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Integration of Multi-Modal Sensors in Aquaponic Farming for IoT-Ready Based on ESP32 and Raspberry Pi Hybrid Platform

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ABSTRACT

This study aims to design and implement a smart agriculture system that integrates multi-modal sensors with an aquaponic farming platform, utilizing Raspberry Pi and ESP32 microcontrollers. The integration approach adopts embedded system-based control to connect and coordinate all multi-modal sensor components within the smart aquaponic environment. The primary function of the multi-modal sensors is to acquire comprehensive environmental and operational data from the aquaponic system through instrumentation-based measurement techniques. These data are intended to be further integrated with Internet of Things (IoT) technology using ESP32 and Raspberry Pi as control units. In this study, the integration of the Raspberry Pi and ESP32 platforms demonstrates superior performance compared to a single platform, as it combines a microcontroller capable of reading analog sensor data and transmitting it to the Raspberry Pi, which subsequently functions as the central data processing unit. Experimental results confirm that all multi-modal sensor devices operate reliably when interfaced with the ESP32 and Raspberry Pi, producing accurate data streams that can be utilized in future implementations of IoT-based control systems.

I. Introduction

Aquaponics is a type of agricultural system that integrates aquaculture and hydroponic farming into a single, mutually beneficial system [1]. In practice, aquaponic systems can be implemented in modern residential farming environments where land availability is limited [2]. However, limited time availability for farmers to manage and maintain aquaponic systems due to work-related commitments and unpredictable weather conditions can pose significant challenges, potentially leading to suboptimal crop yields or even financial losses. In addition, another common issue in modern agricultural systems such as aquaponics is the need for monitoring and control to maintain crop quality [3], including the use of complex sensors to detect various conditions within the agricultural system, control devices, as well as network readiness for remote operation of agricultural equipment. Therefore, the objective of this research is to develop an integrated Multi-Modal Sensor system for smart aquaponic farming that assists farmers in monitoring farming conditions, using a control system based on the combination of ESP32 and Raspberry Pi platforms.

In its implementation, several researchers have developed aquaponic farming systems based on control technologies. Pramana et al. developed a nutrient delivery system for catfish and water spinach in an aquaponic setup using an ESP32 microcontroller [4]. The researchers also built a water quality monitoring system for aquaponics using pH, temperature, nutrient, RTC, TCS3200, and DS18B20 sensors controlled by an ESP32 platform. Isnanta et al. applied Internet of Things (IoT) technology in aquaponic cultivation of catfish (Pangasius) [5]. Their study implemented a monitoring system using pH, turbidity, TDS, LDR, and ultrasonic sensors, all integrated via an ESP32-based control system. A comparative analysis of material productivity in aquaponic farming versus conventional aquaponics was conducted by Wiradani [6], who employed an Arduino Uno-based system to improve crop yields using pH, ultrasonic, LDR, and turbidity sensors. Furthermore, an Arduino Uno-based aquaponic system aimed at enhancing food security and economic independence at the Berkah Box Mosque was developed by Alif [7]. In this study, researchers utilized DHT11 and pH sensors to implement an aquaponic farming system operated by students, using the Arduino Uno as the control platform.

Subsequently, Ristanto et al. implemented an ESP32-based tilapia farming system for the Kalikatok farmer group in Ngabean Village, Kendal [8]. The researchers developed an aquaponic farming system utilizing temperature, ultrasonic, pH, and TDS sensors, all controlled via the ESP32 platform. Syaputra et al. applied ESP32-based technology in modern aquaponics and aquaculture systems to optimize catfish growth [9]. In their study, aquaponic and aquaculture systems were implemented using pH, TDS, and DS18B20 sensors integrated with ESP32 and a web-based interface. The application of smart aquaponics using the Simple Additive Weighting (SAW) method was presented by Ubaidillah [10]. The researchers employed pH and temperature sensors in the smart aquaponics system, which was based on an integration of Arduino Uno and ESP32. Furthermore, the development of an automatic feeding system for catfish aquaculture within an aquaponic setup at *Griya Karya Harapanku* in Cirebon was implemented by Prasetya [11]. In this study, the researchers built an automated aquaponic farming system using ultrasonic and RTC sensors based on the ESP8266 microcontroller.

