Development and Testing of a Real-Time IoT Monitoring System for Aquaponic Farming

Najwan Khambari*[1], Nurul Fakhirah Azlan[1], Nor Azman Mat Ariff[1], Shahkhir Mozamir[1], Norharyati Harum[1], Wahidah Md Shah[1], Bogdan Ghita[2]

[1]Fakulti Teknologi Maklumat dan Komunikasi, Universiti Teknikal Malaysia Melaka, Malaysia

[2]School of Engineering, Computing and Mathematics, University of Plymouth, United Kingdom

***Corresponding Author**

DOI: https://dx.doi.org/10.47772/IJRISS.2025.91100218

Received: 24 November 2025; Accepted: 30 November 2025; Published: 05 December 2025

ABSTRACT

Aquaponics offers a sustainable approach to agriculture by integrating aquaculture and hydroponics, using fish waste as nutrients for plant growth and plants as natural filters for water recirculation. Despite its ecological advantages, maintaining optimal environmental conditions within aquaponic systems remains a significant challenge due to the need for continuous manual monitoring and adjustment. This study aims to address this issue by developing an Internet of Things (IoT)-based monitoring system to automate and optimize key environmental parameters critical to aquaponic farming, namely water temperature, pH levels, and water levels. The system utilizes an ESP32 microcontroller integrated with cost-effective sensors, a local web interface for data visualization, and a real-time alert mechanism via Telegram messaging. A pilot deployment was conducted, and usability was evaluated through the System Usability Scale (SUS) with 19 aquaponic practitioners. The system achieved a SUS score of 77.11%, indicating a "Good" usability rating. Sensor data was successfully transmitted at two-minute intervals, with real-time alerts triggered when thresholds were exceeded. The results demonstrate that the proposed system is not only technically feasible and user-friendly but also contributes to sustainable agriculture by reducing manual labor and enabling proactive intervention. The study supports the adoption of IoT in small- to medium-scale aquaponic farms, aligning with global efforts toward SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production).

Keywords: Aquaponics, ESP32, Internet of Things (IoT), Monitoring system, System Usability Scale (SUS)

INTRODUCTION

In recent years, the combination of population growth and environmental concerns led to a substantial expansion of research aiming to address global food security challenges [1, 2, 3]. The increasing demand for water resources, along with the reduced availability of land, has prompted the development of many innovative and complex food production methods, with aquaponics being one of them [2]. Technological advancements, particularly the introduction and integration of IoT and sensors into aquaponic systems, present a transformative opportunity to explore the potential of IoT-enabled solutions to address the operational challenges and maximize the potential of aquaponic systems for better yield. Recent studies have highlighted the growing role of automated systems, integrated feeders, and predictive models in aquaponic management, improving sustainability and productivity [37], [38], [39].

Aquaponics is a sustainable agricultural method that integrates aquaculture and hydroponics [4]. It represents a closed loop system in food production. In this system, fish are fed and raised in tanks where they produce waste rich in ammonia (NH4) which is harmful to the fish. The water containing this waste is then pumped into a grow bed where plants, typically leafy greens, and herbs, are cultivated. Beneficial bacteria that are present in the grow bed act as a catalyst [5, 6] to establish a self-sustaining ecosystem which converts the ammonia into nitrates (NO3) [7]. This process serves essential nutrients for plants. As the plants absorb these nutrients, they act as a natural filter that purifies the water, which can then be returned to the fish tanks. This cycle, shown in Figure 1, creates a self-sustaining ecosystem where both the fish and plants thrive. This also eliminates any introduction of any chemical-based substance which can be harmful to the environment, as is the case for hydroponics [8].

An aquaponics system is designed to replicate the whole natural ecosystem that makes them organic [9] as shown in Figure 1; one of the regulating factors is the pH value, which must remain neutral (6.8 – 8.0) for the system to remain in balance [10]. The aquaponics system is well-suited for urban environments that have limited land because it can be set up in warehouses, rooftops, or abandoned buildings. While land is not a requirement, a significant drawback of aquaponics systems is the considerable time required for monitoring and adjusting parameters to meet predetermined levels [3].

In response to the growing significance of aquaponics, this paper explores the design and implementation of an Internet of Things (IoT) based monitoring system that maximizes the productivity of aquaponic systems. With a focus on real-time parameter monitoring of water temperature, pH levels, and water level, the system aims to provide valuable insights into the dynamic interactions within the aquaponic ecosystem for proactive management and optimization.

Moreover, aquaponics aligns with several United Nations Sustainable Development Goals (SDGs), particularly SDG 2: Zero Hunger, SDG 6: Clean Water and Sanitation, and SDG 12: Responsible Consumption and Production. By integrating IoT technologies into aquaponics, this work does not only address the technological challenges of modern agriculture but also contributes to the creation of more sustainable, efficient, and resilient food systems, especially in urban and resource-constrained environments.

