Aquaponics Management: Use sensors to monitor and control nutrient levels, water quality, and environmental factors in aquaponic systems.

Mst. Aysa Siddika Meem
Department of CSE
Independent University, Bangladesh
Dhaka, Bangladesh
2220281@iub.edu.bd

Mahmudul Hasan
Department of CSE
Independent University, Bangladesh
Dhaka, Bangladesh
2220622@iub.edu.bd

Hamim
Department of CSE
Independent University, Bangladesh
Dhaka, Bangladesh
2110253.edu.bd

Ripa Sarkar
Department of CSE
Independent University, Bangladesh
Dhaka, Bangladesh
2220107@iub.edu.bd

Fatema Begum Maliha
Department of CSE
Independent University, Bangladesh
Dhaka, Bangladesh
2220556@iub.edu.bd

***Abstract*—Aquaponics, a sustainable fusion of aquaculture and hydroponics, offers a promising solution for modern agriculture. However, the complexity of balancing water quality, nutrient levels, and environmental conditions presents significant challenges. This research introduces a cutting-edge IoT and AI-driven aquaponics management system designed to address these challenges through innovation and automation. By deploying IoT sensors for real-time monitoring and leveraging machine learning algorithms for predictive analytics, the system ensures proactive adjustments to optimize fish and plant growth. A cloud-integrated architecture with intuitive web and mobile interfaces empowers users with seamless control and data-driven insights. Rigorous evaluations demonstrate the system's superior performance in automation, scalability, and energy efficiency compared to traditional setups. This study not only bridges the gap in current aquaponics management but also sets a benchmark for sustainable agriculture, offering a transformative solution to meet the demands of food security and environmental sustainability.**

***Keywords*—Aquaponics, IoT, Machine Learning, Predictive Analytics, Sustainable Agriculture, Real-Time Monitoring, Automation, Cloud Computing.**

I. INTRODUCTION

Aquaponics combines aquaculture (fish farming) with hydroponics (soilless plant cultivation) to create a symbiotic ecosystem that efficiently uses resources. This innovative farming method not only addresses challenges like water scarcity and the overuse of chemical fertilizers but also meets the growing demand for organic and sustainable food production. By leveraging fish waste as a natural fertilizer for plants and using plants to purify water for fish, aquaponics has proven to be an environmentally friendly alternative to traditional farming practices. Despite its benefits, managing aquaponics systems presents challenges, including maintaining water quality, nutrient levels, and optimal environmental conditions. Advanced technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning (ML) have emerged as powerful tools to address these issues. IoT facilitates real-time monitoring and data collection through sensors, while AI and ML enable predictive analytics and automation. Together, these technologies enhance system efficiency, reduce manual labor, and ensure consistent yields.

While similar studies have integrated IoT and ML into aquaponics, many fail to provide a comprehensive solution that combines real-time monitoring with predictive analytics. Existing systems often lack scalability or are limited to specific environmental parameters. For instance, traditional nutrient dosing methods or isolated automation techniques do not adapt dynamically to changes in fish or plant growth rates, leading to inefficiencies. Our approach overcomes these limitations by integrating IoT for precise monitoring and ML for predictive capabilities, ensuring optimal system balance and sustainability.

This paper aims to develop a robust aquaponics management system that leverages IoT and ML technologies to monitor nutrient levels, water quality, and environmental conditions while predicting fish and plant growth patterns. Our contributions include the implementation of scalable IoT architectures, predictive analytics for proactive interventions, and an energy-efficient framework for resource conservation. By addressing existing gaps, this work sets a precedent for sustainable and scalable aquaponics systems, empowering modern agriculture to meet future demands efficiently.

[*]Facilated by the Department of Computer Science & Engineering, Independent University, Bangladesh (IUB)

II. Literature Review

Research in aquaponics management has made significant progress with the integration of IoT, AI, and ML technologies. Recent studies have extensively focused on developing smart aquaponics systems for real-time monitoring and control.

