and user-friendly solution for small-scale urban food production.

DESIGN AND DEVELOPMENT

System Development and Architecture

An IoT-based smart aquaponic system was developed to automate water circulation and irrigation while providing real-time monitoring of the growing environment. The methodology involved four main stages: hardware development, software and IoT configuration, system integration, and experimental validation. The system was designed around a closed-loop monitoring and control concept in which environmental information acquired from the sensors was continuously processed by a microcontroller and subsequently used to determine the operating condition of the water pump. The overall architecture was divided into four functional layers, namely the sensing layer, processing and control layer, actuation layer, and IoT monitoring layer. The sensing layer consisted of a resistive soil moisture sensor [11] and a DHT11 temperature and humidity sensor [12], as shown in Figure 1.

(a) (b)

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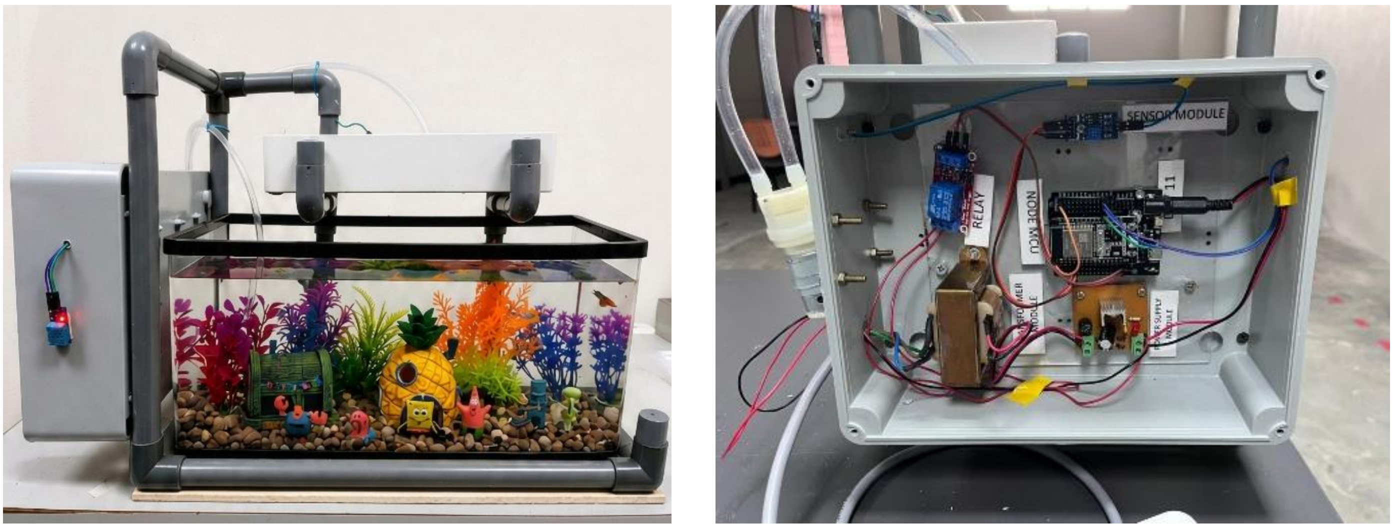
Figure 1. Soil moisture sensor (a), and DHT11 temperature and humidity sensor (b)

Soil moisture was selected as the principal feedback variable for irrigation control, whereas temperature and relative humidity were monitored to provide additional information regarding the surrounding growing conditions. The sensors were connected directly to an ESP32 microcontroller [13], which served as the central processing and communication unit. The ESP32 was selected because it combines sufficient processing capability with built-in Wi-Fi connectivity, allowing sensor acquisition, control execution, and IoT communication to be performed using a single controller. The analog output from the soil moisture sensor was acquired through the analog-to-digital converter (ADC) of the ESP32 and subsequently converted into a percentage representation of soil moisture. The DHT11 provided digital measurements of ambient temperature and relative humidity. The actuation layer consisted of a single-channel 5-V relay module [14] and a 12-V DC water pump [15], as depicted in Figure 2. Since the pump required a different operating voltage and current level from the ESP32, the relay provided the required switching interface and electrical separation between the low-power control circuit and the pump circuit.