From a socio-technical perspective, the adoption of IoT systems in agriculture is influenced not only by cost and efficiency but also by perceived ease of use, accessibility, and support for local livelihoods. The Unified Theory of Acceptance and Use of Technology (UTAUT) model posits that performance expectancy and effort expectancy significantly impact user adoption of new technologies in rural settings [34]. This aligns with Malaysia's commitment to advancing SDG 2, 6, and 12 through technology-driven smart agriculture, as detailed in the Malaysia SDG VNR Report 2021 [35]. Moreover, the World Bank emphasizes that integrating digital tools into agriculture can enhance food security and economic resilience among underserved farming communities [36].

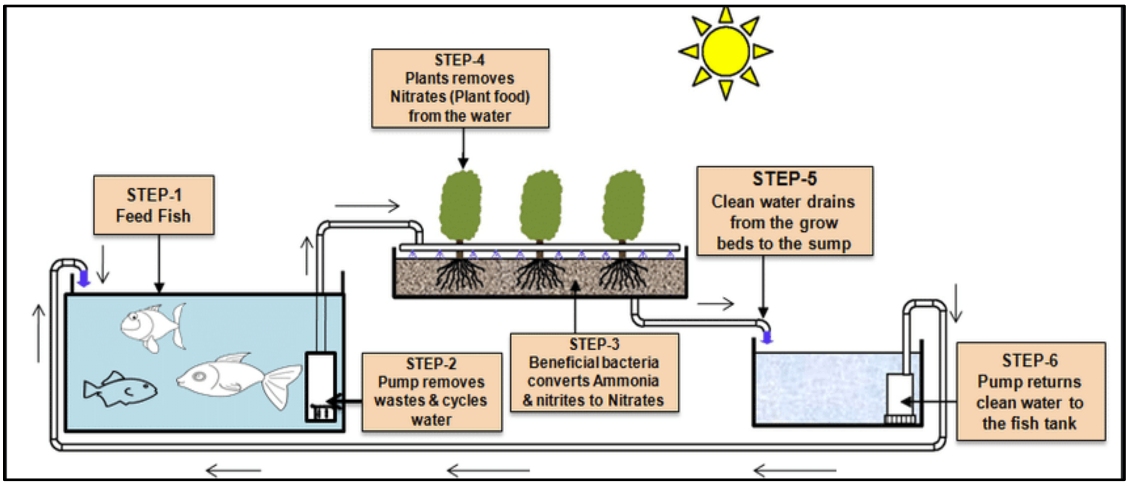

Fig. 1 A cycle in an aquaponic system

As outlined in Figure 1, an aquaponic system requires a balanced interaction between its components, which can be achieved through monitoring the encompassing environmental conditions. The main parameters that define an aquaponic ecosystem are as follows: pH, temperature, Dissolved Oxygen (DO), Electrical Conductivity (EC), Ammonia (NH4), Nitrite (NO2-) and Nitrate (NO3-) [11]. Each one of these parameters plays a pivotal role in maintaining optimal conditions for the health and growth of both aquatic species and plants within the system and significant deviation in any of them will lead to a failure of the system.

pH is one of the aggregating indicators for the environment. It quantifies the concentration of hydrogen ions (H+) in a solution to determine its acidity or alkalinity. This significantly affects the biological processes within

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

the system, as different fish and plant species thrive under specific pH conditions. The suitable pH range for the growth and survival of plants and fish inside the system is between 6.5-8 [12], with the nitrification process occurring where the value of pH is between 7.0 and 9.0 [13]. The pH can be controlled through the addition of lime (CaCO3) or sodium hydroxide (NaOH); a low pH will lead to high levels of dissolved carbon dioxide (CO2), which is toxic to fish [14]. Similarly, temperature regulation is also vital for aquaponic systems as it impacts the metabolic rates of fish and plant growth [15]. Maintaining a stable water temperature within the range of 22°C to 32°C is essential for ensuring the well-being of both fish and plants [16]. Although an aquaponic system can tolerate a temperature range of 15°C to 35°C [10], it is best to keep the water temperature at an average of 26 °C, which ensures a balance between the fish and plants populations [17]. Finally, Electrical Conductivity (EC) expressed as the concentration of dissolved ions in the water and influenced by the concentration of dissolved salts and minerals, is a measure of the water's ability to conduct electricity [11] The optimum EC range for fish is 100-2000 µS/cm, but the ecosystem can function within a wider range (30-5000 µS/cm) [18]. Polluted water will have higher levels of EC indicate and may cause death to the fish population [13].