2016 Shafeena highlighted challenges and opportunities in developing smart aquaponics systems, focusing on the integration of IoT for automation and scalability. This work laid the foundation for subsequent IoT advancements in the field [1]. 2018 Nozzi et al. compared three nutrient management approaches in aquaponics, analyzing their effectiveness in cultivating lettuce, mint, and mushroom herbs. Their findings underscored the necessity of tailored nutrient strategies for diverse crops [2]. 2019 Defa et al. introduced an IoT-based pH control system for aquaponics, employing Arduino and Raspberry Pi for automation. Their system enhanced water quality management through real-time adjustments [3]. Witzel et al. developed a Management Execution System (MES) for integrated aquaponics production, addressing operational challenges with automation [4]. Supriadi et al. designed a proportional control mechanism using IoT to regulate pH and temperature, improving the efficiency of aquaponics systems [5]. Karimanzira et al. leveraged IoT-based predictive analytics to optimize aquaponics management, demonstrating significant improvements in resource utilization [6]. 2020 Yang and Kim characterized nutrient composition in tomato-, basil-, and lettuce-based aquaponics systems, highlighting nutrient imbalances and recommending precise supplementation strategies [7]. Jawadwala and Pingle proposed an IoT framework for aquaponics agriculture, showcasing its potential in resource monitoring [8]. Concepcion et al. developed a fuzzy logic controller for automated nutrient solution management, enabling enhanced control over crop growth conditions [9]. Modu et al. provided a comprehensive survey of smart hydroponic systems, offering insights applicable to aquaponics setups [10]. 2021 Khaoula et al. designed an IoT-based solar-powered monitoring system for aquaponics, integrating energy efficiency with real-time environmental tracking [11]. Ezzahoui et al. conducted a comparative study of IoT applications in hydroponic and aquaponic farming, emphasizing operational benefits [12]. Karimanzira and Rauschenbach proposed an intelligent management system for aquaponics, focusing on adaptive control strategies [13]. Lobanov et al. explored nutrient remineralization techniques, demonstrating their efficacy in improving plant health and system sustainability [14]. 2022 Taha et al. presented a comprehensive review of smart systems and IoT in aquaponics automation, detailing advancements in predictive analytics and real-time monitoring [15]. Alselek et al. introduced a water IoT monitoring system for aquaponics health, emphasizing its utility in fishery applications [16]. Dhal et al. developed a machine learning-based IoT system for optimizing nutrient supply in commercial aquaponics operations, showcasing significant productivity gains [17]. Taha et al. employed spectral data and machine learning to detect nutrient content in aquaponics-grown plants, advancing precision agriculture [18]. 2023 Ibrahim et al. analyzed the role of aquaponics in promoting food sovereignty and enhancing water use efficiency, aligning with global sustainability goals [19]. 2024 Chandramenon et al. reviewed smart approaches to aquaponics 4.0, emphasizing water quality management [20]. Khandakar et al. proposed an innovative ML framework for fish farming optimization, leveraging IoT for predictive analytics [21]. Kok et al. designed an automated water quality management system for urban agriculture, integrating IoT sensors for real-time adjustments [22]. Channa et al. outlined strategies for optimizing small-scale aquaponics systems using AI and IoT, addressing challenges in scalability [23]. Our Contributions This study integrates IoT and ML technologies into a unified aquaponics management framework. Key contributions include the development of scalable IoT architectures for real-time environmental monitoring, the application of ML-driven predictive analytics for proactive system adjustments, and the implementation of energy-efficient practices to reduce resource consumption. By addressing the limitations of existing systems, this research provides a comprehensive solution for sustainable and intelligent aquaponics management, meeting the demands of modern agriculture.

III. Methodology

This section describes the methodology for developing the IoT and AI-based aquaponics management system. The methodology is divided into four subsections: overview, component list, system architecture, and block diagram.

A. Overview

The proposed system integrates IoT sensors, a cloud server, and AI-based analytics to monitor and control aquaponics parameters in real-time. Sensors collect data on environmental parameters such as pH, turbidity, temperature, Humidity and dissolved oxygen. This data is transmitted to a cloud server via APIs, processed, and stored in a secure database. User interfaces (web and mobile) provide visualization and control options, while AI algorithms enable predictive insights for system optimization.

