Design of a Real-Time Monitored Aquaponics System for Sustainable Agriculture and Enhanced Food Security

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ABSTRACT

Sustainable food production has become a global necessity as communities confront challenges related to food security, resource limitations, and environmental degradation. Aquaponics, an integrated system combining aquaculture and hydroponics, offers a sustainable model for resource-efficient farming. However, maintaining water quality is critical to system performance, as imbalances directly affect both fish and plant health. The objective of this research was to design and implement a smart aquaponics system equipped with real-time monitoring to ensure optimal growing conditions while remaining accessible and cost-effective for small-scale and community use. The system was developed using an ESP32 microcontroller integrated with pH, turbidity, temperature, and water-level sensors. Data collection and visualization were managed through the Blynk mobile application, enabling continuous monitoring, one-second data updates, and automated notifications when parameters exceeded predefined thresholds. A prototype aquaponics system was constructed consisting of catfish (Siluriformes) and siow pai-tsai (Chinese cabbage) plants to evaluate system performance. Experimental results demonstrated consistent sensor performance with calibration deviations below ±1%, confirming stable real-time responsiveness. The monitored aquaponics system-maintained water quality within optimal ranges (pH 6–8, turbidity <10 NTU, temperature 27–33°C), supporting improved biological outcomes. Compared with the unmonitored system, fish highlighted greater growth performance (11.5 cm to 13.5 cm versus 11.0 cm to 12.4 cm), and plants revealed more robust development (2.5 cm to 4.8 cm versus 2.4 cm to 3.6 cm). The integration of IoT-based monitoring enhanced productivity, reduced risk of system failure, and demonstrated cost-effectiveness in construction and operation. In conclusion, the developed system highlights the potential of IoT integration in aquaponics as a practical and scalable approach to advancing sustainable agriculture and strengthening community food security. Its affordability and adaptability reinforce its relevance for education, research, and community-based farming initiatives.

Index Terms: Sustainable agriculture, Food security, Aquaponics, IoT monitoring, Water quality management

INTRODUCTION

Sustainable agriculture has become a pressing global priority due to population growth, climate variability, and resource scarcity (Thilakarathne et al., 2025; Lakhiar et al., 2024; Sood et al., 2025). Traditional farming systems increasingly face challenges such as water shortages, soil degradation, and rising input costs, underscoring the need for integrated approaches that ensure food productivity while reducing ecological harm (Goddek et al., 2019; Balamurali et al., 2025; Nag et al., 2024).

Aquaponics, which integrates aquaculture and hydroponics, offers a sustainable and resource-efficient model for food production. In this closed-loop system, fish waste provides nutrients for plant growth, while plants purify the water for aquaculture reuse (Saha et al., 2025; Morkunas & Wang, 2024; Babar & Akan, 2024). This approach minimizes chemical inputs, conserves resources, and suits regions with limited land and water. (Zamani et al., 2024; Mohamad et al., 2024; Muthumalathi & Loganathan, 2025).

Advancements in digital technologies, particularly Internet of Things (IoT)-based monitoring, have further enhanced aquaponics efficiency. Real-time data on pH, water temperature, and nutrient levels support precision control, while microcontroller-driven automation improves system stability and adaptability to environmental fluctuations (Howlader, 2025; Ibrahim et al., 2023; Chandramenon et al., 2024). Maintaining water quality remains critical, as nutrient imbalances can directly affect both fish health and plant growth (Goddek & Körner, 2019; Reyes-Yanes et al., 2020). Furthermore, community-based aquaponics initiatives contribute to local food security, knowledge exchange, and social resilience (Ibrahim et al., 2023; Shreejana et al., 2022; Obirikorang et al., 2021).

The present study develops and evaluates a smart aquaponics system that integrates IoT-enabled real-time monitoring with a mobile interface. Beyond its scalability and affordability for education, research, and community farming, this study also conducts a comparative analysis between systems with monitoring and those without, offering insights into performance, sustainability, and potential impacts on food security and environmental protection.

METHODOLOGY

This study employed a systematic approach to design, implement, and monitor an aquaponic system that integrates aquaculture and hydroponics with IoT-based sensing and control. The methodology was structured to ensure reproducibility, scalability, and suitability for educational, research, and community farming applications. The procedures are described under two major components: the aquaponic system and the monitoring system.