Previous Work

A considerable amount of literature has been published on IoT-based aquaponic monitoring systems with different number of parameters to monitor [3]. Sensors are connected to a microcontroller that are either Arduino-based (Arduino Uno, ESP8266 or ESP32) [6, 11, 12, 15, 19-23] or a Raspberry Pi [10, 24, 26]. These microcontrollers then relay the readings from the sensors via wireless networks mainly through WiFi to be displayed to the users. Some previous studies also considered using LoRa [11, 23, 25] especially for sparse network connectivity environments, such as farms located in rural areas where network coverage is difficult to deploy, given that LoRa is capable to transmit data in a long range communication while keeping very little power usage [26]. The relayed information being displayed to the users are usually privately hosted with their own database [10, 20, 23] or on an IoT platform such as Blynk [19, 27], Favoriot [12] or Amazon Web Services (AWS) [6, 21] to provide tools and services to facilitate the development, deployment, and management of IoT applications. In rural areas and off-grid situations, integrating solar power for aquaponics monitoring system was also considered [28]. In addition, Artificial Intelligence (AI) and machine learning (ML) were included in the ecosystem to optimize water treatment and monitoring applications [25], data visualization tools and smart health monitoring [29] and aquaponics yield estimation [30]. Table 1 shows a summary of previous work that has used microcontrollers in the aquaponic monitoring system.

TABLE I: Summary of the previous work in aquaponicmonitoring system with IoT

Article	Gateway	Media	Middleware and Storage	Sensors
6	Arduino	Wi-Fi	AWS	Water temperature, water flow rate, light, light, pH, ultrasonic (for plant height)
10	Raspberry Pi	Wi-Fi	Personal platform	Air temperature and humidity, pH
11	Arduino	Lora	Personal platform	DO, EC, ORP, pH, water temperature
12	Arduino	Wi-Fi	Favoriot	Air temperature and humidity, pH
15	Arduino	Wi-Fi	Personal platform	Salinity, pH, DO, Nitrite, temperature
19	Arduino	Wi-Fi	Blynk	Air temperature and humidity, soil moisture, ultrasonic (for water level)
20	Arduino	Wi-Fi	Personal platform	Temperature, TDS, pH, Light
21	Arduino	Wi-Fi	AWS	Air temperature, humidity
23	Arduino	Lora	Personal platform	Air Temperature, humidity, pH, turbidity
24	Raspberry Pi	Wi-Fi	Personal platform	Air temperature, Humidity, CO_2, Light intensity, pH, Water temperature, DO
26	Raspberry Pi	Wi-Fi	Thingspeak	Temperature, pH, Pressure, Humidity
27	Arduino	Wi-Fi	Blynk	Temperature, pH, DO, Ammonia

Method And Design Implementation

This paper presents an aquaponic farm monitoring platform that aims to enhance the efficiency and productivity of aquaponic environments in while being cost-effective. This is done by monitoring basic important parameters which are water temperature, water levels and pH levels. Similar to other IoT-enabled systems using ESP32 or Arduino microcontrollers, the proposed design collects and transmits sensor data efficiently while allowing integration with automated feeders and water quality predictors [38], [40], [41]. These data are then sent to a database which will also be displayed on a dashboard. A notification will be sent to users via Telegram if readings from the sensors exceed the threshold set for each parameter.

Hardware Design and Implementation

The monitoring system includes a microcontroller ESP32, waterproof probe DS18B20 1-Wire temperature sensor, HC-SR04 ultrasonic sensor and a liquid pH value detection sensor with electrode probe. The hardware design circuit is shown in Figure 2. ESP32 which acts as a microcontroller, is used to connect and collect data from sensors measuring pH, water level, temperature, and humidity. The data is sent to a local database where it will be stored and displayed on a website, as well as compared to a set threshold to determine whether the current conditions are within a safe range.