In addition, Widiantara et al. designed and developed an aquaponic farming system using Raspberry Pi-based control [12]. The researchers implemented an aquaponic system utilizing pH, temperature, ultrasonic, and RTC sensors, all integrated with the Raspberry Pi platform. The implementation of aquaponics as an approach to utilizing marginal land for increasing household income was carried out by Prayitno [13]. In this study, the researchers utilized marginal land to establish a conventional aquaponic farming system, which contributed to improving family income. Furthermore, the introduction of aquaponic technology to support the development of an educational tourism village in Pojok Village, Sukoharjo, Central Java, was explored by Pitoyo [14]. The researchers applied a conventional greenhouse-based aquaponic system for cultivating mustard greens, lettuce, and water spinach.

Based on the state-of-the-art review, it can be observed that most researchers have employed sensor devices along with ESP32, Arduino Uno, ESP8266, and Raspberry Pi as control platforms in aquaponic farming systems. However, none have yet integrated Multi-Modal Sensors with a hybrid control architecture combining both ESP32 and Raspberry Pi. Therefore, the novelty of this study lies in the integration of multi-modal sensors into a complex aquaponic farming system by utilizing a combination of the ESP32 microcontroller and Raspberry Pi as the data processing platform. This integration enhances the quality of control in aquaponic farming devices compared to previous studies. In an aquaponic farming system, aquaculture and hydroponic cultivation are combined, involving both fish and vegetable farming. Thus, the implementation of complex multi-modal sensors can support farmers in uniformly monitoring the agricultural system. Furthermore, the integration of the ESP32 microcontroller and Raspberry Pi is considered reliable, as it combines two technologies to optimize data processing in the control system. In this study, the multi-modal sensors are utilized for agricultural data acquisition, Raspberry Pi functions as the central data processing unit, and ESP32 serves as the control device responsible for converting analog sensor signals into digital data, which are then transmitted to the Raspberry Pi via serial communication protocols. This research is expected to serve as a breakthrough in agricultural control systems by integrating ESP32 and Raspberry Pi two platforms with distinct strengths and limitations into a unified, reliable control architecture based on microcontroller–microcomputer integration.

The researchers in this study present the implementation of their work elaborated across four sections of this paper. The first section provides an introduction that outlines the research background, state of the art, and novelty of the study. The second section describes the methodology employed to integrate the Multi-Modal Sensors with Raspberry Pi and ESP32. The third section presents the results and discussion, focusing on the output measurements from the Multi-Modal Sensor devices interfaced with the Raspberry Pi and ESP32 controllers using instrumentation techniques. Finally, the fourth section delivers the conclusion and recommendations for future research development.

II. Method

A Multi-Modal Sensor is a combination of various types of sensors integrated into a single module that functions as an input device for control systems [15]. In this study, we utilize a hybrid integration of the ESP32 microcontroller and the Raspberry Pi microcomputer to read input data from the Multi-Modal Sensor and process it using instrumentation measurement techniques. Table 1 presents the differences, advantages, and limitations of microcontrollers and microcomputers, which are combined in this research.

TABLE I
COMPARISON OF THE ADVANTAGES OF THE ESP32 MICROCONTROLLER AND THE RASPBERRY PI MICROCOMPUTER

Systems	ESP32 Microcontroller	Raspberry Pi Microcomputer
Analog Pin	18 Pins	-
Digital Pin	34 Pins	26 Pins
Processor	Up to 240 MHz	Up to 2.4GHz
Storage	Flash Memory up to 16MB	MicroSD up to 256GB
Data Processes	Single-Processing	Multi-Processing
Purposes	Single	General