Aquaponic System

The aquaponic system was designed as a closed-loop model that combines fish farming (aquaculture) and plant cultivation without soil (hydroponics). The system was designed to be self-sustaining: fish waste provides nutrients for plants, and plants help clean and recycle water for the fish. This approach supports sustainable food production, reduces water use, and minimizes waste discharge into the environment.

At the center of the system was a fish tank, which acted as the main water reservoir. The tank size was chosen carefully to provide enough space for fish growth and to handle the amount of waste they produce. A larger water volume helps keep water conditions stable by reducing sudden changes in temperature, pH, and ammonia levels. The tank was made of food-grade material to ensure that no harmful chemicals could leach into the water.

A submersible water pump was used to move nutrient-rich water from the fish tank to the grow beds. The pump capacity was selected so that all the water could circulate through the system at least once every one to two hours. Proper water flow is important to keep the roots supplied with oxygen, prevent stagnation, and evenly distribute nutrients. To ensure smooth operation, flow sensors were added to detect any blockages or irregular flow.

The grow beds were filled with inert media, such as clay pebbles, which provided support for plant roots and surfaces for beneficial bacteria to grow. These bacteria play a key role by converting fish waste (ammonia) into nitrate, a form of nitrogen that plants can easily absorb. This natural biofiltration process helps maintain water quality and balance between the fish and plants.

Leafy vegetables and herbs, such as Siow pai-tsai (Chinese cabbage) were chosen for their fast growth and high nutrient uptake. IoT-based sensors were installed in the grow beds to measure pH, turbidity and temperature. These sensors helped monitor plant conditions in real time and improve the efficiency of water and nutrient use.

Catfish (Siluriformes) were selected for the fish culture because they are hardly and adaptable, and able to tolerate moderate changes in water quality. The stocking density (number of fish per liter of water) was carefully balanced to match the nutrient output from the fish with the nutrient needs of the plants. Additional aeration units were installed to maintain sufficient dissolved oxygen levels, which are essential for both fish and bacterial activity.

Overall, the system was designed for balance, efficiency and sustainability. It provides a model that supports integrated food production with minimal environmental impact.

Monitoring System

To ensure continuous and efficient operation of the aquaponic system, an IoT-based monitoring and control framework was developed. By combining smart technology with automation, the system was able to collect real-time data, allow remote access, and make automatic adjustments when required. This approach improved reliability, efficiency, and ease of management.

At the core of the setup was a NodeMCU (ESP32) microcontroller, which acted as the main controller for collecting, processing, and transmitting sensor data. Four sensors were connected to monitor key parameters that influence fish health, plant growth, and overall water quality, pH, temperature, turbidity, and water level. The readings were sent wirelessly through Wi-Fi to the Blynk cloud platform, where users could view live data on web and mobile dashboards.

The pH sensor tracked water acidity, maintaining an ideal range of 6.5 to 7.0 for both fish and plants. The DS18B20 temperature sensor monitored water temperature continuously and sent mobile alerts when readings exceeded 33°C. The turbidity sensor detected suspended solids that indicate waste buildup or filter issues, while the water-level sensor observed losses from evaporation or plant uptake and sent refill alerts when levels dropped.

Before installation, all sensors connected to the NodeMCU (ESP32) were carefully calibrated to ensure that the readings were accurate and reliable. Each sensor was tested against certified reference standards under controlled laboratory conditions, and the calibration data was recorded for verification.

The pH sensor was adjusted using buffer solutions of pH 4.00, 7.00, and 10.00 to create a three-point calibration curve. The DS18B20 temperature sensor was verified against a laboratory thermometer at 20°C, 25°C, and 30°C. For the turbidity sensor, Formazin standards of 0, 5, and 10 NTU confirmed a consistent linear response, while the water-level sensor was checked against manual measurements taken every 5 cm to validate its accuracy.

Once calibrated, the sensors provided dependable data that fed directly into the monitoring dashboard. The Blynk interface displayed live graphs, trend lines, and alerts. Automated responses were programmed for specific conditions, for example, switching on the aerator when oxygen levels dropped or activating the circulation pump to maintain water flow. These automated controls reduced manual work, kept water conditions stable, and improved system consistency.