B. Component List

The system incorporates the following components:

- **Sensors:**
  - **pH Sensor:** Monitors water acidity and alkalinity.
  - **DS18B20 Temperature Sensor:** Tracks water temperature using 1-Wire protocol.
  - **Dissolved Oxygen Sensor:** Ensures optimal oxygen levels for aquaculture.
  - **Turbidity Sensor:** Measures water clarity.
  - **TDS Sensor:** Monitors nutrient levels in the water.
  - **Humidity Sensor:** Monitors the moisture levels in the surrounding environment, ensuring optimal conditions for plant growth and preventing issues such as mold or excessive dryness.
- **Microcontroller:**

- **ESP32-S3:** Central processing unit for data acquisition and control.
- **Database:**
  - **Supabase:** Cloud database for storing real-time and historical data.
- **User Interfaces:**
  - Web and mobile applications for data visualization and remote control.
- **Features:**
  - Automated water quality monitoring, energy efficiency, and real-time data analysis.

C. Block Diagram

Figure 1 illustrates the block diagram of the system. It highlights the interaction between sensors, microcontroller, cloud server, and user interfaces.

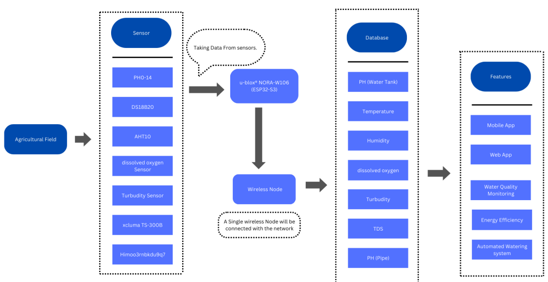

Fig. 1. Block Diagram of IoT-Based Aquaponics Management System.

This methodology ensures a scalable, efficient, and user-friendly system for real-time aquaponics management, leveraging IoT and AI for improved productivity and sustainability.

IV. System Architecture

The proposed IoT-based aquaponics management system is designed to monitor and control key environmental parameters using a cloud-enabled architecture. Figure 2 depicts the system architecture, which integrates aquaculture (fish farming) and hydroponics (plant cultivation) to create a symbiotic ecosystem. The system incorporates IoT devices, cloud servers, and user interfaces for seamless operation and monitoring.

A. Key Components of the System Architecture

1) IoT Sensors: The system monitors critical environmental factors using the following sensors:

- **Temperature (water and air):** Ensures optimal conditions for fish and plant growth.
- **Humidity:** Regulates moisture levels in the hydroponic system.
- **Dissolved Oxygen:** Tracks oxygen levels in the water for aquaculture.
- **Turbidity:** Measures water clarity to identify contaminants.
- **pH and TDS:** Monitors water quality and nutrient concentration for efficient plant and fish health management.

2) Data Collection and Communication: Sensor data is transmitted to a **Cloud Server** using *Application Programming Interfaces (APIs)* for centralized storage and processing.

3) Database: A secure database stores historical sensor data, which supports AI-driven predictive analysis and optimization. This allows the system to adapt dynamically to environmental changes.

4) User Interfaces: The system provides two types of user interfaces for real-time monitoring and management:

- **Web Interface:** Displays graphical and tabular representations of real-time data, accessible via desktop or laptop devices.
- **Mobile Interface:** Provides a user-friendly dashboard for monitoring and managing the aquaponics system remotely.

5) Control Mechanism: The system automates critical processes, such as water flow and nutrient dosing, based on sensor inputs and predefined thresholds. Users can override automation via the web or mobile interface.

6) Cloud-Based Analytics: Historical and real-time data is processed using machine learning models for predictive analytics. This enables proactive system management and enhanced productivity.

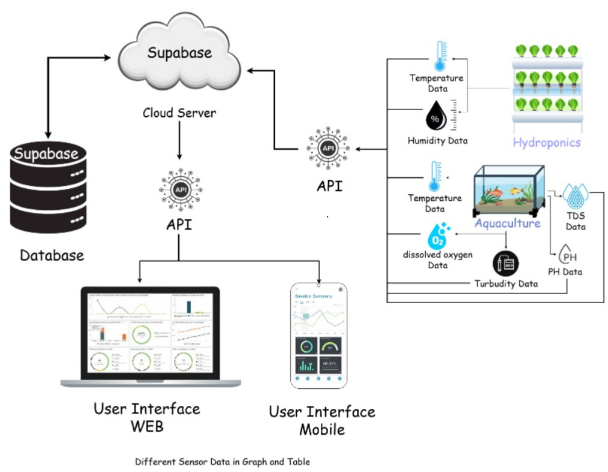

Fig. 2. System Architecture of IoT-based Aquaponics Management System.