Based on the information presented in Table 1, this study integrates the advantages of the ESP32 microcontroller and the Raspberry Pi microcomputer to process data from the Multi-Modal Sensor. One of the key advantages of the ESP32 microcontroller is its built-in Analog-to-Digital Converter (ADC) pins, which allow it to read analog sensor signals and convert them into digital data—capability that the Raspberry Pi microcomputer lacks. In this research, the ESP32 is used to read analog sensor inputs and transmit the converted digital data to the Raspberry Pi via serial communication protocols for further processing. Furthermore, the Raspberry Pi microcomputer offers several notable advantages, including high processing speed, support for multiprocessing, large data storage capacity, and general-purpose computing capabilities. In this study, the Raspberry Pi is utilized as the central data processing unit due to its superior computational power, comparable to that of a standard computer. Figure 1 illustrates the Multi-Modal Sensor architecture used in this study, which is connected to the integrated ESP32 and Raspberry Pi control system.

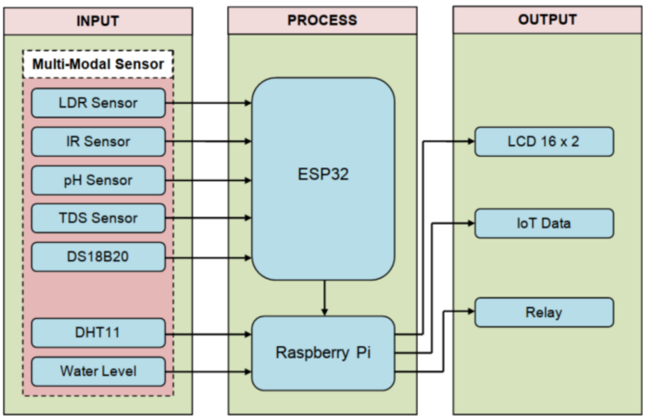

Figure 1. Architecture systems design

Based on the information in Figure 1, several sensors are used as input components of the Multi-Modal Sensor system to monitor the conditions of the aquaponic farming environment. These sensors include the LDR sensor, IR sensor, pH sensor, TDS sensor, DS18B20 sensor, DHT11 sensor, and a water level sensor.

TABLE 2
TYPES OF SENSORS USED IN MULTI-MODAL SENSORS

Sensors	Types
LDR	GL5516
IR	YL-38
pH	PH-4502C
TDS	TDS Meter V1.0
DS18B20	Dallas DS1820
DHT11	10756W
Water Level	YL-69

According to the information of Figure 1 and Table 2, the LDR (Light Dependent Resistor) sensor is used to detect light intensity, where the sensor's resistance changes based on the amount of light it receives [16]. In this study, the LDR sensor functions to detect lighting conditions such as clear, cloudy, or overcast weather, as well as distinguish between day and night. Next, the IR (Infrared) sensor is used to detect infrared light [17]. In this research, the IR sensor is applied to monitor the intensity of sunlight's infrared radiation used to illuminate aquaponic plants. The pH sensor is included to measure the acidity level of the water in the aquaponic system [18], while the TDS (Total Dissolved Solids) sensor is used to evaluate the nutrient concentration in the fish pond water [19]. Additionally, the DS18B20 sensor is employed to measure the water temperature in the aquaponic pond [20], and the DHT11 sensor is used to measure ambient air temperature and humidity around the aquaponic farming area [21]. Finally, a water level sensor is utilized to detect the volume or water level within the aquaponic plant piping system [22].

In the processing section, the ESP32 microcontroller functions to read analog output data from sensors and transmit it to the Raspberry Pi via serial communication. The sensors connected to the ESP32 include the LDR, IR, pH, TDS, and DS18B20 sensors. The ESP32 is a System-on-Chip (SoC) microcontroller equipped with built-in Wi-Fi, Bluetooth, and GPIO pins for reading both analog and digital sensor inputs, as well as for controlling output devices [23]. The Raspberry Pi in this study is responsible for reading digital output data from sensors such as the DHT11 and water level sensor, and it serves as the central data processing unit. This data will later be utilized in control systems and Internet of Things (IoT) applications. The Raspberry Pi operates similarly to a general-purpose computer and is equipped with GPIO pins for reading digital sensor outputs and controlling external devices [24].

