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Article

Implementation of IoT Technology in Aquaponics and Modern Aquaculture Systems for Optimizing Catfish Growth

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Abstract: In the modern era, various systems of agriculture and aquaculture have evolved rapidly. One remarkable innovation is modern aquaponics, a method that is gaining recognition as a sustainable solution for food production. This system combines fish farming and agriculture into a unified and mutually beneficial approach. Modern aquaponics has proven to be effective in overcoming the constraints of urban land, providing a viable solution for both agriculture and aquaculture. For optimal results in fish farming, it is crucial to consistently monitor the conditions of fish growth and health to avoid the risk of crop failure. In response to this challenge, this study aims to implement an Internet of Things (IoT) system in modern aquaponics, focusing primarily on enhancing the growth of catfish in a controlled and efficient manner. This system employs a range of IoT sensors, including pH sensors, Total Dissolved Solids (TDS) sensors, and temperature sensors, to monitor the water quality within the aquaponics setup continuously. Such monitoring not only ensures optimal conditions for healthier fish but also increases plant productivity, thereby enhancing the overall sustainability and effectiveness of the cultivation process. The results of sensor testing revealed a pH value of 7.2, indicating that the water's acidity level is within a balanced and optimal range for supporting the health of catfish. TDS sensor readings showed a value of 300 ppm, suggesting that the concentration of dissolved particles is ideal for the well-being of the fish. Furthermore, temperature measurements from the DS18B20 sensor recorded a water temperature of 28°C, which falls within the optimal range for catfish growth (28–30°C). These conditions create a stable environment that supports the healthy growth of fish in the aquaponics system.

Keywords: Aquaponics, Aquaculture, Catfish Growth Optimization, IoT

1. Introductions

Freshwater fish farming and growth processes typically require substantial space for development. However, the growing demand for food, coupled with limited land availability in urban areas, poses a significant challenge for city dwellers attempting to engage in gardening or fish farming activities. An effective solution to this issue is the adoption of aquaponic systems, which integrate fish farming and plant cultivation into a single, efficient, and eco-friendly system. The aquaponic system operates by utilizing waste products from fish, such as excrement and uneaten feed, as a nutrient source for plants [1]. These nutrients are absorbed by the plants, which simultaneously clean and purify the water before it is recirculated back into the system for reuse by the fish. This process establishes a mutually supportive ecosystem where fish and plants thrive together in a sustainable cycle. One pressing challenge in urban areas is ensuring food security, which aquaponic systems address by enabling sustainable food production within limited spaces [2]. According to the Ministerial Regulation of Marine Affairs and Fisheries of the Republic of Indonesia Number 17/PERMEN-KP/2020 on the Strategic Plan of the Ministry of Marine Affairs and Fisheries for 2020–2024, the per capita fish consumption target was set at 56.39 kilograms in 2020, rising to 58.08 kilograms in 2021 [3]. This upward trend indicates a growing public awareness of the nutritional benefits of fish as a rich protein source. It also underscores the increasing recognition of fish as a vital component of a healthy and balanced diet for individuals and families alike.

To meet this goal, substantial efforts are necessary to guarantee a sufficient and affordable fish supply for all segments of society, especially in regions lacking direct access to fishing grounds such as oceans or open waters. This limitation highlights the need for reliable and sustainable alternative sources of fish production. One viable solution is the advancement of freshwater fish farming, which can be implemented through traditional pond systems or more innovative methods like aquaponics. Aquaponic systems offer dual benefits: they maximize land-use efficiency and enable the simultaneous cultivation of fish and plants. This integrated approach not only strengthens food security but also improves the availability of locally sourced food in a sustainable and environmentally friendly way.