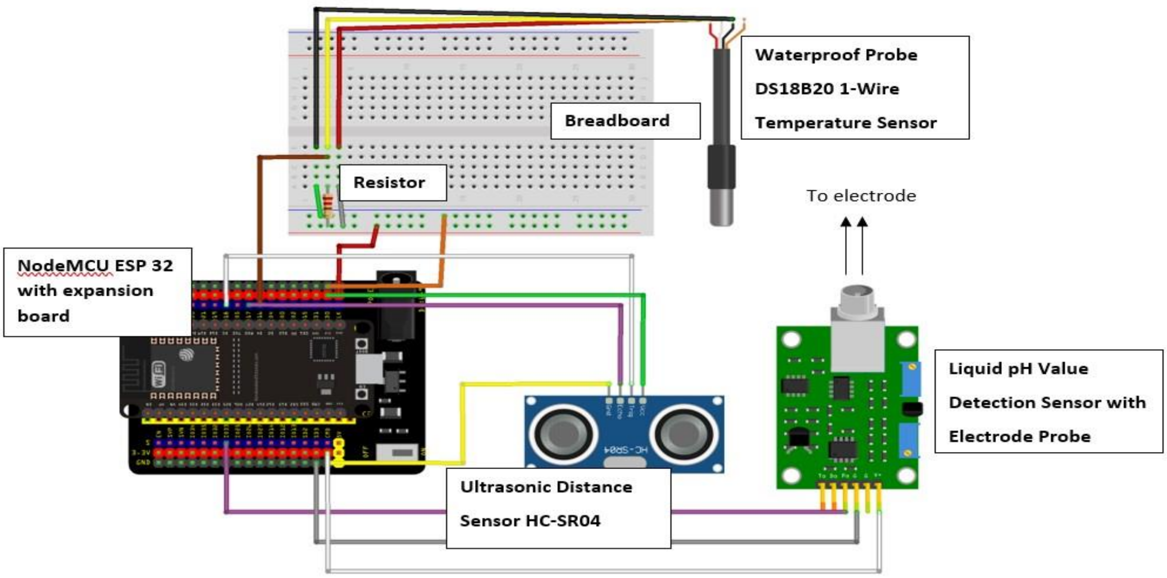

Fig. 2 Hardware implementation of the aquaponic system

Figure 3 shows the prototype of the aquaponic monitoring system being tested in a real environment. Once the ESP32 microcontroller is powered, all sensors will start the monitoring process immediately. The data will be sent to a database every two minutes.

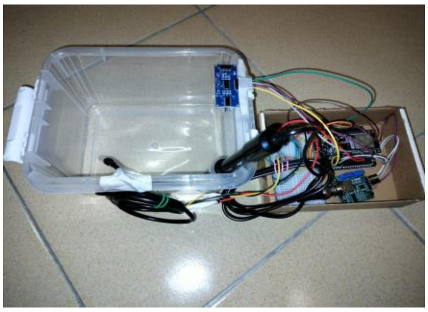


Fig. 3 Testing the prototype of aquaponic monitoring system

TEST RESULTS AND DISCUSSION

The test phase comprises performance testing and system usability testing. During the performance testing, the IoT-based monitoring system is used to capture the readings of the various sensors and configurations to determine its accuracy and reliability in monitoring an aquaponic system. For the system usability testing, 19 aquaponics farmers and users were asked to evaluate the system to assess its effectiveness, efficiency, and user satisfaction.

Performance Test

Tests were conducted to assess the efficacy of the sensors. The sensor readings are systematically gathered and transmitted to a centralized database. These datasets hold significant value, serving as a repository of historical parameter readings essential for anomaly detection. Moreover, automated alerts are generated and dispatched to users in instances where sensor readings trigger predetermined thresholds. The visualization of data is facilitated through a web-based monitoring interface. An illustrative example of the current real-time data display on the dashboard is provided in Figure 4.

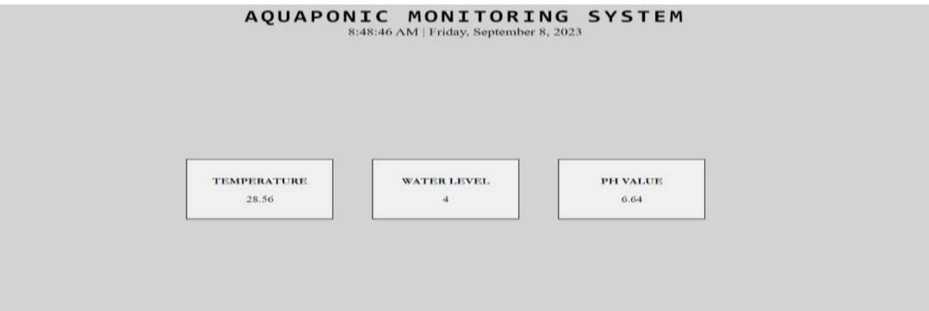

Fig. 4 Monitored data on dashboard

Within the dashboard interface, users have the flexibility to customize their data viewing preferences. They can choose to select from a range of options, including accessing the most recent 15, 30, or the overall historical readings stored within the database. Figure 5 illustrates the user interface design, showcasing the various options available for data viewing selection.

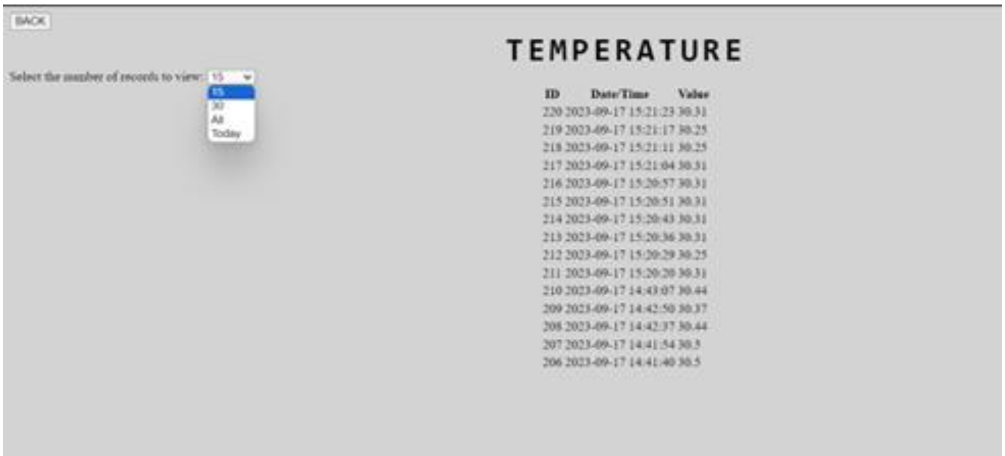

Fig. 5 Data viewing options

When a parameter is not within a safe range, a notification will be sent to users to notify the current situation via Telegram. Figure 6 is the example on how the notifications are sent to users.