When the monitoring setup was fully stable, catfish juveniles were added to the fish tank and Siow pai-tsai seedlings were transplanted into the grow beds. Weekly measurements of fish length and plant height were taken to study how water quality and environmental changes affected growth.

In summary, the IoT-based monitoring and control system transformed the aquaponic unit into a smart, responsive, and data-driven environment. By combining digital sensing technology with ecological design, it increased productivity, minimized waste, and demonstrated how simple, connected tools can enhance sustainable agriculture.

RESULTS AND DISCUSSION

The aquaponic monitoring system was developed using the Blynk platform to provide real-time data tracking and notifications. Users were able to access the system through both web and mobile applications, allowing flexible and convenient monitoring at any time.

The system continuously measured important water quality parameters such as pH, turbidity, temperature, and water level. When any of these values went beyond the acceptable range, the system automatically sent an alert notification to the user. This early warning helped users take quick corrective actions, reducing the risk of stress or harm to both fish and plants.

Figure 1(a) shows the Blynk web dashboard displaying live readings of all monitored parameters. Figure 1(b) presents the mobile dashboard, which provides the same data together with alert notifications. These two interfaces demonstrate that the system is accessible and responsive across different platforms, ensuring reliable monitoring even when users are away from the site.

(a) Web interface

(b) Mobile interface

Fig.1 Aquaponic monitoring system dashboards on the Blynk platform: (a) web interface showing real-time readings of pH, turbidity, temperature, and water level; (b) mobile interface displaying the same parameters with alert notifications.

The monitoring module successfully detected and recorded changes in environmental conditions. It provided continuous feedback, which is essential for maintaining system stability and optimal operation. Data was collected over a three-week observation period, focusing on pH, turbidity, temperature, and water level.

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The following subsections discuss the observed trends for each parameter and explain how these variations influenced the overall performance of the aquaponic system. The results confirm that real-time monitoring plays a vital role in maintaining water quality and supporting healthy growth of both aquatic and plant components.

pH and turbidity monitoring

The temporal dynamics of pH and turbidity over the 21-day monitoring period revealed a strong inverse relationship between the two parameters. Fig.2 illustrates the inverse relationship between pH and turbidity throughout the 21-day monitoring period. The pH values generally fluctuated between 6.5 and 8.5, with notable peaks observed on Days 7-8 and Day 15, where levels reached approximately 8.2-8.4. These alkaline conditions align with optimal ranges for nutrient solubility and fish–plant symbiosis in aquaponics systems (Goddek et al., 2019; Chandramenon et al., 2024). Conversely, pronounced declines in pH were detected on Days 3-6, 12-13, and 19-21, where minimum levels fell to approximately 6.5. Such reductions suggest episodic acidification events likely associated with elevated organic load, microbial respiration, and suspended solids (Chandramenon et al., 2024; Ani et al., 2022).

These changes can be understood through the natural biological processes happening inside the aquaponic system. When uneaten feed and fish waste build up, they add organic matter to the water, encouraging bacteria to break it down. During this breakdown, nitrifying bacteria convert ammonia (NH_3) into nitrite (NO_2^-) and then nitrate (NO_3^-). This process uses up alkalinity and causes the water to become slightly more acidic. On the other hand, when the system filters out solids effectively and has enough oxygen, the bacterial activity becomes more balanced, turbidity goes down, and the pH returns to a slightly alkaline level. This interaction shows why it is important to keep good filtration and aeration, to maintain steady water quality and avoid acidification that could stress both the fish and the plants.

Turbidity, expressed in nephelometric turbidity units (NTU), exhibited intermittent but sharp spikes corresponding to these declines in pH. Peaks of 8-10 NTU occurred on Days 5- 6, 12-13 and 21, coinciding with the lowest recorded pH values. In contrast, turbidity remained negligible (0.0 NTU) during periods when pH was more stable and slightly alkaline, such as Days 7-11 and 14-17. This alternating pattern reinforces the strong negative correlation between the parameters, with statistical analysis confirming a Pearson coefficient of –0.76 ($p < .001$, $n=21$) calculated using daily average values collected over the 21-day monitoring period. This finding underscores the sensitivity of pH to turbidity fluctuations and suggests that increased particulate and microbial activity directly compromise water buffering capacity (Abdullah & Mazalan, 2022; Raman & Vasmatkar, 2024).