(a) (b)

Figure 2. 5-V relay module (a), and a 12-V DC water pump (b)

The pump was connected to the water circulation network constructed using PVC pipes, through which water from the fish tank was delivered to the plant growing bed. This arrangement allowed nutrient containing water from the aquaculture section to be reused for plant irrigation before being returned to the system. The system was physically assembled on a supporting platform containing the fish tank, plant growing bed, water circulation piping, sensors, pump, and electronic control enclosure as shown in Figure 3.



(a) (b)

Figure 3. Smart aquaponic system (a), and the control unit (b)

Particular attention was given to sensor placement. The soil moisture probe was inserted vertically into the growing medium to obtain direct moisture measurements, while the DHT11 was positioned above the growing bed to measure the surrounding air temperature and humidity. The complete hardware configuration therefore

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formed an integrated sensing cum control cum actuation structure suitable for autonomous operation. The mechanical design of the system is portrayed in Figure 4.

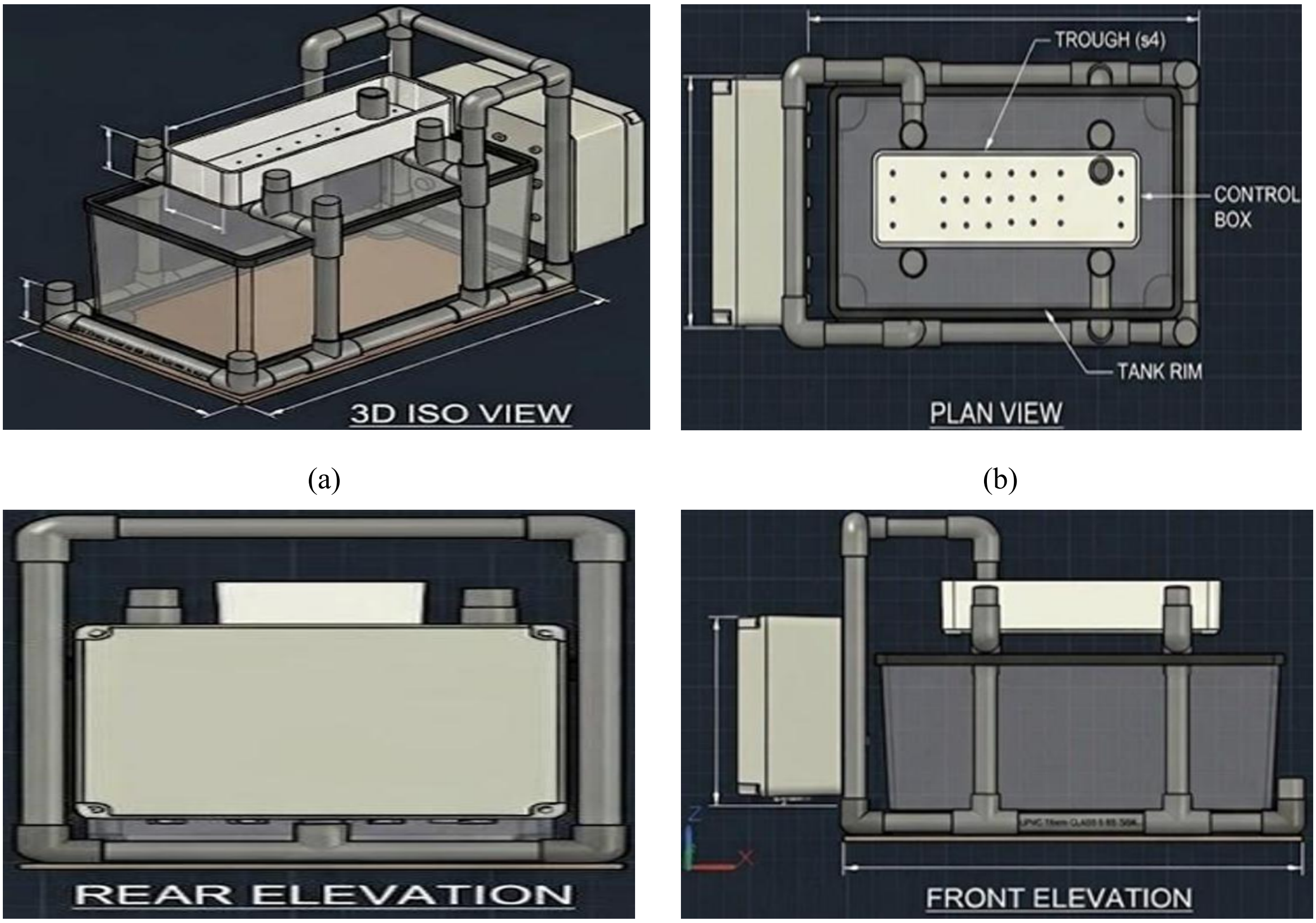

Figure 4. A 3D view of the mechanical design

Development of electrical and electronic circuitry

Figure 5 illustrates the electrical circuit showing the interconnection between the sensing, processing, and actuation components. The circuit was designed around the ESP32 microcontroller, which serves as the central processing unit for acquiring environmental measurements and generating the corresponding control signals.