This architecture ensures scalability, real-time monitoring, and efficient management of aquaponics systems, catering to both small-scale and commercial operations.

V. Schematic Design

A. Circuit Design

The circuit design of the proposed IoT-based aquaponics system integrates an ESP32 microcontroller with multiple sensors and actuators to ensure real-time monitoring and control of key environmental parameters. The system's architecture is illustrated in Figure 3.

The ESP32 microcontroller serves as the central hub, collecting data from various sensors and triggering actuators

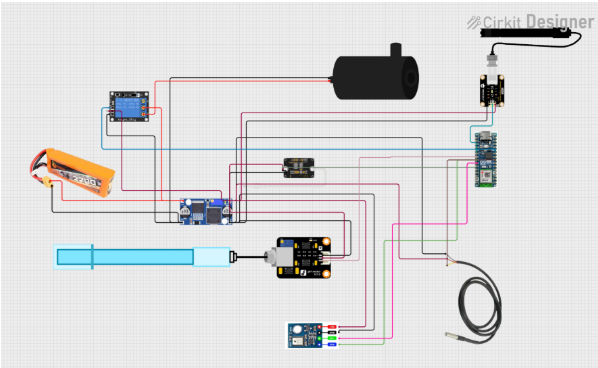

Fig. 3. Circuit Design of IoT-Based Aquaponics Management System.

to maintain optimal conditions for both aquaculture and hydroponics components. The circuit also includes a power supply unit and cloud-based communication for real-time data analytics and remote monitoring.

1) Description of the Circuit Components:

1) **ESP32 Microcontroller:**
   - Central processing unit for sensor data acquisition and actuator control.
   - Facilitates wireless communication with a cloud server.
2) **Sensors:**
   - **pH Sensor:** Monitors water acidity/alkalinity.
   - **TDS Sensor:** Measures water nutrient concentration.
   - **DS18B20 Temperature Sensor:** Captures water temperature using a 1-Wire protocol.
   - **Turbidity Sensor:** Detects water clarity.
   - **Dissolved Oxygen Sensor:** Tracks oxygen levels in the water.
3) **Actuators:**
   - **Relay Module:** Controls water pump for tank circulation.
   - **Peristaltic Pump:** Dispenses nutrients when required.
   - **Solenoid Valve:** Regulates water flow within the system.
4) **Power Supply:**
   - A 12V LiPo battery powers the entire system.

VI. Implementation and Result Analysis

The implementation of the proposed IoT-based aquaponics system is evaluated in terms of its system performance, scalability, and usability. This section presents the outcomes of the implementation, compares it with existing solutions, and provides a detailed analysis of its mobile and web application interfaces.

A. Hardware Implementation

The hardware setup for the proposed IoT-based aquaponics management system integrates various sensors, actuators, and a microcontroller to monitor and control key environmental parameters. Figure 4 illustrates the complete hardware assembly.

Fig. 4. Hardware Setup of the IoT-Based Aquaponics System.

B. System Performance

The system's performance was assessed based on its ability to monitor, control, and maintain key environmental parameters such as water pH, temperature, dissolved oxygen levels, and nutrient concentration. Key achievements include:

- **Real-Time Monitoring:** Sensors provided accurate and instantaneous readings of environmental parameters, ensuring a responsive system.
- **Automated Regulation:** Actuators controlled water flow, nutrient dosing, and aeration automatically based on sensor inputs.
- **Energy Efficiency:** The use of low-power IoT devices and optimized actuator usage reduced overall energy consumption.
- **AI-Driven Predictive Analytics:** Historical data analysis enabled proactive adjustments to maintain optimal conditions.

C. Scalability and Usability

The modular design of the system allows it to scale seamlessly from small-scale aquaponics systems to larger commercial setups. Usability testing with diverse user groups revealed the following:

- **User-Friendly Interfaces:** Both web and mobile platforms were intuitive and accessible to users with minimal technical expertise.
- **Customizable Thresholds:** Users could define specific thresholds for environmental parameters based on plant and fish species.
- **Simple Installation:** Step-by-step guides and modular hardware design facilitated easy installation and maintenance.