Catfish is one of the most suitable fish species for cultivation in aquaponic systems due to its ease of production and relatively low cost. It is highly nutritious, offering essential nutrients such as protein, carbohydrates, fats, calcium, phosphorus, and iron, making it a valuable addition to human diets. Because of its significant nutritional benefits, catfish has become a key commodity in national agricultural initiatives [4]. In aquaponic systems, catfish play a vital role in supplying essential nutrients like nitrogen (N) and phosphorus (P) through their waste and uneaten feed. The natural processes within the system rely on beneficial bacteria to convert fish waste and leftover feed into nitrates, which serve as primary nutrients for plant growth. This conversion establishes a symbiotic cycle between fish and plants, ensuring the sustainability of both components in the aquaponic ecosystem while enhancing the overall efficiency of food production [5].

Meanwhile, plants in aquaponic systems play a crucial role in filtering water by removing toxic gases generated as metabolic waste from fish, such as ammonia and carbon dioxide. This filtration process is essential, as the purified water is recirculated back into the system, creating a healthier environment for the fish throughout the cultivation period [6]. During aquaculture, fish produce nitrogen in various forms, including ammonia (NH3-N), nitrite (NO2-N), and nitrate (NO3-N), all of which contribute to the nutrient cycle that supports plant growth. Approximately 80–90% of the ammonia is excreted by fish through osmoregulation, while the remaining 10–20% is released via faeces and urine, which also contain total ammonia nitrogen (TAN). Total ammonia nitrogen consists of two main forms: un-ionized ammonia (NH3), which is toxic at high concentrations, and ionized ammonia (NH4), less harmful to fish. These ammonia compounds are natural byproducts of protein metabolism within the fish, and managing their levels is critical to maintaining a balanced and healthy aquaponic ecosystem. In this system, fish and plants work symbiotically, supporting each other to achieve optimal growth and sustainability [7].

In addition to the challenges posed by limited urban land for catfish farming, farmers encounter several other obstacles in cultivating catfish, whether on a large scale or through aquaponic systems. One of the most significant challenges is the instability of freshwater temperatures, which can inhibit catfish growth. Additionally, maintaining stable levels of Total Dissolved Solids (TDS), water pH, and water turbidity plays a crucial role in determining the growth rate of catfish. These factors are critical as they directly impact the quality of the aquatic environment, which is vital for ensuring fish health and avoiding disruptions that could hinder growth. The three key factors, water pH, TDS levels, and turbidity, significantly influence the quality of the fish's habitat, thereby affecting their health and development [8]. Maintaining optimal water conditions, such as balanced pH, suitable levels of dissolved particles, and adequate water clarity, supports efficient fish metabolism, ultimately enabling their maximum growth potential [9].

To effectively address the issues previously highlighted, adopting innovative and efficient technologies is crucial for comprehensive problem resolution. One promising solution is the implementation of Internet of Things (IoT) technology, which offers an integrated monitoring and control system to optimize catfish growth in modern aquaponic setups [10]. This IoT system is meticulously designed to enable real-time tracking of environmental parameters through advanced sensors capable of measuring key factors such as water pH, temperature, and density [11]. By continuously monitoring these conditions, IoT technology enables faster, data-driven decisions to maintain optimal water quality and environmental conditions, ultimately improving the efficiency and productivity of the aquaponic system [12].

Every shift in these parameters can be quickly identified, and the gathered data can be monitored live on mobile devices like smartphones, linked directly to a web-based application. This allows fish farmers to supervise more efficiently and take immediate corrective measures if the environmental conditions fall out of line, which ultimately boosts both productivity and the overall health of the fish in the aquaponics system. With this kind of monitoring and control in place, farmers can easily keep track of water quality and act quickly should any abnormalities arise, thus reducing the risk of crop failure. In addition to IoT technology, the system also features a portable function to identify the aquaponics setup location, making it adaptable for both indoor and outdoor placements.