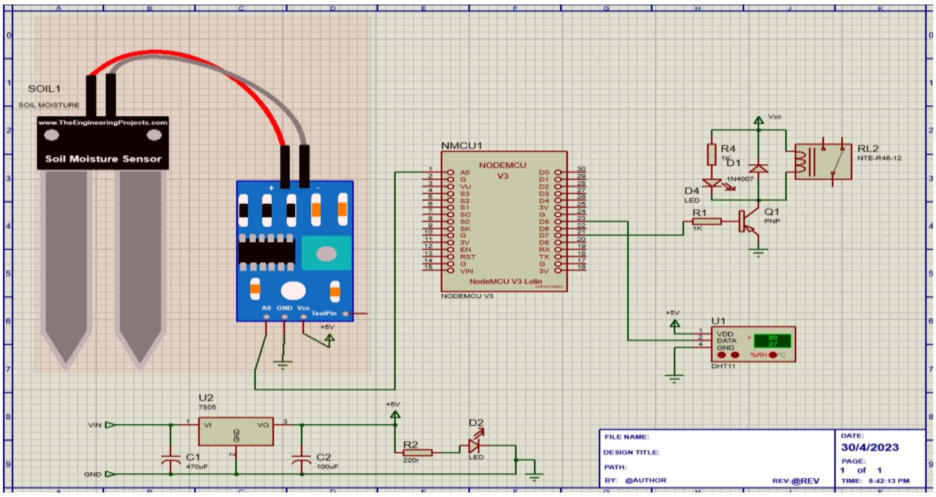

Figure 5. A wiring diagram connection for sensing, control and actuator layer

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The actuation circuit consists of a transistor-driven relay interface controlled by the ESP32. The microcontroller output is connected through resistor (R_1) to transistor (Q_1), which functions as an electronic switching element for energizing the relay coil. This configuration allows the low-power control signal generated by the ESP32 to operate the relay without directly driving the higher-current load. A 1N4007 diode (D_4) is connected across the relay coil as a flyback protection device to suppress the reverse voltage generated when the relay is de-energized. The relay contacts subsequently provide the switching mechanism required to control the water-pumping subsystem. This arrangement provides a practical interface between the low-voltage microcontroller circuit and the electrical load associated with water circulation. A regulated power supply section is also incorporated into the circuit to provide an appropriate operating voltage for the electronic components. The supply stage includes a 7805 voltage regulator together with input and output filtering capacitors (C_1) and (C_2), producing a regulated +5V supply for the relevant circuit components. An LED indicator (D_2) and current-limiting resistor (R_2) are included to provide a visual indication of the power-supply condition.