These observations align with earlier studies that highlight how closely connected different water quality indicators are in aquaponic systems and why monitoring them together is essential for maintaining system efficiency (Ibrahim et al., 2023; Huang et al., 2021). The repeated fluctuations seen in this study suggest that turbidity-related acidification is not a one-time event but a recurring issue, pointing to the need for flexible and proactive management.

Although the 21-day experimental period was sufficient to validate system functionality and demonstrate initial biological responses, it may not fully capture the long-term ecological stability or nutrient balance within the aquaponic loop. Over time, processes such as biofilter maturation, microbial succession, and nutrient cycling could alter water quality and growth dynamics. Future studies should therefore extend the monitoring period across multiple growth cycles to evaluate sustained performance and long-term equilibrium.

Recent IoT-based monitoring tools now make it possible to track water conditions in real time and alert farmers before serious imbalances occur (Thilakarathne et al., 2025; Yadav et al., 2025; Muthumalathi & Loganathan, 2025). Incorporating these technologies into aquaponic operations can help reduce nutrient-related risks, maintain stable biological conditions, and support the long-term sustainability of the system (Nag et al., 2024; Saha et al., 2025).

Furthermore, the findings reinforce the broader narrative on aquaponics as a sustainable yet delicate food production system. Balancing nutrient cycling, water quality, and biological interactions is central to system resilience (Goddek & Körner, 2019; Jose et al., 2025). By embedding IoT-based control, renewable energy sources, and smart fertigation, as recommended in recent studies (Zamani et al., 2024; Balamurali et al., 2025), aquaponics systems can become more adaptive, scalable, and resource-efficient in meeting future agricultural demands.

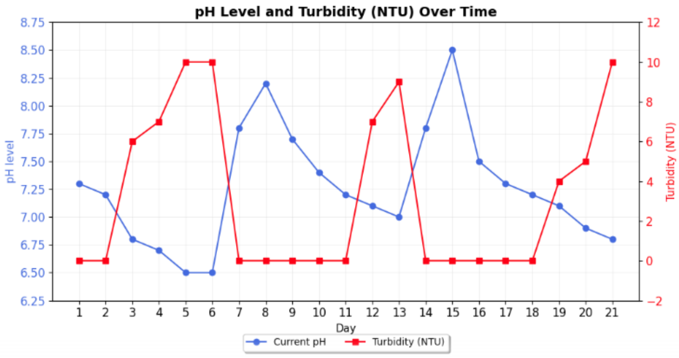

Fig. 2 Daily variation of pH and turbidity in the monitored aquaponic system over a 21-day observation period.

Temperature and water level monitoring

The aquaponic system was continuously observed for 21 days to record variations in temperature and water level as illustrated in Fig. 3. Throughout the monitoring period, the daytime temperature stayed within 30°C to 32°C, while the nighttime temperature ranged between 27°C and 29°C. The small temperature difference of 2-4°C between day and night indicates that the system maintained a stable thermal environment, which is favorable for both fish and plant growth. Stable temperature conditions help reduce stress on aquatic species and promote consistent biological and nutrient activities, as also noted in previous studies by Goddek et al. (2019) and Huang et al. (2021).

The water level indicated a gradual decline from 30 cm at the start of the study to approximately 26 cm by the end of the 21- day period. Slight increases were observed around Days 8 and 15, which could be attributed to manual refilling or changes in environmental conditions. The overall downward trend is likely caused by evaporation and water uptake by plants, both common in aquaponic systems. This observation is consistent with earlier findings that report water level fluctuations are strongly influenced by biological usage and environmental factors such as temperature and humidity (Mohamad et al., 2024; Ani et al., 2022).

When comparing the temperature and water level data, a clear relationship was observed. During periods when the daytime temperature exceeded 32°C, the water level decreased more rapidly, indicating higher evaporation rates and greater plant water consumption. Conversely, when the temperature remained slightly cooler, around 30-31°C, the water level tended to remain stable or show a small increase, particularly on Days 8 and 16-17. These results align with previous reports that describe how temperature fluctuations directly influence water balance and overall system efficiency in aquaponic operations (Ibrahim et al., 2023; Abdullah & Mazalan, 2022; Yadav et al., 2025).