2. Materials and Methods

Research on aquaponics has been conducted by Asep and colleagues in their work titled "*Environmental Management Through Education on Catfish Cultivation Utilizing Aquaponics and Hydroponics as Alternative Solutions for Optimizing Limited Land Use.*" This study involved two months of observation with four fish farmers in Pagar Alam City, a region in Indonesia recognized as one of the areas whose primary income is derived from agriculture and tourism. According to Law No. 23 of 1997 concerning Environmental Management, the environment is a unified space that includes all objects and living beings, including humans and their behaviour, which supports the life and well-being of humans and other living creatures. Humans, as the entities with the greatest control over the environment on Earth, play a critical role in maintaining the sustainability of the natural environment [13].

The research findings indicate that the village has significant potential for land utilization in the development of aquaponic systems. Utilizing this land could enhance agricultural and aquaculture productivity in the area. However, to realize this potential fully, it is recommended that the community innovate by adopting more modern hydroponic or aquaponic systems. Such innovations would contribute to improving the local economy and help meet the food demands of Pagar Alam City in the future. Based on the challenges identified, the application of Internet of Things (IoT)-based technology is necessary to address the observed constraints while supporting Indonesia's agenda for the Fourth Industrial Revolution (Industry 4.0). The Minister of Industry, Airlangga Hartarto, has emphasized the importance of digital transformation for Indonesia to remain competitive in the global market, given the rapid advancements in digitalization that now span various industrial sectors.

This study employs the ESP32 and Arduino UNO microcontrollers as the primary control units, integrated with pH sensors, TDS sensors, and DS18B20 temperature sensors to measure water quality parameters. Additionally, the system incorporates several supporting components, including a power supply, step-down module, relay, and aquarium heater.

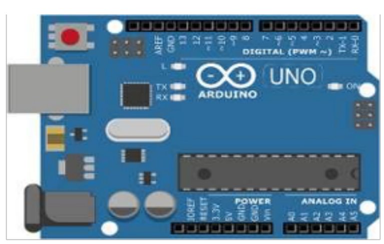

Figure 1. Arduino UNO

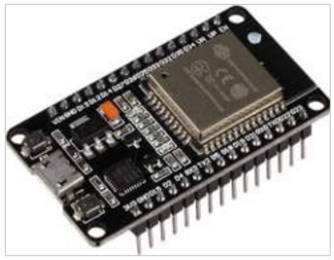

Figure 2. Arduino UNO

As a microcontroller, the Arduino UNO is responsible for transmitting the values obtained from the pH sensor to the ESP32, as illustrated in Figure 1.
As a microcontroller, the ESP32 functions to control various electronic devices and other sensors, as illustrated in Figure 2.

Figure 3. Sensor pH

This sensor functions to measure the acidity or alkalinity of a solution by detecting the concentration of hydrogen ions (H^+) within it. The optimal pH range for catfish habitats is between 6 and 8, as illustrated in Figure 3

Figure 4. DS18B20 Temperature Sensor

This device is used to measure the water temperature in aquaponics systems to enhance the survival and growth of catfish. The measurement is conducted by monitoring the water temperature after it has been filtered through the filter bucket and plant roots. The optimal temperature range for catfish habitats is between 28°C and 35°C, as illustrated in Figure 4.

Figure 5. Sensor TDS

This device is used to measure the concentration of dissolved solids in the water for catfish habitats. The Total Dissolved Solids (TDS) concentration serves as an important indicator of water cleanliness and health. The optimal dissolved solid level for catfish habitats is approximately 300 ppm, as illustrated in Figure 5.

2.1 Research Flowchart

The initial stage of this research involves hardware design, beginning with the development of the Nutrient Film Technique (NFT) module. NFT is a system that utilizes a thin layer of nutrient solution, or 'film,' with a thickness of approximately 1-3 mm. This solution is pumped and continuously circulated over the plant roots at a flow rate of around 1-2 litres per minute. This stable nutrient flow ensures that the plant roots receive an optimal supply of nutrients for growth.