In this study, we leverage the advantages of the ESP32 to read analog sensor output values so they can be processed by the Raspberry Pi in real-time. This approach is particularly beneficial when the Raspberry Pi functions as an edge device that processes IoT data before transmitting it to end-user devices. Furthermore, we utilize the strengths of the Raspberry Pi to perform real-time data processing, which facilitates the development of algorithms and supports system operations through multi-processing capabilities. Its high-speed processor and substantial RAM enable computational data handling, while its large MicroSD storage capacity allows for extensive program and data storage.

In the output section of the system architecture, there are three main components: a 16x2 LCD, IoT data output, and a relay module connected to the GPIO pins of the Raspberry Pi. The 16x2 LCD is an output device used in embedded control systems, capable of displaying 16 characters per line across two rows, and can be operated using either I2C communication or conventional control methods [25]. In this study, the 16x2 LCD functions to display sensor data generated by the embedded system, including output values from the Multi-Modal Sensors such as LDR, IR, pH, TDS, DS18B20, DHT11, and water level sensors. Additionally, the system includes an IoT data output design, which will be used in the future when the system is integrated with cloud-based Internet of Things (IoT) technologies. A relay module is also part of the output section, functioning to control the water pump during irrigation into the aquaponic plant pipes. The relay is triggered automatically based on water level conditions in the pond and plant piping system. A relay is an electronic component that contains a coil and acts as an electrical switch when a control voltage is applied [26].

III. Results and Discussion

In this study, the researchers have developed a design for an aquaponic farming system that combines aquaculture and hydroponic cultivation. In an aquaponic system, a mutualistic symbiotic relationship is established, providing reciprocal benefits between the hydroponic plants and the fish in the pond. The hydroponic plants benefit from the nutrients produced by fish waste, while the fish receive natural food generated from the roots of the hydroponic plants. Figures 2 and 3 illustrate the front and side views of the designed aquaponic farming system, which is integrated with a control system based on Multi-Modal Sensors processed through a hybrid ESP32 and Raspberry Pi platform.

Based on the information presented in Figures 2 and 3, the developed aquaponic farming system in this study consists of three main components: the aquaculture section, which includes the fish pond used for fish cultivation; the hydroponic section, consisting of pipes and net pots that serve as planting media for hydroponic vegetables; and the control box section, which houses all control and electronic components in a single enclosure. Additionally, the system includes a Multi-Modal Sensor unit used to detect environmental conditions and monitor the aquaponic farming status. Furthermore, Figures 4 and 5 show the design of the control box from external and internal views, respectively.