Temperature plays a major role in maintaining balance within the aquaponic system. Warmer water holds less dissolved oxygen, which can make fish breathe faster and feel more stressed. At the same time, higher temperatures speed up evaporation and increase how much water the plants take up, which explains the drop in water level during hot days. When temperatures are cooler, oxygen levels remain higher and water loss slows down, keeping the system more stable. These observations suggest that using temperature-responsive shading, proper ventilation, or simple cooling methods could help regulate heat and reduce the need for frequent water refilling.

Overall, the results confirm that temperature plays a key role in maintaining the water balance of aquaponic systems. Nonetheless, other elements such as plant transpiration rates, fish activity, and system management practices also contribute significantly to the observed variations. Effective monitoring and control of these factors are therefore essential to maintain system stability and ensure sustainable performance (Goddek & Körner, 2019; Khodary et al., 2023).

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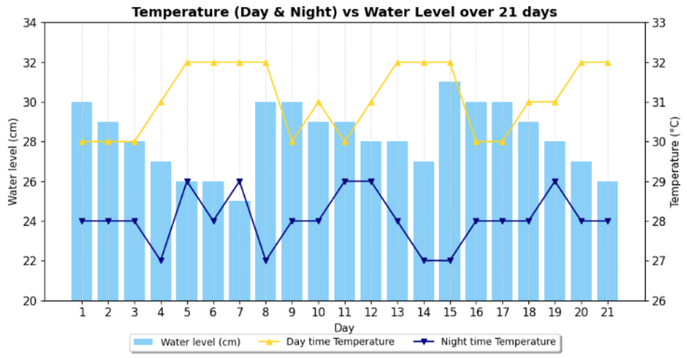

Fig. 3 Daytime and nighttime temperature fluctuations (°C) and corresponding water-level changes (cm) over 21 days.

Growth performance of fish and plants in monitored vs. unmonitored

The results of this study demonstrate the clear benefits of continuous monitoring in aquaponic systems. As summarized in Table I, both fish and plants in the monitored setup exhibited higher and more consistent growth rates than those in the unmonitored system. This improvement reflects the stabilizing influence of real-time sensor monitoring, which maintains water quality and minimizes fluctuations that could otherwise hinder biological performance.

In terms of fish growth, catfish in the monitored group achieved a rate of 17.4 ± 0.8%, compared to 12.7 ± 1.2% in the unmonitored system. Plant growth showed an even stronger response, with Siow pai-tsai increasing by 92.0 ± 2.4% under monitoring, while plants in the unmonitored setup grew by only 50.0 ± 3.0% over the same 21-day period.

These values represent descriptive means from a single experimental cycle. Formal statistical validation, such as t-tests or ANOVA, was not conducted, as multiple trials would be required for reliable comparison. Future studies should therefore include replicated experiments and statistical analysis to confirm the significance of these observed differences.

Table I Comparative growth performance of catfish and Siow pai-tsai under monitored and unmonitored aquaponic systems during the 21-day study

Parameter	Week 1	Week 2	Week 3	% Growth (3 Weeks)
Catfish Width (cm) – Unmonitored	11.0	11.8	12.4	12.7%
Catfish Width (cm) – Monitored	11.5	12.8	13.5	17.4%
Siow pai-tsai Height (cm) – Unmonitored	2.4	3.0	3.6	50.0%
Siow pai-tsai Height (cm) – Monitored	2.5	3.7	4.8	92.0%

While the growth patterns appear clearly different both visually and numerically, these findings should be viewed with caution. Because this study was based on only one experimental cycle, the results are considered preliminary and should be verified through repeated trials and statistical analysis to ensure they are consistent and reliable.

The observed growth trends are illustrated in Fig. 4, where the monitored system shows steeper and more consistent growth curves for both species. Real-time monitoring allowed early detection of pH, temperature, and water-level changes, enabling timely interventions that reduced stress on fish and plants. This environmental stability helped fish maintain regular feeding and metabolism, while plants benefited from balanced nutrient availability and adequate root-zone oxygen. Maintaining these conditions within optimal ranges resulted in faster growth and healthier biological performance.