According to S. Wibowo and A. Asriyanti, the steeper the slope of the trough in the NFT system, the higher the plant productivity [14]. This method offers several advantages, including ease of root zone control, ensuring optimal water supply, and the ability to adjust the uniformity and concentration of the nutrient solution based on the plant's age and type. It also offers benefits such as low maintenance costs, better resistance to pests and diseases, and eliminates the need for special fertilization. These advantages make it an efficient solution for plant cultivation systems [15]. Meanwhile, in the aquaculture component, the authors applied the sump filter method to direct water into a bucket tube, replacing the previous chamber setup. After passing through the filtration process in the bucket tube, the filtered water is then pumped back and directed into the aquaponic pipes, ensuring efficient water circulation and maintaining water quality within the system.

2.2 Stages of Equipment Assembly

This graphic representation provides an overview of the workflow and key components in the system design of this study. The diagram illustrates how each part of the system operates and interacts to achieve the goal of monitoring and controlling pH, TDS, and water temperature in the aquaponics system. Figure 2 shows a block diagram outlining the operational mechanism of the device, including how sensors (pH, TDS, and temperature) transmit data to the microcontroller (ESP32 or Arduino UNO), which processes the data and controls devices such as heaters or pumps to maintain optimal water conditions.

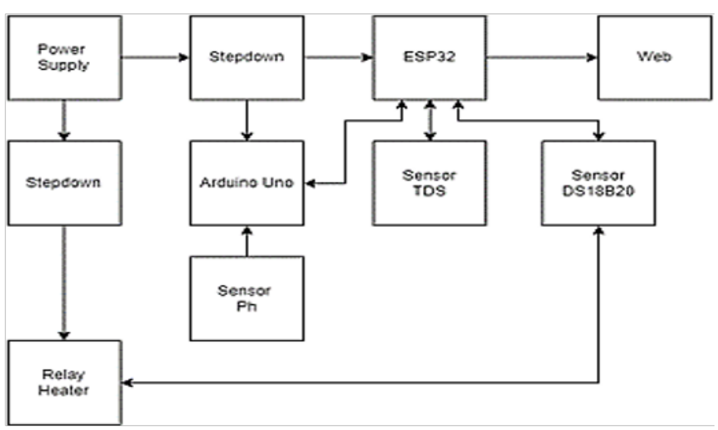

Figure 6. Diagram Blok

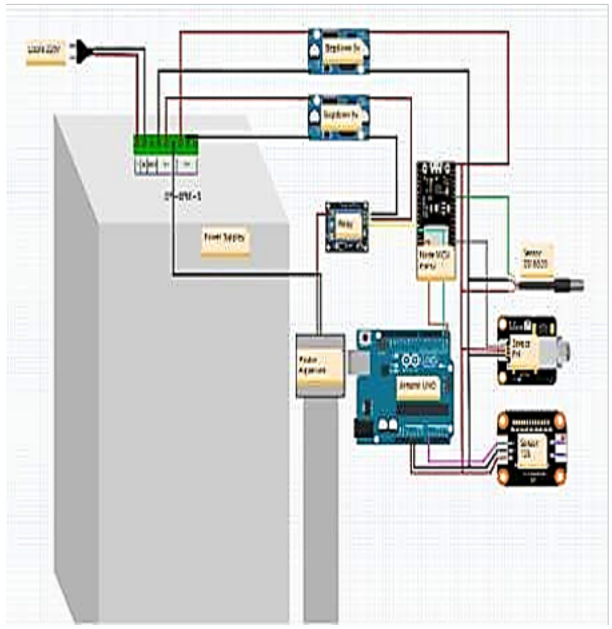

Figure 7. Integration Device Circuit

The schematic diagram of the system can be described as follows:

1. The 12V 20A Power Supply converts AC to DC, providing the necessary power to all components within the system.
2. LM2596 Step-down converter reduces the voltage from 12V to 5V or 3.3V, depending on the requirements of the microcontroller and sensors.
3. NodeMCU ESP32 serves as the primary microcontroller, connecting the system to the Wi-Fi network. It also processes signals from the sensors and transmits data to the user's device via the internet.
4. Arduino UNO receives data from the pH sensor and sends the information in serial data format to the ESP32, enabling the pH values to be displayed on the website.
5. The relay functions as an automatic switch controlled by the microcontroller, allowing the activation or deactivation of devices such as the heater or water pump based on the system's needs.
6. pH Sensor measures the pH level of the water in the catfish aquarium, which is a crucial parameter in maintaining water quality for the health of the fish.
7. TDS Sensor measures the concentration of dissolved solid particles (ppm) in the catfish aquarium water, serving as an important indicator of water quality and health.
8. DS18B20 Sensor monitors the water temperature in the catfish aquarium, as stable and optimal water temperature is essential for the fish's health and comfort.
9. The Aquarium Heater is used to heat the aquarium water, stabilizing the temperature to maintain it within the optimal range for catfish growth.

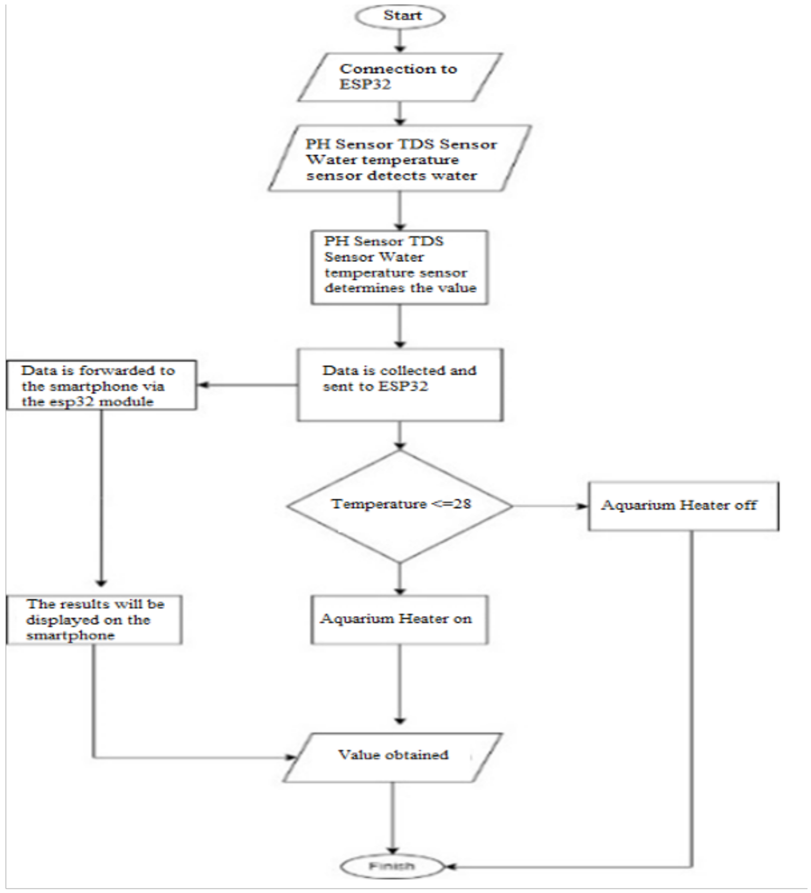

Figure 8. Flowchart of the Process for Displaying Data on the Smartphone

To ensure the clarity and systematic representation of the aquaponics monitoring and control process, a detailed flowchart was developed. The flowchart outlines the sequential flow of activities within the system, starting from data acquisition to controlling specific components based on predefined thresholds. The system begins by initializing the ESP32 and Arduino UNO microcontrollers, which serve as the central control units. Once initialized, the system enters the data acquisition phase, where the pH sensor, TDS sensor, and DS18B20 temperature sensor measure the respective water quality parameters. The microcontrollers then process the collected data, comparing it against preprogrammed threshold values. If any parameter falls outside the acceptable range, the system triggers corrective actions. For instance, when the water temperature drops below the set threshold, the microcontrollers activate the aquarium heater via the relay module. Similarly, the system could send alerts for maintenance if pH or TDS levels deviate significantly. These processes are powered by the LM2596 step-down converter, which ensures a stable voltage supply while the overall power requirement is met by the connected power supply unit.