D. Comparison with Existing Systems

The proposed system was compared with existing solutions, highlighting its advantages in functionality and cost-effectiveness. Table I summarizes the comparison.

TABLE I
COMPARISON OF IOT-BASED AQUAPONICS SYSTEM WITH EXISTING SYSTEMS

Feature	Proposed System	Existing System 1	Existing System 2
Approximate Cost (USD)	250	300 - 600	500 - 1000
Real-Time Monitoring	Yes	Limited	Limited
Water Quality Detection (pH, TDS)	Yes	Yes	No
Temperature Monitoring	Yes	Yes	Yes
Dissolved Oxygen Monitoring	Yes	No	No
Humidity Monitoring	Yes	No	No
Nutrient Control (Automated)	Yes	No	No
Cloud Storage and Analytics	Yes	Limited	No
AI-Based Predictive Insights	Yes	No	No
Remote Monitoring (Web/Mobile App)	Yes	Limited	No
Automated Actuation	Yes	No	No
Scalability	High	Moderate	Low
Energy Efficiency	High	Moderate	Moderate
Ease of Installation	Easy	Moderate	Difficult

E. Mobile Version

The mobile application provides users with a comprehensive dashboard for remotely monitoring and controlling the aquaponics system. As shown in Figure 5, the interface presents several key features to enhance user experience and system management. Users can view real-time data on various parameters, including pH, turbidity, TDS, dissolved oxygen, water temperature, and humidity, ensuring they have up-to-date information on system conditions at all times.

In addition to real-time monitoring, the application also offers historical data graphs for each parameter, enabling users to analyze trends over time and make informed decisions. For users who require offline analysis, there is an option to download the data in CSV format, facilitating further processing and review. The user interface is designed to be intuitive and user-friendly, ensuring seamless navigation and ease of use across various functionalities.

The mobile application is fully optimized for both Android and iOS platforms, ensuring broad accessibility for users across different devices. Furthermore, it provides timely notifications for threshold breaches and system alerts, allowing users to take immediate action when necessary and maintain optimal system performance.

F. Web Version

The web interface, as illustrated in Figure 6, provides users with an in-depth view of the aquaponics system's performance. The interface features a centralized dashboard that displays both real-time and historical data, offering users a comprehensive overview of system conditions at any given time. Graphical representations of parameter trends over time allow for easy visualization and analysis of key metrics, enabling users to track performance and identify patterns in system behavior.

In addition to monitoring, the web interface also offers remote control functionalities, allowing users to adjust system settings as needed. This capability ensures that users can manage the system efficiently and respond to changes in conditions promptly. Integration with the cloud server further enhances the system's functionality by enabling real-time updates and secure data storage, ensuring that all data is accessible and up to date.

