Design and Implementation of a Real-Time Aquaponics Automation System for Water Quality Management

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Abstract. Rapid population growth in cities like Jakarta has led to a decline in green open spaces and environmental quality. Aquaponics serves as a viable solution that can be implemented within the community. However, this system requires accurate water quality monitoring to ensure optimal plant growth and fish health. This study aims to develop an automated aquaponics system for real-time water quality control and fish maintenance. The system integrates temperature, pH, and gas sensors to monitor critical environmental parameters, utilizing actuators such as water pumps, peristaltic pumps, and compressors to maintain ecosystem stability. The main components include an Arduino Uno microcontroller, a DS18B20 temperature sensor, a pH-4502C sensor, an MQ-135 gas sensor, and a Nextion HMI LCD for real-time data display. The system's algorithm is designed to activate the cooling mechanism when the temperature exceeds the ideal threshold and initiate water circulation when the pH falls outside the 6.0–7.0 range. The system was developed using the ADDIE model, and the sensors were validated through calibration and statistical analysis. Test results indicate that the sensors operate accurately, and the MQ-135 sensor successfully detects ammonia gas concentrations at three different points. The system has proven to be stable for long-term operation and can serve as an efficient prototype for a small-scale automated aquaponics system.

1 Introduction

Rapid population growth in major cities like Jakarta drives massive land conversion, particularly from agricultural land to residential areas and infrastructure. This phenomenon has a direct impact on the reduction of green open spaces and the degradation of environmental quality [1]. According to data from the Statistics Indonesia (BPS) of DKI Jakarta, harvested land area dropped drastically from 559.7 hectares in 2021 to only 498.31

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hectares in 2024 [2]. This condition exacerbates both food and environmental crises in urban areas.

On the other hand, the community's demand for food continues to rise alongside population growth. To address this challenge, innovations in agricultural systems that are adaptable to limited spaces and environmentally sustainable are necessary. One increasingly relevant approach is the aquaponics system, an integrated farming method that combines fish farming and plant cultivation within a closed ecosystem [3].

In an aquaponics system, fish produce ammonia-rich waste, which is subsequently converted by bacteria into nitrites and nitrates. These compounds are then utilized as nutrients by the plants [4]. Conversely, the plants filter the water and help purify the aquatic environment, allowing clean water to return to the fish tank. This process creates an efficient mutualistic symbiosis within the water and nutrient cycles [5].

However, the success of an aquaponics system relies heavily on stable water quality. The main parameters influencing this stability are temperature, pH, and nutrient content. Water temperature affects fish metabolism and plant growth rates. The ideal temperature range for freshwater fish is 22–28 °C, while for hydroponic plants it is 18–24 °C [6], [7]. A balanced water pH is also a crucial factor in supporting the nitrification process and nutrient absorption by plants, typically ranging between 6.0 and 7.0 [8].

To maintain the stability of these parameters, a reliable monitoring and control system is required. Manual measurements are considered inefficient and prone to human error, especially in the event of sudden temperature and pH fluctuations. Therefore, a microcontroller-based automation system, such as the open-source Arduino Uno, serves as a highly relevant approach to monitor water conditions in real-time and adaptively control the actuators [9].

As primary components in water quality measurement, the DS18B20 temperature sensor offers the advantage of high-accuracy digital reading [10]. The pH-4502C sensor enables continuous monitoring of the solution's acidity level [11], while the MQ-135 gas sensor is utilized to detect ammonia gas concentrations within the system [12]. To support the automatic control system, actuators such as peristaltic pumps and cooling compressors are used, operating based on sensor inputs and controlled directly by the microcontroller.

Previous research by haryanto et al. [13] implemented smart aquaponic system based Internet of Things (IoT) without considering nutrient content control. Based on these research gaps, this research develops a microcontroller-based aquaponics system equipped with real-time monitoring features for temperature, pH, and gas, integrated with automatic control using water pumps, peristaltic pumps, and compressors.