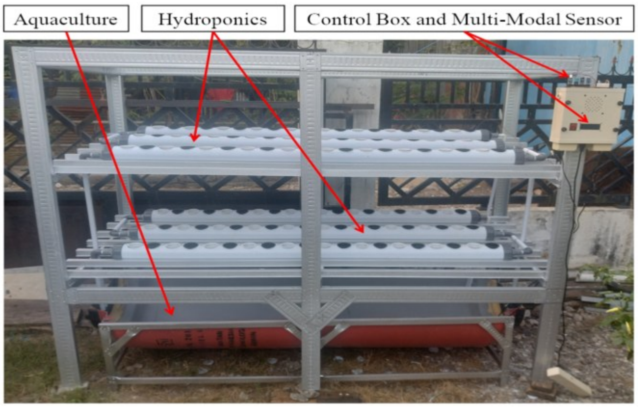

Figure 2. The results of the design of the aquaponic farm look like the front

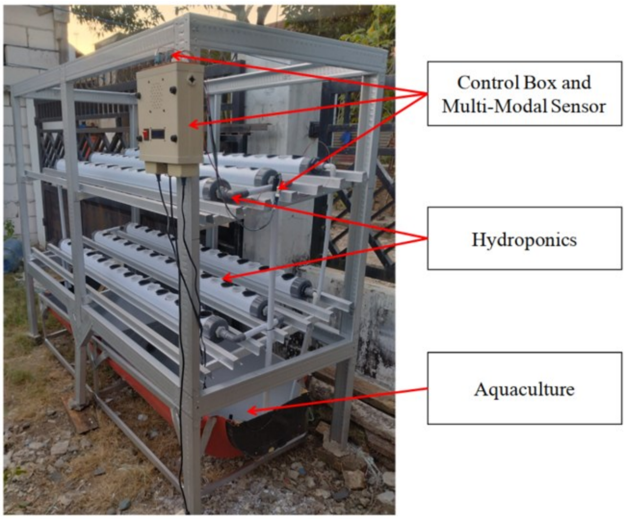

Figure 3. The results of the aquaponic farming design, side view

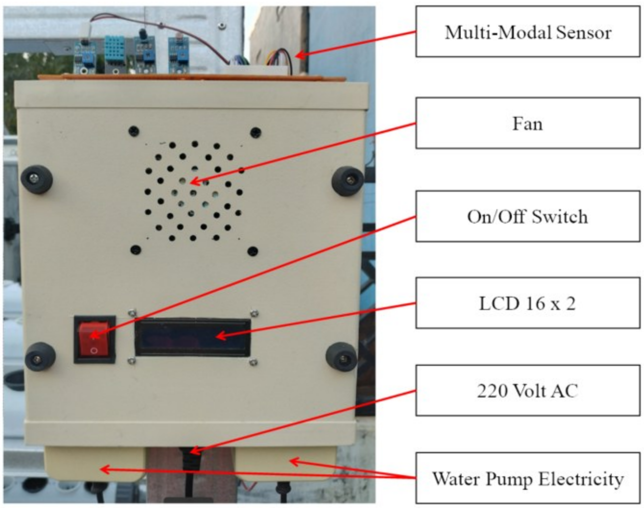

Figure 4. The results of the control box design appear outside

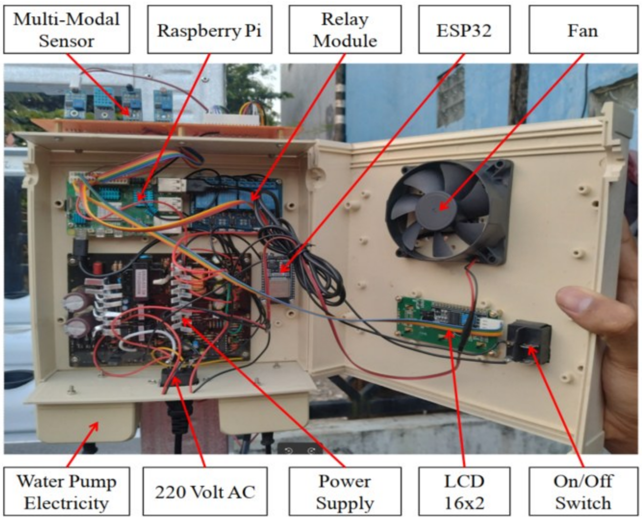

Figure 5. The results of the control box design are shown in

According to the information presented in Figures 4 and 5, the control box consists of several integrated components designed to manage the smart aquaponic farming system through the combination of Multi-Modal Sensors, ESP32, and Raspberry Pi. The main components within the control box include: Multi-Modal Sensors, cooling fan, on/off switch, 16x2 LCD, 220V AC input voltage, water pump power outlet, Raspberry Pi, relay module, ESP32, and power supply unit. The function of the Multi-Modal Sensors in this study is to monitor the environmental conditions of the aquaponic system, including ambient and solar light intensity, air temperature and humidity, hydroponic water level, water temperature, aquaculture pond pH, and nutrient levels. The cooling fan within the control box serves to regulate internal temperature and ensure proper air circulation for all electrical components. The on/off switch is used to power the system on and off, while the 220V AC input supplies the main power source. In addition, the control box contains an electrical outlet to power the aquaponic water pump, a Raspberry Pi functioning as the central microcomputer for control data processing, a relay module to control the on/off operation of the water pump, an ESP32 microcontroller to read analog sensor data, and a power supply unit to convert AC voltage into DC, providing power to all internal components of the control box.

In this study, we have utilized several types of sensors integrated into a single unit to form a Multi-Modal Sensor module. Figure 6 and 7 illustrate the types of sensors used to construct the Multi-Modal Sensor.