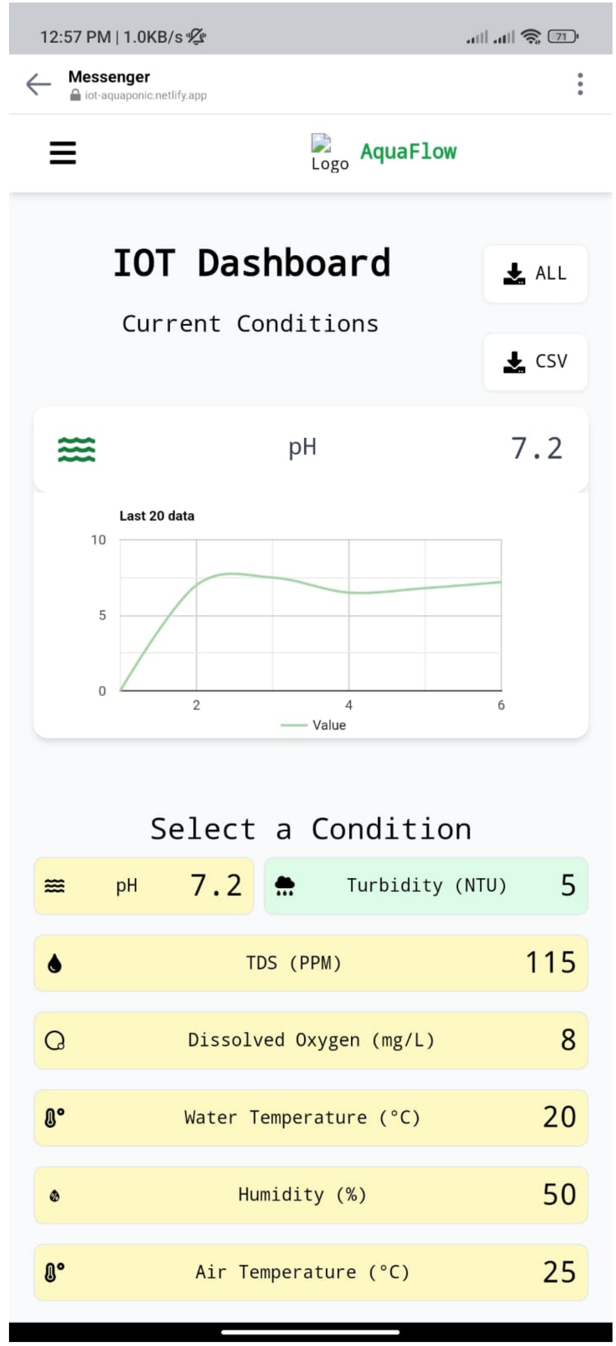

Fig. 5. Mobile Dashboard Interface of the Proposed System.

The web version is optimized for desktop and laptop access, providing advanced analytics tools and features suitable for large-scale operations. Furthermore, it supports multi-user access, making it ideal for collaborative management of more complex aquaponics systems, where different users may need to view or adjust system parameters simultaneously.

G. Key Features of the Interfaces

Both the mobile and web versions ensure accessibility, scalability, and usability with the following features:

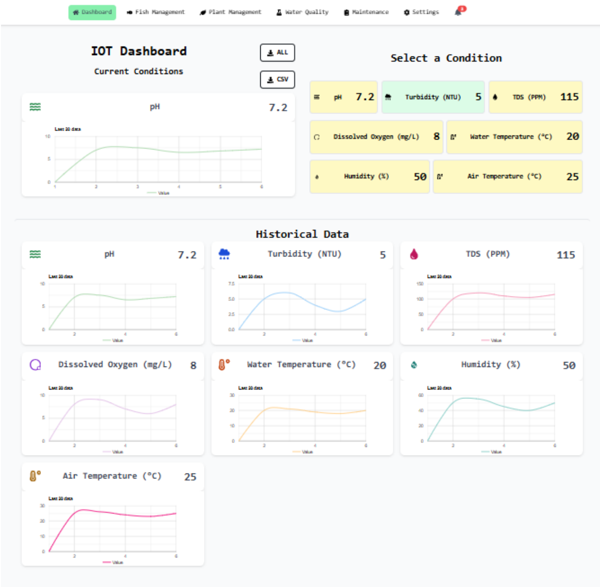

Fig. 6. Web Dashboard Interface of the Proposed System.

- **Real-Time Alerts:** Instant notifications for parameter deviations.
- **Data Visualization:** Clear and concise graphical representations.
- **Customizable Settings:** User-defined thresholds and controls.
- **Data Export Options:** CSV downloads for offline analysis.

H. Limitations and Future Work

Although the proposed IoT-based aquaponics management system demonstrates promising results, several limitations have been identified that could affect its performance and scalability. One major limitation is its dependency on stable internet connectivity for cloud-based operations. This reliance on constant internet access could pose challenges in remote or off-grid environments where connectivity is inconsistent or unavailable. Additionally, the initial calibration of sensors and actuators requires precise adjustments to ensure accurate measurements and system responsiveness, which can be time-consuming and may introduce errors if not performed carefully. Another limitation is the system's current lack of comprehensive integration with existing third-party platforms, which restricts its potential for wider adoption in diverse IoT ecosystems.

To address these limitations, future work will focus on several key areas of improvement. First, efforts will be made to enhance the system's offline functionality by incorporating local storage and processing capabilities, allowing the system to operate independently of internet connectivity for certain tasks. Second, the system will be expanded to support seamless integration with external APIs, enabling easier connectivity with other IoT ecosystems and third-party platforms. Lastly, additional sensor and actuator types will be incorporated to increase the system's versatility, allowing it to accommodate a broader range of aquaponics setups and environmental conditions.