2 Material and methods

This research employs a hardware engineering approach by adapting the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) system development model. The research and system testing were conducted at the Applied Physics Laboratory, Universitas Negeri Jakarta. The implementation of the ADDIE model in this study was carried out systematically across its five phases. In the Analysis phase, the system requirements were determined by identifying critical parameters such as temperature limits (>30°C), ideal pH (6.0–7.0), and ammonia monitoring needs, which dictated the selection of specific sensors and actuators. During the Design phase, the physical prototype's 3D architecture, the automated logic workflow, and the graphical HMI layout were structured. The Development phase involved the physical assembly of the hardware, coding the control algorithms using the Arduino IDE, programming the Nextion LCD, and calibrating the sensors with standard buffer solutions. In the Implementation phase, the integrated system was deployed at the Applied Physics Laboratory to commence the real-time monitoring and control of the cultivation tanks. Finally, the Evaluation phase assessed the system's operational performance, specifically verifying the automated responsiveness of the cooling compressor and peristaltic pump to environmental fluctuations, ensuring reliable real-time data display and overall system stability.

2.1 Materials

The primary materials and instruments utilized in developing this system consist of hardware and software components. The hardware includes an Arduino Uno microcontroller as the central processing unit, a DS18B20 temperature sensor, a pH-4502C sensor, and an MQ-135 gas sensor. Actuators used to maintain environmental stability comprise a DC water pump, a peristaltic pump, and a cooling compressor. The Human-Machine Interface (HMI) is facilitated by a Nextion LCD screen. For software development, the system is programmed using the Arduino IDE with C language, while the graphical interface on the LCD is designed using the Nextion Editor. Additional supporting materials include standard buffer solutions used for the calibration process of the pH sensor.

2.2 Hardware

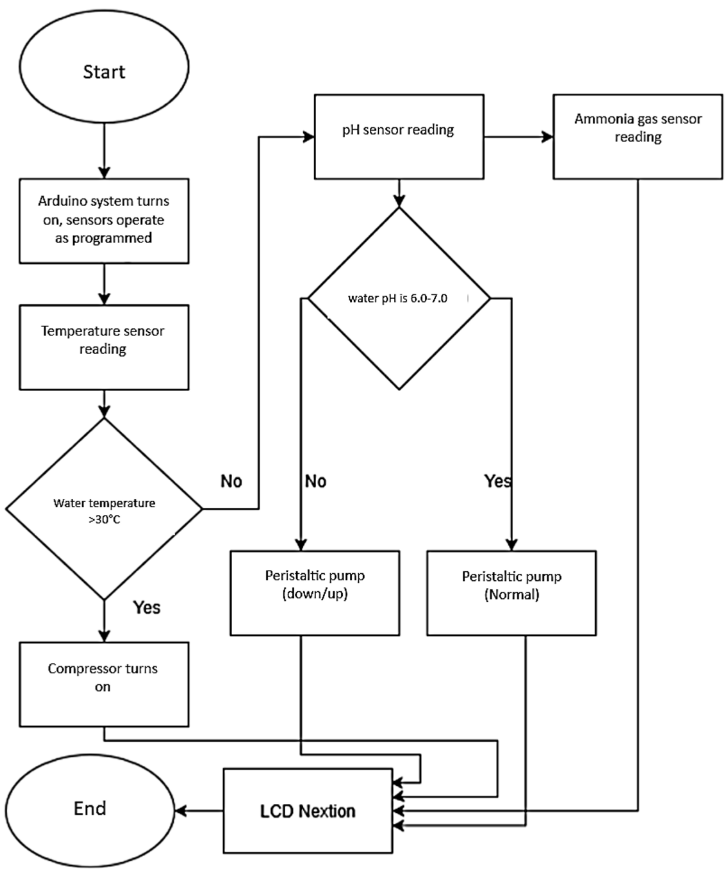


Fig. 1. System overview.