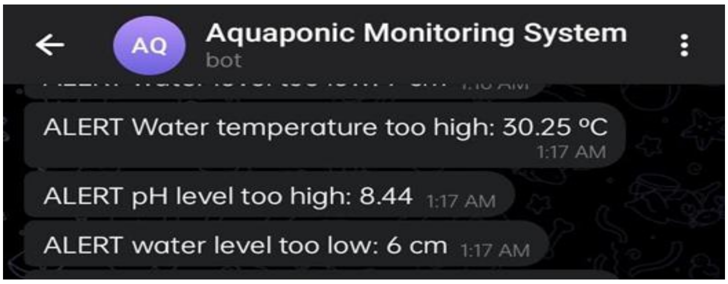

Fig. 6 Notifications sent to users on unsafe parameters detection

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

Usability Test

The System Usability Scale (SUS) [31] provides a straightforward and effective approach to evaluating the usability of products and designs. Similar usability testing methods for measuring user satisfaction can be seen in other journal papers by several authors [32][33]. For this testing method, feedback from 19 respondents has been obtained to evaluate the developed system.

Table 2 provides analysis of System Usability Scale (SUS) data obtained from 19 respondents. Each respondent, question, raw score and final score is denoted by 'R', 'Q', 'RS' and 'FS' respectively. The developed system attained a final SUS score of 77.11% which falls in the “Good” SUS adjective rating that indicates users generally find the system easy to use and are satisfied with its functionality.

TABLE II: Data collection from the conducted SUS Test

R	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	SUS Score
1	4	2	4	1	4	2	3	2	4	1	77.50
2	4	2	4	2	4	1	3	3	4	1	75.00
3	4	3	4	2	3	2	4	1	4	2	72.50
4	3	1	4	2	3	1	4	1	4	3	75.00
5	4	1	4	2	4	2	2	3	5	2	72.50
6	3	1	3	2	4	1	4	2	5	2	77.50
7	5	2	3	2	3	1	5	1	5	2	82.50
8	4	1	4	1	4	1	3	1	3	3	77.50
9	5	3	5	2	4	1	4	1	4	2	82.50
10	5	2	4	3	4	3	4	3	5	2	72.50
11	4	2	4	2	4	2	5	2	5	2	80.00
12	4	2	5	3	5	2	4	2	4	2	77.50
13	3	2	4	2	4	2	3	1	4	3	70.00
14	4	2	4	3	5	2	4	1	4	1	80.00
15	4	1	4	2	3	1	3	1	5	1	82.50
16	4	2	4	3	4	3	5	1	4	2	75.00
17	4	2	3	1	5	1	5	3	4	2	80.00
18	5	2	5	1	3	2	3	2	4	2	77.50
19	4	3	5	2	5	1	3	2	3	1	77.50
Average score						**77.11**					

Comparison with Existing Systems and Contributions

To better evaluate the effectiveness and novelty of the proposed system, a comparison with related works is presented in Table 3. The comparison focuses on key implementation aspects such as the microcontroller used, types of sensors, communication protocols, user alert mechanisms, usability evaluation, and data access platforms.

TABLE III: Comparison of the proposed system with selected previous works

Feature	[12] Favoriot IoT	[19] Blynk Platform	[6] AWS-based	Proposed System
Microcontroller	Arduino	Arduino	Arduino	ESP32 NodeMCU
Sensor Types	Temp, Hum, pH	Temp, Hum, Soil Moisture	Temp, Flow, Light, pH	pH, Temp, Water Level
Platform	Favoriot	Blynk	AWS	Local web + Telegram
Notification Mechanism	None	None	Email/AWS	Telegram Alert
Usability Evaluation	Not Reported	Not Reported	Not Reported	SUS Score = 77.11%
Update Interval	Not specified	Not specified	Not specified	Every 2 minutes

Compared to [12], which utilized Favoriot and did not implement real-time alerts or usability evaluation, the proposed system integrates Telegram messaging, providing timely alerts when sensor readings exceed safe thresholds. Similarly, although [19] employed Blynk for remote monitoring, the system lacked a usability assessment, making it difficult to gauge user satisfaction or effectiveness. Meanwhile, [6] used AWS for cloud storage and management but introduced more complex infrastructure not easily replicable in small-scale or educational environments.

Furthermore, the proposed system uses the ESP32 microcontroller, which offers built-in Wi-Fi and greater processing power compared to the Arduino Uno used in most previous works. This improves cost-effectiveness and energy efficiency.