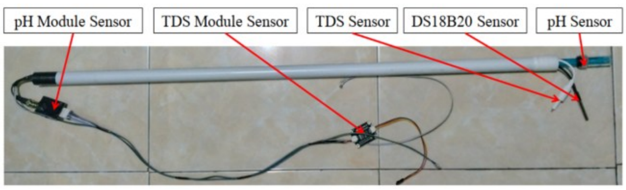

Figure 6. Multi-modal sensor (pH, TDS, and DS18B20)

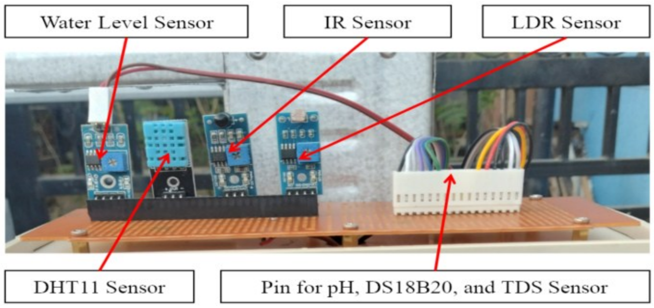

Figure 7. Multi-modal sensor (water level, IR, LDR, and DHT11)

Regarding the information in Figure 6 and 7, it can be seen that several sensors have been integrated to form a Multi-Modal Sensor. The table 3 following are the types of sensors used in this study to construct the Multi-Modal Sensor.

TABLE 3
SENSOR FUNCTIONS IN MULTI-MODAL SENSORS MODULES

Sensors	Function
LDR	Reading light intensity in the morning, afternoon, evening, and weather
InfraRed	Reading the intensity of the sun's infrared light
pH Kit E-201C	Reading water acidity levels in aquaculture ponds
TDS	Read the nutrient levels contained in the water
DS18B20	Reading water temperature in aquaculture ponds
DHT11	Read air temperature and humidity
Water Level	Reading the water level in hydroponic pipes

In this study, the researchers analyzed the output data generated by each sensor using measurement techniques based on analog output data read by the ESP32, which is then converted into digital data, as well as digital output data received by the Raspberry Pi. Table 4 below presents the results of sensor data measurements using instrumentation techniques.

TABLE 4
OUTPUT DATA RESULTS FOR EACH SENSOR

Sensors	Output	Devices	Data
LDR	Analog	ESP32	0 ~ 1023
InfraRed	Analog	ESP32	0 ~ 1023
pH Kit E-201C	Analog	ESP32	0 ~ 14
TDS	Analog	ESP32	0 ~ 1000
DS18B20	Analog	ESP32	-55 ~ 125
DHT11	Digital	Raspberry Pi	0 ~ 50
Water Level	Digital	Raspberry Pi	0 / 1

Focus on the information in Table 4, it can be observed that each sensor output has its own value according to its respective function. The output data generated from the sensors connected to the ESP32, which are in analog form, are converted into digital data and then transmitted to the Raspberry Pi using a serial communication protocol. Meanwhile, all sensors connected to the Raspberry Pi's GPIO produce digital data, as the Raspberry Pi does not have GPIO pins capable of converting analog sensor signals into digital signals.

In future research development, the researchers will implement the output data generated by the ESP32 and Raspberry Pi to be processed within a cloud-based Internet of Things (IoT) system. Table 5 presents the data type design that will be used for the development of the IoT-based aquaponics system.

TABLE 5
IOT DATA TYPE DESIGN

Sensors	Data	Data Type
LDR	0 ~ 1023	Float
InfraRed	0 ~ 1023	Float
pH Kit E-201C	0 ~ 14	Float
TDS	0 ~ 1000	Float
DS18B20	-55 ~ 125	Float
DHT11	0 ~ 50	Float
Water Level	0 / 1	Boolean

Based on the information in Table 5, it can be seen that the sensor output data will be utilized for control and monitoring through an Internet of Things (IoT)-based system. This approach will greatly assist the community in developing aquaponics systems by implementing IoT-based technologies.