The entire hardware system operates based on an automated workflow regulated by the microcontroller is shown on Figure 1. Upon system startup, the Arduino initializes all sensors to begin monitoring environmental parameters. According to the system's flowchart, the process begins with the temperature sensor reading; if the water temperature is detected at >30°C, the system automatically activates the cooling compressor. Next, the system reads the water's pH value; if the pH is within the ideal range (6.0–7.0), the peristaltic pump operates in normal mode. However, if the pH falls outside this range, the peristaltic pump operates adaptively (down/up) to correct the acidity level. Concurrently, the MQ-135 sensor reads the ammonia gas levels within the system. All reading data from these sensors are constantly transmitted and displayed on the Nextion LCD for real-time monitoring.

2.3 Design and development of system

The physical prototype of the aquaponics system is designed to optimize water circulation and sensor integration within a limited space. Based on the 3D design of the system that shown on Figure 2, the structure consists of several cylindrical cultivation tanks interconnected through a centralized piping network. The main framework of the system has overall dimensions of 115 x 112 cm. The cultivation containment is designed with dimensions of 100 x 20 cm, supported by a 2.6 x 50 cm piping system to distribute the water.This design ensures that actuators can respond to changes in water quality evenly across all tanks.

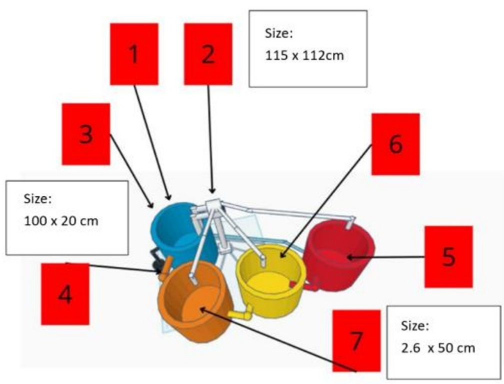


Fig. 2. Design of Prototype.

3 Result and discussion

3.1 Sensor Characterization

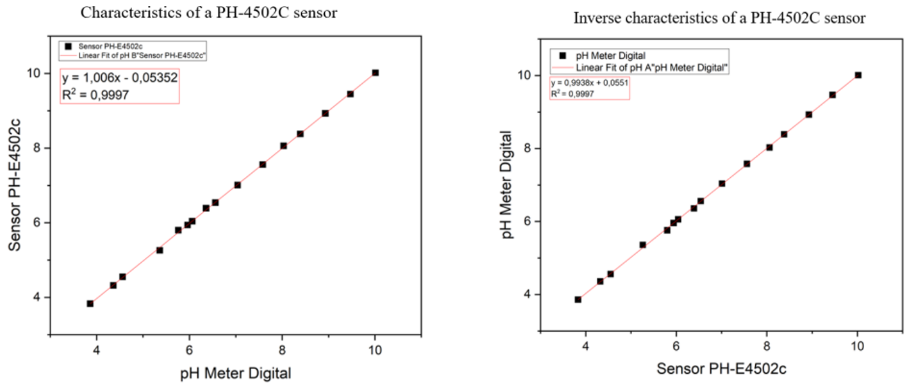
Characterization was performed on the two main sensors in the system, namely the pH-4502C sensor and the DS18B20 temperature sensor, to ensure the accuracy and linearity of their readings against standard measuring instruments prior to their integration into the automated system. The pH-4502C sensor was compared against a digital pH meter as a reference within a pH range of 3 to 10, as shown in Figure 3.

The characterization results in Figure 3 yield a linear relationship with the regression equation:

$$y = 1{,}006x - 0{,}05352\ (R^2) = 0{,}9997 \tag{1}$$

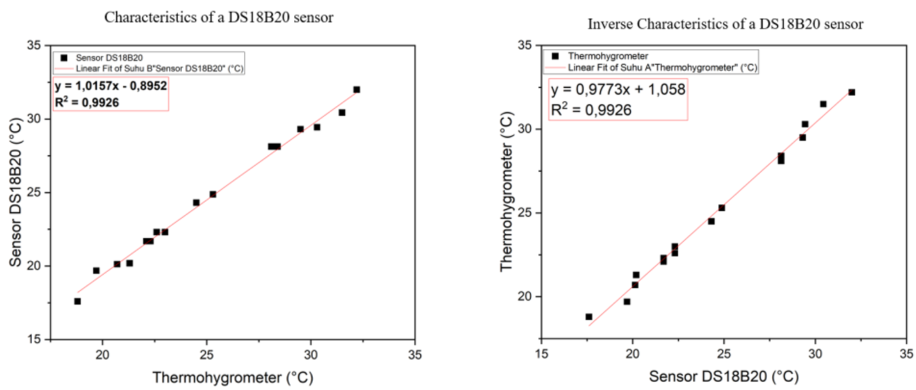
and the inverse graph:

$$y = 0{,}9938x + 0{,}0551\ (R^2) = 0{,}9997 \qquad (2)$$



(a) (b)

Fig. 3. Characterization graph of the pH-4502C sensor; (b) Inverse characterization graph of the pH-4502C sensor.



(a) (b)

Fig. 4. (a) Characterization graph of the DS18B20 sensor; (b) Inverse characterization graph of the DS18B20 sensor.

The DS18B20 sensor was characterized against a digital thermohygrometer within a temperature range of 18.8°C to 32.2°C. The obtained regression equation is:

$$y = 1{,}0157x - 0{,}8952\ (R^2) = 0{,}9926 \qquad (3)$$

and the inverse graph:

$$y = 0{,}9973x + 1{,}058\ (R^2) = 0{,}9926 \qquad (4)$$

These results demonstrate that the temperature sensor also possesses good accuracy and stability for an automated temperature monitoring system. Both characterizations serve as the foundation for designing the control logic of the microcontroller-based automated system.

3.2 System Testing and Performance Analysis

Functional testing of the system was conducted to ensure that all primary components operate as designed when the system is activated and receives input from the sensors. The test results are presented in Table 1.

Table 1. Functional System Testing.

Description	Yes	No
The system turns on when connected to a power source	✓	-
The temperature sensor can measure water temperature	✓	-
The pH sensor can read the water's pH level	✓	-
The gas sensor can read gas levels	✓	-
The cooling system can turn on according to sensor readings	✓	-
The peristaltic pump can turn on according to sensor readings	✓	-
The Nextion LCD can display the interface and measurement results	✓	-

The test results presented in Table 1 demonstrate the system's functional reliability across all main components. Upon connection to an electrical power source, the entire circuit powers on without interruption, confirming that the electronic circuitry and power distribution are correctly installed without any errors in the microcontroller or its supporting devices. In terms of data acquisition, the DS18B20 sensor accurately measures the water temperature, indicated by real-time value changes that correspond to actual conditions. Similarly, the pH-4502C sensor provides stable readings that successfully trigger the actuation of the peristaltic pump, while the MQ-135 gas sensor demonstrates a highly responsive detection of changes in ammonia gas concentration. These three sensors operate simultaneously, supplying valid data to the LCD and serving as the primary basis for automated decision-making. Furthermore, the actuators and control logic function exactly as intended; the cooling compressor turns on and off automatically based on temperature inputs, verifying the success of the thermal control logic. Concurrently, the peristaltic pump effectively injects corrective solutions when the pH falls outside the ideal range and subsequently returns to a normal standby mode once stability is achieved. Finally, the Nextion LCD screen successfully serves as the user interface by displaying all parameters in real-time with responsive visualization, thereby establishing the system as a communicative and efficient monitoring device.

3.3 Discussion

Following the successful basic functional testing, further observation was conducted on the system's performance under actual operating conditions. Data collection was carried out for five consecutive days at varying time intervals to observe the system's response to fluctuations in temperature, pH, and ammonia, as well as actuator activity. The observation results are presented in Table 2.