Another notable contribution is the inclusion of usability testing using the System Usability Scale (SUS). The score of 77.11% places the system within the "Good" usability rating, indicating a high level of user satisfaction. This is particularly relevant for aquaponic farmers who may not be technologically savvy and require intuitive interfaces.

In summary, the proposed system makes the following contributions:

1. A simplified, low-cost architecture suitable for small farms or educational purposes using ESP32.
2. Real-time monitoring and alerting via Telegram, improving responsiveness and system engagement.
3. Inclusion of a usability study, which is often missing in similar works, providing empirical user feedback.
4. A flexible, web-based visualization interface with historical data access, allowing for better monitoring and record-keeping.

These contributions address the limitations found in previous systems and support a more user-centric approach to aquaponic farming management.

FUTURE WORK AND CONCLUSION

To further enhance the functionality and efficiency of the monitoring system, several future improvements are proposed. First, the integration of an ammonia (NH_4^+) sensor could provide early warning capabilities in the event of toxic spikes, improving the robustness of the aquaponic environment. Second, incorporating actuators to allow remote control of water pumps and pH adjustment mechanisms via mobile devices would increase automation and user convenience. Finally, temperature control mechanisms such as automated heaters or coolers could be added to maintain optimal aquatic conditions dynamically. Future iterations may also explore AI-based prediction models [39], solar-powered frameworks [37], and integration of cloud-based analytics as demonstrated in recent works [42].

In conclusion, this study has presented an IoT-based aquaponic farming monitoring system designed to address the key challenges of real-time environmental parameter monitoring. The system utilizes an ESP32 microcontroller and cost-effective sensors to collect and transmit data on water temperature, pH, and water level. Data visualization is handled through a local web-based dashboard, and real-time alerts are pushed to users via Telegram, enabling prompt corrective actions.

Compared to prior research, the proposed system demonstrates several key improvements. Unlike previous works that used proprietary platforms without notification mechanisms or usability testing [6, 12, 19], our system includes a built-in Telegram alert system and was evaluated using the System Usability Scale (SUS), achieving a score of 77.11% which indicates strong user satisfaction. The use of the ESP32 also enhances scalability and integration while reducing cost and complexity, particularly in small-scale or educational settings.

These contributions confirm the potential of the proposed system to serve as a practical, user-friendly, and low-cost solution for aquaponic farm monitoring. Its design is adaptable to various aquaponic setups and supports broader sustainability goals. By enhancing food production efficiency, promoting water conservation through closed-loop systems, and encouraging responsible use of natural resources, the project contributes directly to the achievement of SDG 2, SDG 6, and SDG 12. Future research can further expand its impact by incorporating predictive analytics and decision-making support to advance the role of AIoT in sustainable agriculture.

ACKNOWLEDGMENT

This study was supported by research from Universiti Teknikal Malaysia Melaka (UTeM). The authors would like to express their sincere gratitude to colleagues at the Fakulti Teknologi Maklumat & Komunikasi, UTeM, for their valuable technical input and constructive feedback during the development of this work. The authorship of this article reflects equal contribution from all authors involved in the study. Special thanks are extended to individuals who assisted in formatting and proofreading the manuscript.