The integration of Arduino IDE and Fritzing software plays a crucial role in designing the electronic circuit and programming the microcontrollers. The flowchart visually depicts this process, highlighting key decision points and interactions between components, thus enhancing the system's comprehensibility for both developers and researchers. This flowchart-driven approach underscores the efficiency and robustness of the system, aligning with the goals of sustainable aquaponics management. The incorporation of both monitoring and control mechanisms ensures optimal water quality, directly impacting plant and fish health within the aquaponics setup.

3. Results and Analysis

This section presents the results of testing the designed and implemented device, along with an analysis to evaluate the effectiveness of its design and application in a modern aquaponics system specifically implemented in limited land areas within communities. The implementation of this device aims to address the challenges of urban land constraints, where limited space is a major obstacle in simultaneously cultivating fish and plants. The tests conducted are intended to measure the device's ability to monitor and control key parameters required in the aquaponics system, such as pH, Total Dissolved Solids (TDS), and water temperature. The data obtained from the sensors integrated into the IoT system, which can be monitored in real-time, will be analyzed to assess whether the system can maintain the optimal conditions necessary to support the growth of catfish and plants. Through this analysis, the authors will evaluate the extent to which the device successfully maintains aquaponic environmental quality and provide insights into areas that may require further development to improve system performance and sustainability, particularly in maximizing the potential for agriculture and fish farming in limited spaces.

The pH sensor plays a crucial role in monitoring the environmental conditions within the catfish aquaponics system by ensuring that the water's pH level remains within the optimal range to support the growth and health of both fish and plants. Continuous pH monitoring is essential, as the stability of water quality directly affects the effectiveness and productivity of the overall aquaponics system.

pH sensor testing was conducted over five consecutive days, with data collection once per day, to evaluate the consistency and stability of the pH values within the system's environment. The results of this testing, detailed in Table I, provide insights into the effectiveness of the monitoring process and the potential need for pH adjustments to optimize growth in the aquaponics system.

Figure 9. Implementation of the Device Display

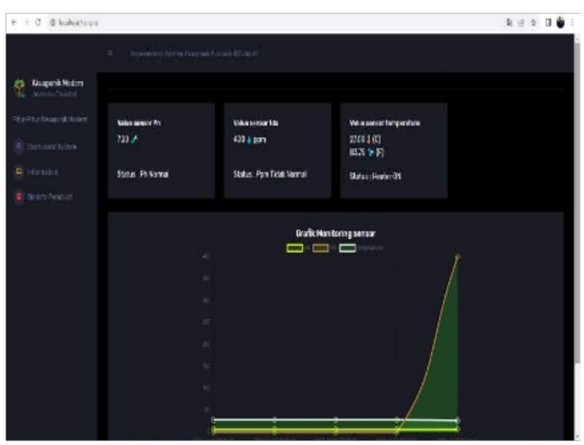

Figure 10. Sensor Data Display on the Web

Table 1. pH Sensor Test Results

Measurement Time	pH Value	Fish Condition	Description
Day -1	7.2	Healthy	pH within the ideal range
Day -2	7.5	Healthy	A slight increase in pH, but it is still within the optimal range
Day -3	7.8	Healthy	The pH continued to increase, requiring immediate action
Day -4	8.1	Fish are stressed	The pH is too high and requires immediate reduction to return to the optimal level
Day -5	7.7	Fish have recovered	The pH has been adjusted back to the optimal range