VII. Discussion

The proposed IoT-based aquaponics management system offers a holistic approach to monitoring and automating critical parameters within aquaponics ecosystems. By leveraging real-time data acquisition, cloud analytics, and AI-driven predictive insights, the system addresses existing challenges faced in traditional aquaponics setups, including the lack of proactive management and scalability.

The comparative analysis demonstrates that the proposed system surpasses existing solutions in terms of cost-effectiveness, functionality, and ease of deployment. Real-time monitoring capabilities combined with predictive analytics not only ensure optimal fish and plant growth but also minimize resource wastage, making it environmentally sustainable.

However, certain limitations remain. The system's reliance on stable internet connectivity for cloud-based analytics may hinder its applicability in areas with limited network access. Furthermore, the initial calibration process for sensors and actuators requires technical expertise, which could pose challenges for non-technical users. Addressing these limitations through future enhancements, such as offline functionality and plug-and-play components, will improve accessibility and usability.

Overall, the integration of IoT and AI into aquaponics management sets a benchmark for modern agricultural systems, emphasizing sustainability, efficiency, and user-friendliness.

VIII. Conclusion

This study presents an Internet of Things (IoT)-based aquaponics management system that integrates real-time monitoring, cloud analytics, and AI-driven predictive capabilities. The proposed system successfully automates critical functions, such as nutrient dosing and water quality regulation, ensuring optimal conditions for both aquaculture and hydroponics. By leveraging a scalable and energy-efficient IoT architecture, the system not only reduces operational costs but also enhances overall system efficiency. Additionally, the incorporation of predictive analytics empowers the system to anticipate environmental changes, facilitating proactive management and minimizing potential risks.

A comprehensive comparison with existing systems demonstrates the superior functionality and cost-effectiveness of the proposed solution. The automation of essential processes minimizes the need for manual intervention and ensures that optimal conditions for plant and fish growth are maintained at all times. The results of this research validate the potential of the IoT-based aquaponics management system to transform aquaponics into a more sustainable and efficient agricultural practice.

Future directions for this work will focus on several key enhancements, including the development of offline capabilities to support remote or off-grid deployments, the expansion of sensor compatibility to monitor additional parameters, and the integration of third-party IoT ecosystems to promote broader adoption. These advancements aim to increase the versatility and scalability of the system, enabling its application in a wider range of aquaponics setups and contributing to the sustainability of agricultural practices globally.

References

[1] T. Shafeena, "Smart aquaponics system: Challenges and opportunities," *European Journal of Advances in Engineering and Technology*, vol. 3, no. 2, pp. 52–55, 2016.

[2] V. Nozzi, A. Graber, Z. Schmautz, A. Mathis, and R. Junge, "Nutrient management in aquaponics: comparison of three approaches for cultivating lettuce, mint and mushroom herb," *Agronomy*, vol. 8, no. 3, p. 27, 2018.

[3] R. Defa, M. Ramdhani, R. Priramadhi, and B. Aprillia, "Automatic controlling system and iot based monitoring for ph rate on the aquaponics system," in *Journal of Physics: Conference Series*, vol. 1367, no. 1. IOP Publishing, 2019, p. 012072.

[4] O. Witzel, S. Wilm, D. Karimanzira, and D. Baganz, "Controlling and regulation of integrated aquaponic production systems–an approach for a management execution system (mes)," *Information Processing in Agriculture*, vol. 6, no. 3, pp. 326–334, 2019.

[5] O. Supriadi, A. Sunardi, H. Baskara, and A. Safei, "Controlling ph and temperature aquaponics use proportional control with arduino and raspberry," in *IOP Conference Series: Materials Science and Engineering*, vol. 550, no. 1. IOP Publishing, 2019, p. 012016.

[6] D. Karimanzira and T. Rauschenbach, "Enhancing aquaponics management with iot-based predictive analytics for efficient information utilization," *Information Processing in Agriculture*, vol. 6, no. 3, pp. 375–385, 2019.

[7] T. Yang and H.-J. Kim, "Characterizing nutrient composition and concentration in tomato-, basil-, and lettuce-based aquaponic and hydroponic systems," *Water*, vol. 12, no. 5, p. 1259, 2020.