REFERENCES

1. K. A. Obirikorang, W. Sekey, B. A. Gyampoh, G. Ashiagbor, and W. Asante, “Aquaponics for Improved Food Security in Africa: A Review,” Front. Sustain. Food Syst., vol. 5, no. August, pp. 1–10, Aug. 2021, doi: 10.3389/fsufs.2021.705549.
2. I. Ezzahoui, R. A. Abdelouahid, K. Taji, and A. Marzak, “Hydroponic and Aquaponic Farming: Comparative Study Based on Internet of things IoT technologies.,” Procedia Comput. Sci., vol. 191, pp. 499–504, 2021, doi: 10.1016/j.procs.2021.07.064.
3. T. Shafeena, “Smart Aquaponics System: Challenges and Opportunities,” Eur. J. Adv. Eng. Technol., vol. 3, no. 2, pp. 52–55, 2016.
4. R. Nalwade and T. Mote, “Hydroponics farming,” in 2017 International Conference on Trends in Electronics and Informatics (ICEI), IEEE, May 2017, pp. 645–650. doi: 10.1109/ICOEI.2017.8300782.
5. FAO, “Integrated Aquaculture and Aquaponics,” in Sustainable Food and Agriculture, Elsevier, 2019, pp. 251–257. doi: 10.1016/B978-0-12-812134-4.00028-5.
6. T. Y. Kyaw and A. K. Ng, “Smart Aquaponics System for Urban Farming,” Energy Procedia, vol. 143, pp. 342–347, Dec. 2017, doi: 10.1016/j.egypro.2017.12.694.
7. L. Beecher, “Aquaponics: System Layout and Components,” in Land-Grant Press by Clemson Extension, 2021. [Online]. Available: https://lgpress.clemson.edu/publication/aquaponics-system-layout-and-components/
8. J. E. Rakocy, “Aquaponics—Integrating Fish and Plant Culture,” in Aquaculture Production Systems, Wiley, 2012, pp. 344–386. doi: 10.1002/9781118250105.ch14.
9. A. R. Yanes, P. Martinez, and R. Ahmad, “Towards automated aquaponics: A review on monitoring, IoT, and smart systems,” J. Clean. Prod., vol. 263, p. 121571, Aug. 2020, doi: 10.1016/j.jclepro.2020.121571.
10. A. Dutta, P. Dahal, P. Tamang, E. Saban Kumar, and R. Prajapati, “IoT based Aquaponics Monitoring,” 1st KEC Conf. Proc., vol. I, no. September, pp. 75–80, 2018, [Online]. Available: https://www.researchgate.net/publication/327953706
11. M. Alselek, J. M. Alcaraz-Calero, J. Segura-Garcia, and Q. Wang, “Water IoT Monitoring System for Aquaponics Health and Fishery Applications,” Sensors, vol. 22, no. 19, pp. 1–20, 2022, doi: 10.3390/s22197679.
12. Muhammad Naufal Mansor et al., “Aquaponic Ecosystem Monitoring with IOT Application,” J. Adv. Res. Appl. Sci. Eng. Technol., vol. 31, no. 3, pp. 345–357, Aug. 2023, doi: 10.37934/araset.31.3.345357.
13. A. R. Yanes, P. Martinez, and R. Ahmad, “Towards automated aquaponics: A review on monitoring, IoT, and smart systems,” J. Clean. Prod., vol. 263, p. 121571, Aug. 2020, doi: 10.1016/j.jclepro.2020.121571.
14. A. K. Jena, P. Biswas, and H. Saha, “Advanced Farming Systems in Aquaculture: Strategies To Enhance the Production,” Innov. Farming, vol. 1, no. 1, pp. 84–89, 2017, [Online]. Available: www.innovativefarming.in
15. M. Ula, Muliani, and H. A. K. Aidilof, “Optimization of Water Quality in Shrimp-Shallot Aquaponic Systems: A Machine Learning-Integrated IoT Approach,” Int. J. Intell. Syst. Appl. Eng., vol. 12, no. 1, pp. 480–491, 2024.
16. M. A. S. M. Noordin, S. Saon, A. K. Mahamad, and M. Abbas, “Aquaponic Monitoring System and Fish Feeding with Favoriot,” Int. J. Interact. Mob. Technol., vol. 17, no. 12, pp. 132–148, 2023, doi: 10.3991/ijim.v17i12.38485.
17. Haryanto, M. Ulum, A. F. Ibadillah, R. Alfita, K. Aji, and R. Rizkyandi, “Smart aquaponic system based Internet of Things (IoT),” J. Phys. Conf. Ser., vol. 1211, no. 1, 2019, doi: 10.1088/1742-6596/1211/1/012047.