In this study, we validated the error accuracy of the sensors by comparing their readings with actual conditions. Figure 8 presents the experimental results of error accuracy testing on multi-modal sensor readings using real measurement instruments.

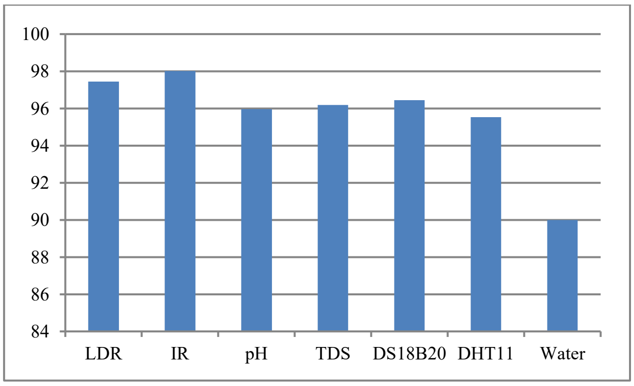

Figure 8. Multi-modal sensor testing accuracy level

Based on the accuracy results shown in the graph in Figure 8, it can be observed that the average sensor detection accuracy exceeds 95%. This occurs because the sensor output data is generated based on fuzzy computations embedded in the program. Therefore, according to the detected accuracy results, it can be concluded that the multi-modal sensors used in this study are feasible for detecting conditions in aquaponic farming systems.

Furthermore, in this study we also conducted an analysis of the power consumption of each sensor and device. Table 6 presents the average power consumption of each aquaponic farming device.

TABLE 6
POWER CONSUMPTION OF EACH DEVICE

Devices	Voltage	Current	Power (Avg)
LDR	5V	~0.5 mA	~2.5 mW
InfraRed	5V	30–50 mA	150–250 mW
pH	5V	5–10 mA	25–50 mW
TDS	3.3-5V	3–6 mA	10–30 mW
DS18B20	3.3-5V	1–1.5 mA	3–7 mW
DHT11	5V	2,5 mA	1 – 12 mW
Water Level	5V	3–5 mA	15–25 mW
Raspberry Pi	5V	0.6–1.5A	3–7.5 W
ESP32	3.3V	20–250 mA	0.1–0.8 W
LCD 16x2	5V	20–30 mA	120–160 mW

Based on the results of this study, it can be concluded that the findings can be applied to the development of IoT-based control applications. The topology that can be adopted for integrating this system into an IoT framework is a mesh topology, where all devices are dynamically interconnected within the network. Furthermore, IoT protocols such as MQTT and HTTP can be utilized in future implementations, along with serial communication systems for data exchange between the ESP32 and Raspberry Pi. From the software development perspective, this study employs the C programming language to read analog sensor data and transmit it to the Raspberry Pi via serial communication, while Python, running on the Raspberry Pi, functions as the central data processing platform. Therefore, based on the outcomes of this research, the data output is ready to be connected to an IoT network through both on-premise and cloud-based internet infrastructures. Moving forward, IoT network analysis will be conducted on the devices by considering quality parameters such as delay, throughput, latency, and the scalability of sensor deployment in large-scale and long-term applications.

IV. CONCLUSION

The implementation of multi-modal sensor integration in the aquaponic farming system for monitoring and control based on a combination of ESP32 and Raspberry Pi control systems has been developed in this study. The multi-modal sensors used in this research include an LDR to detect weather conditions, an IR sensor to measure sunlight intensity, a pH sensor to monitor the pH level of the aquaponic water, a TDS sensor to monitor nutrient levels, a DS18B20 to measure water temperature, a DHT11 to measure air temperature and humidity, and a water level sensor to detect the water level. The results of this study demonstrate that the ESP32 can effectively transmit analog sensor data—converted into digital form—to the Raspberry Pi through serial communication. Furthermore, the Raspberry Pi is capable of receiving and reading digital sensor data. This research has also designed the data types and structures required for further development of an IoT-based aquaponic farming system. A recommendation for future research is to implement the developed system using cloud-based Internet of Things technology and smart greenhouse farming systems.

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