Control Strategy and IoT Implementation

A threshold-based feedback strategy was implemented for automatic irrigation. Instead of operating the water pump according to a fixed timer, the irrigation decision was determined from the actual moisture condition of the growing medium. Two moisture thresholds were defined to prevent excessive switching of the pump. When the measured soil moisture decreased below 35%, the ESP32 generated a control signal to energize the relay, thereby switching the water pump ON. Water was transferred from the fish tank to the growing bed. The pump remained active until the soil moisture reached the upper threshold of 55%, at which point the ESP32 deactivated the relay and switched the pump OFF. The use of separate ON and OFF thresholds created a 20-percentage-point operating band. This approach avoided repeatedly switching the pump when the moisture measurement fluctuated around a single threshold. In practical operation, the control mechanism can therefore be expressed as

$$u(k) = \begin{cases} 1, & M(k) < 35\% \\ 0, & M(k) \geq 55\% \\ u(k-1) & 35\% \leq M(k) \leq 55\% \end{cases} \tag{1}$$

where $M(k)$ represents the measured soil moisture (in %) at sampling instant k. While $u(k)$ represents the pump operating state. The signal $u(k) = 1$ turns ON the pump, $u(k) = 0$ turns OFF the pump, and $u(k-1)$ maintains the previous state. This hysteresis-type implementation was intended to provide more stable pump operation while maintaining sufficient moisture in the growing medium.

The control firmware was developed using the Arduino Integrated Development Environment (IDE), with the program structured to perform continuous sensor acquisition, conversion of sensor readings, threshold comparison, pump control, Wi-Fi communication, and transmission of operating data to the IoT platform. Following system initialization, the ESP32 established a Wi-Fi connection and communicated with the Blynk cloud server using the authentication credentials assigned to the device, after which the controller entered a continuous monitoring loop to periodically update the sensor readings and actuator status. Blynk was employed as the remote monitoring interface, with the graphical user interface shown in Figure 6. A dedicated dashboard was configured to display soil moisture (%), ambient temperature (°C), relative humidity (%), and the current operating status of the water pump. In addition to automatic operation, a manual switching function was incorporated into the dashboard to facilitate system testing and enable direct pump control when required. Through this integration, the developed aquaponic prototype could be monitored and controlled remotely using an Internet-connected device.