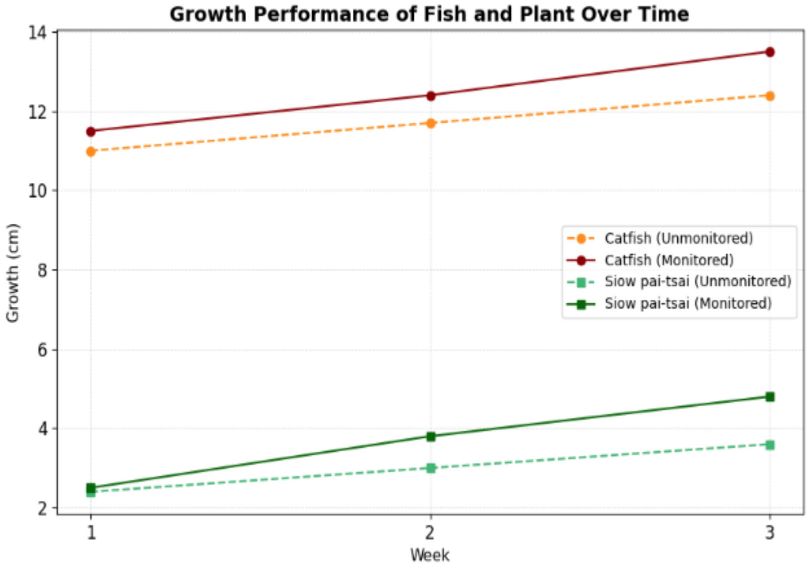

Fig. 4 Growth performance of catfish and *Siow pai-tsai* in monitored and unmonitored aquaponic systems during a single 21-day experimental cycle. Each point represents the mean weekly growth measurement, and the lines show the overall growth trend. Since this study involved only one experimental cycle, error bars are not included.

The comparative outcomes suggest that continuous monitoring not only enhances growth but also reduces variability, improving overall system reliability. This effect was more pronounced in plants, which appeared more sensitive to environmental fluctuations than fish. These results are consistent with earlier reports by Ibrahim et al. (2023), Raman and Vasmatkar (2024), and Chandramenon et al. (2024), who found that sensor-assisted aquaponic systems improve biological outcomes and contribute to sustainable food production.

In summary, the findings highlight that maintaining stable water quality is crucial for achieving better performance in aquaponic systems. Real-time monitoring helps farmers detect changes before they become critical, enabling quick corrective actions that protect both fish and plants. By combining low-cost sensors with responsive automation, the system effectively bridges the gap between environmental monitoring and practical farm management. Even a simple and affordable monitoring setup can significantly enhance productivity and support the long-term sustainability of aquaponic farming.

CONCLUSION

This study successfully developed and tested an IoT-based aquaponics system integrating pH, turbidity, temperature, and water-level sensors with an ESP32 microcontroller and the Blynk platform. Real-time monitoring helped maintain stable water conditions, supporting healthier fish growth and more consistent plant development. The automated system reduced manual intervention, minimized water-quality fluctuations, and improved overall reliability.

The findings show that IoT integration can significantly enhance the efficiency and sustainability of aquaponic systems. Continuous data feedback allows farmers to make informed management decisions while keeping the setup affordable and practical for small-scale and community farming. This technology-driven approach strengthens the link between innovation and food production, highlighting its potential to support resilient and sustainable agriculture in the future.

Future Works

Future research should focus on adding predictive and intelligent functions to further automate the system. Machine learning models could be trained to analyze real-time and historical data, enabling the system to predict pH, turbidity, or temperature changes and take corrective actions automatically before imbalances occur.

Computer-vision tools could also be developed to detect fish or plant stress through image analysis, improving early response and reducing losses.

Integrating renewable energy sources, such as solar power, would further increase system independence and reduce long-term operational costs. Combining smart automation with green energy could transform this design into a self-regulated and scalable aquaponic model that supports sustainable food production in both rural and urban environments. With continued innovation, aquaponics can evolve into a smart and eco-efficient farming solution that contributes meaningfully to food security and environmental conservation.

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