Based on the data presented in Table 2, a comprehensive analysis of the monitoring and control system reveals its operational efficacy across all measured parameters. During the testing period, the water temperature fluctuated between 25.00°C and 36.81°C. The cooling system successfully activated automatically whenever the temperature reached or exceeded 30°C. To protect the hardware, the system executes a specific cycle logic where the cooler remains active for a maximum of 30 minutes and then enters a 5-minute standby mode to prevent the compressor from overheating. The recorded data corroborates this responsive behavior; for example, on Day 2 at 15:20, the temperature reached 36.31°C, triggering the compressor to turn on. It subsequently turned off automatically when the temperature dropped below the threshold, as observed on Day 4 at 08:15 with a temperature of 29.25°C. This mechanism effectively secures an ideal thermal environment for both fish and plants.

Table 2. System Performance Observation Data (5 Days).

Day	Time	Temperature (°C)	pH	Gas 1 (PPM)	Gas 2 (PPM)	Gas 3 (PPM)	Peristaltic Pump	Cooling System
1	16:00	34.56	7.27	577	677	447	Down	On
	16:50	30.75	6.51	573	672	452	Normal	On
	17:20	30.63	6.52	538	657	364	Normal	On
2	15:20	36.31	7.04	681	597	425	Down	On
	16:05	32.75	6.91	667	595	405	Normal	On
	16:40	30.38	6.26	661	595	400	Normal	On
3	10:33	31.38	8.24	625	278	86	Down	On
	11:48	31	7.18	530	276	40	Down	On
	12:37	32.06	6.91	346	310	102	Normal	On
	13:42	32.69	6.58	332	320	84	Normal	On
4	8:15	29.25	5.94	365	341	25	Up	Off
	9:20	30.25	6.07	277	237	26	Normal	On
	10:25	31.31	6.3	227	364	104	Normal	On
	11:37	31.3	6.87	228	302	173	Normal	On
5	8:20	29.25	7.26	222	350	22	Down	Off
	9:20	31	6.02	215	300	42	Normal	On

In terms of acidity regulation, the recorded pH values ranged from 5.94 to 8.24. Whenever the pH deviated from the ideal 6.00–7.00 range, the system accurately activated the peristaltic pump. For instance, on Day 3 at 10:33, the pH reached an alkaline level of 8.24, prompting the pump to operate in "Down" mode to inject the required corrective solution. Conversely, when the pH dropped to 5.94 on Day 4 at 08:15, the pump operated in "Up" mode. This dynamic corrective mechanism is crucial for maintaining the continuity of biological nitrification processes within the aquaponics system.

Furthermore, the distribution of MQ-135 sensors across three distinct points revealed a significant rate of ammonia reduction throughout the system's operation. The ammonia concentration at the mechanical filter (Gas 1) dropped drastically from 577 PPM to 215 PPM. Similarly, the concentration at the biofilter (Gas 2) decreased from 677 PPM to 300 PPM, while the post-nitrification stage (Gas 3) reached the safest level, dropping from 447 PPM down to just 42 PPM. This consistent downward trend serves as a strong indicator that the aquaponics ecosystem is functioning optimally, successfully converting toxic fish ammonia waste into safe and beneficial nitrite and nitrate compounds for plant uptake.

Holistically, the automation system demonstrated reliable and stable performance over the five days of continuous testing. All actuators provided a rapid response time of less than two seconds to any parameter changes detected by the sensors. These findings validate that this microcontroller-based aquaponics system prototype is highly capable of operating independently and adaptively. Ultimately, the system effectively addresses the primary challenges of water quality maintenance inherent in urban farming environments.

4 Conclusion

This research has successfully developed a microcontroller-based aquaponics automation system capable of monitoring and controlling water quality parameters in real-time. The system integrates a temperature sensor (DS18B20), a pH sensor (pH-4502C), and a gas sensor (MQ-135), and utilizes actuators including a peristaltic pump and a cooling compressor to maintain the stability of the aquaponics environment. Test results indicate that all sensors function with high accuracy and the system can automatically respond to parameter changes with a rapid response time (2 seconds). This system can serve as an efficient prototype for a small-scale aquaponics system and can be implemented in urban communities to enhance technology-based integrated agricultural productivity.

Future development can focus on integrating the system with the Internet of Things (IoT) for remote access, as well as adding humidity and light control features to support more complex and precise cultivation systems.

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