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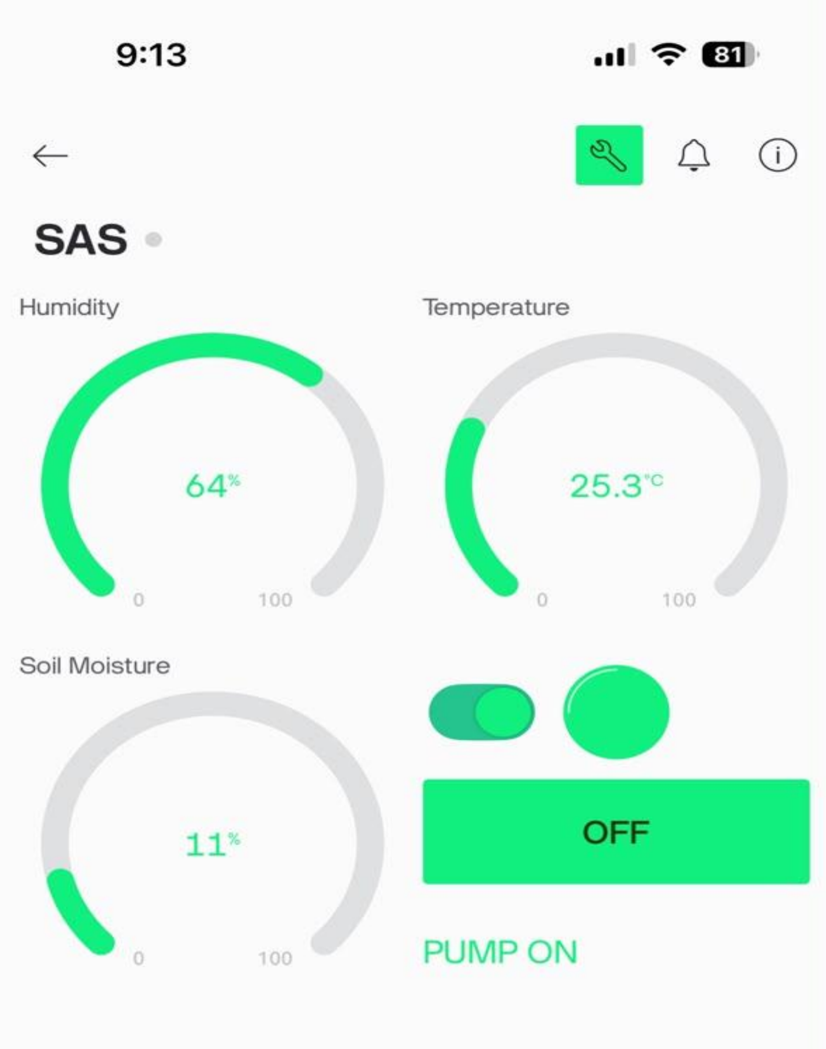

Figure 6. A graphical user interfaces

Sensor Calibration and System Validation

Prior to system integration, the sensors and actuators were individually tested to ensure reliable operation. The soil moisture sensor was calibrated from dry to saturated conditions by mapping raw ADC readings to moisture percentages, while the DHT11 measurements were verified against reference temperature and humidity instruments. During testing, stable soil moisture readings of 69%, 65%, and 61% were recorded, with representative temperature and humidity values of approximately 21°C and 59%, respectively. The actuator response was evaluated around the programmed moisture thresholds, where readings of 33% and 31% successfully activated the relay and water pump. The complete system was subsequently tested from sensor acquisition and ESP32 processing to pump actuation, Wi-Fi connectivity, and Blynk data transmission. Measurements displayed on the Blynk dashboard were compared with serial monitor readings, confirming successful integration of the sensing, control, actuation, and remote monitoring functions.

SUSTAINABILITY AND SOCIETAL IMPACT OF THE DEVELOPED SYSTEM

The increasing scarcity of agricultural land, population growth, and pressure on water resources present significant challenges to conventional food production, particularly in urban environments. In this context, the developed IoT-based smart aquaponic system provides a compact approach that combines automated monitoring and control with the natural nutrient-recycling mechanism of aquaponics. The closed-loop configuration allows water to circulate between the aquatic and plant-growing sections, thereby reducing water losses associated with surface runoff and deep soil percolation. Water replacement is mainly required to compensate for evaporation and plant transpiration. Based on the operational consideration of the developed system, approximately 5% to 10% of the total water volume may require replenishment, corresponding to an estimated reduction in water consumption of approximately 80% to 90% compared with conventional cultivation. These characteristics make the proposed system particularly relevant to small-scale urban agriculture where land and water availability are constrained. The sustainability of the system is further supported by its nutrient recycling and demand-driven irrigation mechanisms. Fish waste and residual feed provide a source of nitrogenous compounds that can be biologically converted into nutrients available for plant uptake, reducing dependence on external chemical fertilizers. At the same time, nutrient uptake by the plants contributes to maintaining water quality before recirculation to the aquatic section. The IoT-based control system further improves resource utilization by using real-time soil moisture measurements to determine when irrigation is required. Consequently, the water pump operates only when the measured moisture falls below the predefined threshold and is switched off when the desired moisture level is restored. This demand-driven operation reduces unnecessary pumping, overwatering, and associated electrical energy consumption compared with continuous pump operation.