[8] M. Jawadwala and Y. Pingle, "Aquaponics for agriculture using iot," *International Journal of Engineering Research and Technology (IJERT)*, pp. 410–415, 2020.

[9] R. Concepcion, S. Ronnie *et al.*, "Automated nutrient solution control system using embedded fuzzy logic controller for smart nutrient film technique aquaponics," *J. of Computational Innovations and Engineering Applications*, vol. 4, no. 2, pp. 39–46, 2020.

[10] F. Modu, A. Adam, F. Aliyu, A. Mabu, and M. Musa, "A survey of smart hydroponic systems," *Advances in Science, Technology and Engineering Systems Journal*, vol. 5, no. 1, pp. 233–248, 2020.

[11] T. Khaoula, R. A. Abdelouahid, I. Ezzahoui, and A. Marzak, "Architecture design of monitoring and controlling of iot-based aquaponics system powered by solar energy," *Procedia Computer Science*, vol. 191, pp. 493–498, 2021.

[12] I. Ezzahoui, R. A. Abdelouahid, K. Taji, and A. Marzak, "Hydroponic and aquaponic farming: Comparative study based on internet of things iot technologies." *Procedia Computer Science*, vol. 191, pp. 499–504, 2021.

[13] D. Karimanzira and T. Rauschenbach, "An intelligent management system for aquaponics," *at-Automatisierungstechnik*, vol. 69, no. 4, pp. 345–350, 2021.

[14] V. P. Lobanov, D. Combot, P. Pelissier, L. Labbé, and A. Joyce, "Improving plant health through nutrient remineralization in aquaponic systems," *Frontiers in plant science*, vol. 12, p. 683690, 2021.

[15] M. F. Taha, G. ElMasry, M. Gouda, L. Zhou, N. Liang, A. Abdalla, D. Rousseau, and Z. Qiu, "Recent advances of smart systems and internet of things (iot) for aquaponics automation: A comprehensive overview," *Chemosensors*, vol. 10, no. 8, p. 303, 2022.

[16] 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, p. 7679, 2022.

[17] S. B. Dhal, K. Jungbluth, R. Lin, S. P. Sabahi, M. Bagavathiannan, U. Braga-Neto, and S. Kalafatis, "A machine-learning-based iot system for optimizing nutrient supply in commercial aquaponic operations," *Sensors*, vol. 22, no. 9, p. 3510, 2022.

[18] M. F. Taha, A. I. ElManawy, K. S. Alshallash, G. ElMasry, K. Alharbi, L. Zhou, N. Liang, and Z. Qiu, "Using machine learning for nutrient content detection of aquaponics-grown plants based on spectral data," *Sustainability*, vol. 14, no. 19, p. 12318, 2022.

[19] L. A. Ibrahim, H. Shaghaleh, G. M. El-Kassar, M. Abu-Hashim, E. A. Elsadek, and Y. Alhaj Hamoud, "Aquaponics: a sustainable path to food sovereignty and enhanced water use efficiency," *Water*, vol. 15, no. 24, p. 4310, 2023.

[20] P. Chandramenon, A. Aggoun, and F. Tchuenbou-Magaia, "Smart approaches to aquaponics 4.0 with focus on water quality- comprehensive review," *Computers and Electronics in Agriculture*, vol. 225, p. 109256, 2024.

[21] A. Khandakar, I. Elzein, M. Nahiduzzaman, M. A. Ayari, A. I. Ashraf, L. Korah, A. Zyoud, H. Ali, and A. Badawi, "Smart aquaponics: An innovative machine learning framework for fish farming optimization," *Computers and Electrical Engineering*, vol. 119, p. 109590, 2024.

[22] C. L. Kok, I. M. B. P. Kusuma, Y. Y. Koh, H. Tang, and A. B. Lim, "Smart aquaponics: An automated water quality management system for sustainable urban agriculture," *Electronics*, vol. 13, no. 5, p. 820, 2024.

[23] A. A. Channa, K. Munir, M. Hansen, and M. F. Tariq, "Optimisation of small-scale aquaponics systems using artificial intelligence and the iot: Current status, challenges, and opportunities," *Encyclopedia*, vol. 4, no. 1, pp. 313–336, 2024.