Table 2. TDS Sensor Test Results

Measurement Time	TDS Value (PPM)	Fish Condition	Description
Day -1	300	Healthy	TDS Value is Vulnerable Within the Optimal Range.
Day -2	350	Healthy	The increase is still within an acceptable range.
Day -3	400	Healthy	The TDS level increased, requiring a reduction to reach the optimal condition.
Day -4	380	Fish are stressed	TDS level decreased and is within a good range.
Day -5	300	Fish have recovered	The TDS level has been adjusted back to the optimal range

TDS sensors play a role in measuring the concentration of dissolved solid particles in the water used for catfish farming, which is an important indicator of water quality in the aquaponics system. Careful monitoring of this parameter is crucial, as optimal water quality directly supports the growth of catfish and maintains their health. The TDS sensor testing was conducted over five consecutive days, with data collection once each day, and the results are presented in Table II. Consistent monitoring is expected to maintain the stability of the aquarium environment and improve the overall productivity of the aquaponics system.

The DS18B20 temperature sensor plays a crucial role in monitoring and controlling the water temperature in the catfish aquaponics system. This sensor works by activating the heater to maintain water temperature stability when it drops below 28°C. Proper and consistent temperature regulation is essential for maintaining the quality of the aquaponics environment, as optimal temperatures support better fish metabolism and plant growth. If the water temperature is too low or high, it can disrupt the health of the fish and plants, as well as reduce the efficiency of the aquaponics system. Therefore, the DS18B20 temperature sensor was tested for five consecutive days to ensure its performance in maintaining the temperature within the appropriate range. Daily recorded temperature data provides valuable information for analyzing the sensor's ability to automatically regulate the water temperature, as shown in the following Table. With effective temperature monitoring, the aquaponics system is expected to operate more optimally, maintaining ideal conditions for the success of both fish farming and crop cultivation in limited spaces.

Table 3. DS18B20 Sensor Test Results

Measurement Time	Water Temperature	Heater Action	Fish Condition	Description
Day -1	28°C	Off	Healthy	The water temperature is within the optimal range without the need for additional heating.
Day -2	25°C	On	Healthy	The water temperature is below the ideal range, so the heater is activated
Day -3	28°C	Off	Healthy	The water temperature has been adjusted back to the optimal range.
Day -4	30°C	Off	Healthy	The water temperature remains stable within the optimal range without the need for heating
Day -5	27°C	On	Healthy	The water temperature did not reach the optimal level, so the heater was activated to stabilize it

4. Conclusion

This study examines the application of Internet of Things (IoT) technology in modern aquaponic cultivation to support the growth of catfish (Oreochromis niloticus) and enhance crop yields. The findings of this research indicate that the application of IoT systems in aquaponics enables real-time, direct monitoring of environmental parameters, including water temperature, total dissolved solids (TDS), and pH levels. With more efficient and accurate monitoring, farmers can take more precise, quick, and appropriate actions in response to changes in environmental conditions. This is crucial to avoid extreme fluctuations that could negatively affect the growth of both fish and plants. Furthermore, the implementation of IoT ensures that environmental parameters remain within the optimal range required by catfish and plants, which in turn has the potential to increase productivity and the quality of aquaponic yields. The study also emphasizes the important role of IoT technology in supporting the sustainability of aquaponic farming. By improving resource efficiency and reducing negative environmental impacts, aquaponics can evolve into a more environmentally friendly system. The application of IoT technology in aquaponics also opens opportunities to integrate other advanced technologies, such as artificial intelligence (AI) and machine learning, which can enhance operational efficiency and productivity in fish and plant cultivation. These technologies enable more accurate and automated decision-making, improve monitoring processes, and optimize environmental conditions to support more optimal growth. Thus, the findings of this study highlight the significant potential of IoT technology in optimizing aquaponic systems, making them a more efficient and sustainable solution in agriculture and aquaculture.

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