From a broader sustainability perspective, the developed system contributes particularly to *Sustainable Development Goal (SDG) 7: Affordable and Clean Energy* and *SDG 13: Climate Action* [16]. Its contribution to SDG 7 is primarily associated with the application of low-power electronic components and intelligent control to improve energy utilization. The ESP32 microcontroller, environmental sensors, and relay-based switching system require relatively low operating power, while automatic pump control limits energy consumption to periods when irrigation is required. Moreover, the relatively low-voltage and compact architecture provides an opportunity for future integration with renewable energy technologies, particularly photovoltaic systems. With respect to SDG 13, the system demonstrates an alternative approach to food production that emphasizes water recirculation, reduced chemical input, efficient use of space, and automated resource management. These characteristics have the potential to reduce some of the environmental burdens associated with conventional agricultural practices.

Lifecycle considerations were also incorporated into the prototype development. The system was constructed using affordable and readily available components, including the ESP32 microcontroller, sensors, relay module, water pump, and structural materials, with a total prototype implementation cost of MYR 307.14 (approximately USD 76.25 / AUD 106.25). More importantly, the modular hardware architecture allows individual components to be inspected, calibrated, replaced, or upgraded without requiring replacement of the entire system. Such modularity can extend the useful operational life of the prototype while reducing unnecessary material consumption and electronic waste. Periodic sensor calibration and preventive maintenance remain necessary to preserve measurement accuracy and reliable long-term operation.

CONCLUSION

This study demonstrated the design, development, and validation of an IoT-based smart aquaponic system as a practical and didactic platform for small-scale sustainable agriculture. The developed prototype successfully integrated sensing, processing, actuation, and IoT communication within a compact architecture. An ESP32 microcontroller was employed as the central controller, while soil moisture, temperature, and humidity were monitored to provide real-time information on the growing environment. The implemented hysteresis-based control strategy automatically activated the water pump when soil moisture decreased below 35% and deactivated it when the moisture reached 55%, thereby reducing unnecessary pump switching and water application. Experimental testing confirmed successful sensor acquisition, relay and pump actuation, Wi-Fi connectivity, and data transmission to the Blynk monitoring interface. Beyond its technical functionality, the system demonstrates the potential of combining IoT engineering with the natural resource-recycling principles of aquaponics. Its closed-loop water circulation, demand-driven irrigation, low-power electronics, and modular construction support more efficient utilization of water, energy, and physical space. With a prototype implementation cost of MYR307.14, the proposed system also demonstrates the feasibility of developing an affordable platform for small-scale urban applications. These characteristics support its contribution toward SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Future work should incorporate additional water-quality parameters, such as pH, dissolved oxygen, ammonia, and electrical conductivity, together with renewable energy integration and long-term experimental evaluation. Overall, the developed prototype provides a useful foundation for both engineering education and further research into sustainable IoT-enabled smart agriculture.

RECOMMENDATIONS AND FUTURE WORK

For the future work, the studies will be extended to 3–6 months of continuous operation to obtain comprehensive quantitative data on water consumption, plant growth, fish survival, nutrient cycling efficiency, sensor accuracy, and control system reliability over multiple operational cycles. Additional water-quality sensors, including pH, electrical conductivity, and dissolved oxygen sensors, will be integrated to enable more comprehensive monitoring of the aquaponic environment. Future studies will also provide detailed information on crop and fish species, stocking densities, and growth performance. Furthermore, failure-mode analysis, maintenance requirements, and benchmarking against existing aquaponic systems will be conducted. Solar photovoltaic integration will also be explored to improve energy sustainability and further strengthen the system's contribution to SDG 7.

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