18. N. M. Stone and H. K. Thomforde, “Understanding your fish pond water analysis report,” 2004. [Online]. Available: http://www.ianrpubs.unl.edu/liveg.pdf
19. M. S. T. Abdullah and L. Mazalan, “Smart Automation Aquaponics Monitoring System,” JOIV Int. J. Informatics Vis., vol. 6, no. 1–2, p. 256, May 2022, doi: 10.30630/joiv.6.1-2.925.
20. N. Ahmad, M. M. Hasan, M. Rohomun, R. Irin, and R. M. Rahman, “IoT and Computer Vision Based Aquaponics System,” in 2022 IEEE/ACIS 23rd International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing (SNPD), IEEE, Dec. 2022, pp. 149–155. doi: 10.1109/SNPD54884.2022.10051814.
21. R. K. Kodali and A. C. Sabu, “Aqua Monitoring System using AWS,” in 2022 International Conference on Computer Communication and Informatics (ICCCI), IEEE, Jan. 2022, pp. 1–5. doi: 10.1109/ICCCI54379.2022.9740798.
22. S. B. Dhal et al., “An IoT-Based Data-Driven Real-Time Monitoring System for Control of Heavy Metals to Ensure Optimal Lettuce Growth in Hydroponic Set-Ups,” Sensors, vol. 23, no. 1, p. 451, Jan. 2023, doi: 10.3390/s23010451.
23. N. C. Azemi et al., “IOT-based intelligent green houses (IGH) using Lo-Ra technology,” Int. J. Innov. Creat. Chang., vol. 9, no. 11, pp. 274–283, 2019.
24. S. Wan, K. Zhao, Z. Lu, J. Li, T. Lu, and H. Wang, “A Modularized IoT Monitoring System with Edge-Computing for Aquaponics,” Sensors, vol. 22, no. 23, p. 9260, Nov. 2022, doi: 10.3390/s22239260.
25. M. Lowe, R. Qin, and X. Mao, “A Review on Machine Learning, Artificial Intelligence, and Smart Technology in Water Treatment and Monitoring,” Water, vol. 14, no. 9, p. 1384, Apr. 2022, doi: 10.3390/w14091384.
26. D. Saraswathi, P. Manibharathy, R. Gokulnath, E. Sureshkumar, and K. Karthikeyan, “Automation of Hydroponics Green House Farming using IOT,” 2018 IEEE Int. Conf. Syst. Comput. Autom. Networking, ICSCA 2018, no. 1997, pp. 1–4, 2018, doi: 10.1109/ICSCAN.2018.8541251.
27. T. B. Pramono, N. I. Qothrunnada, F. Asadi, T. W. Cenggoro, and B. Pardamean, “Water quality monitoring system for aquaponic technology using the internet of things (IoT),” Commun. Math. Biol. Neurosci., vol. 2023, pp. 1–18, 2023, doi: 10.28919/cmbn/8221.
28. M. N. H. Zainal Alam et al., “Smart Farming Using a Solar Powered Aquaponics System for a Sustainable Food Production,” Malaysian J. Sci., vol. 42, no. 1, pp. 68–77, Feb. 2023, doi: 10.22452/mjs.vol42no1.7.
29. A. Reyes Yanes, R. Abbasi, P. Martinez, and R. Ahmad, “Digital Twinning of Hydroponic Grow Beds in Intelligent Aquaponic Systems,” Sensors, vol. 22, no. 19, p. 7393, Sep. 2022, doi: 10.3390/s22197393.
30. A. Siddique, J. Sun, K. J. Hou, M. I. Vai, S. H. Pun, and M. A. Iqbal, “SpikoPoniC: A Low-Cost Spiking Neuromorphic Computer for Smart Aquaponics,” Agriculture, vol. 13, no. 11, p. 2057, Oct. 2023, doi: 10.3390/agriculture13112057.
31. J. Brooke, “SUS: A ‘Quick and Dirty’ Usability Scale,” in Usability Evaluation In Industry, CRC Press, 1996, pp. 207–212. doi: 10.1201/9781498710411-35.
32. N. A. Nik Ahmad and M. Hussaini, “A Usability Testing of a Higher Education Mobile Application Among Postgraduate and Undergraduate Students,” Int. J. Interact. Mob. Technol., vol. 15, no. 09, p. 88, May 2021, doi: 10.3991/ijim.v15i09.19943.
33. F. M. Ghabban, M. Hajjar, and S. Alharbi, “Usability Evaluation and User Acceptance of Mobile Applications for Saudi Autistic Children,” Int. J. Interact. Mob. Technol., vol. 15, no. 07, p. 30, Apr. 2021, doi: 10.3991/ijim.v15i07.19881.
34. [V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis, “User acceptance of information technology: Toward a unified view,” MIS Quarterly, vol. 27, no. 3, pp. 425–478, 2003.
35. United Nations Malaysia, “Malaysia Sustainable Development Goals Voluntary National Review 2021,” 2021. [Online]. Available: https://malaysia.un.org/en/130612-malaysia-sustainable-development-goals-voluntary-national-review-2021
36. World Bank Group, “The Future of Food: Harnessing Digital Technologies to Improve Rural Livelihoods,” 2019. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/31565
37. T. Patil, T. S. Hari, and M. Anitha, “Real-Time Smart Aquarium Monitoring System Driven by IoT,” in Proc. 1st Int. Conf. Sustainable Energy Technol. Comput. Intell. (SETCOM), 2025.
38. A. T. Naputol, J. I. Ituriaga, B. M. Yu Jeco-Espaldon, and M. G. Giner, “Development of an IoT-Based Aquaponics Monitoring System with Automated Feeder,” in 2024 IEEE Symp. Industrial Electronics and Applications (ISIEA), 2024.
39. S. Kalaivani, N. S. Kurian, T. D. Subha, and K. C. Sai, “IoT Enabled Aquaponics with AI Prospects:

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

Advancing Automated Monitoring and Sustainable Food Production," in Proc. 6th Int. Conf. Intelligent Communication Technol. Virtual Mobile Netw. (ICICV), 2025.

40. J. R. B. Caluag, L. V. D. Cruz, C. F. L. Delfin, and D. R. dela Cruz, "Internet of Things-Based Water Quality Monitoring System for Brackish Water Fishponds," in Lecture Notes on Data Engineering and Communications Technologies, 2025.
41. M. E. Ali, K. Sultan Jasim, and A. Hafeez, "A Smart Monitoring and Observation Framework for Aquaponics Ecosystem," ARPN J. Eng. Appl. Sci., vol. 19, no. 4, 2024.
42. M. Dutta, D. Gupta, S. Tharewal, and J. M. Alanazi, "Internet of Things-Based Smart Precision Farming in Soilless Agriculture: Opportunities and Challenges for Global Food Security," IEEE Access, vol. 13, 2025.