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IoT-Powered Aquaponics System for Enhanced Crop Yield and Fish Health : A Review

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Peer Review Information	Abstract
<i>Submission: 11 Feb 2025</i> <i>Revision: 20 Mar 2025</i> <i>Acceptance: 22 April 2025</i> Keywords <i>IoT</i> <i>Aquaponics</i> <i>Real-Time Monitoring</i> <i>Machine Learning</i>	The integration of Internet of Things (IoT) technology in aquaponics offers a modern, sustainable approach to farming by enhancing crop yield and fish health through real-time monitoring and automation. Using sensors to measure vital parameters like water level, pH, and temperature, the system ensures optimal environmental conditions. A centralized control unit processes this data and applies machine learning algorithms to automate essential functions such as water circulation, aeration, and nutrient delivery. This reduces human intervention while maximizing efficiency. The system promotes resource optimization by converting fish waste into nutrients for plants, creating a self-sustaining, closed-loop ecosystem. Compared to traditional farming, it significantly lowers water usage and eliminates the need for chemical fertilizers. While challenges include high initial costs and ongoing maintenance, the system's benefits—such as improved food security, reduced environmental impact, and increased productivity—make it a viable solution for the future of smart agriculture. This study explores its benefits, limitations, and real-world applications.

INTRODUCTION

In recent years, sustainable agricultural practices have gained significant attention due to increasing concerns about food security, water scarcity, and environmental degradation. One such innovative and eco-friendly solution is aquaponics, a method that integrates aquaculture (fish farming) with hydroponics (soilless plant cultivation) to create a self-sustaining ecosystem. This technique provides an efficient way to produce food while conserving water and reducing dependency on chemical fertilizers. When combined with Internet of Things (IoT) technology, aquaponics can be further

optimized by automating critical processes such as water quality monitoring, nutrient management, and system maintenance, making it a smart and scalable solution for modern agriculture [1].

Aquaponics works on a symbiotic relationship between fish and plants, where fish produce waste in the form of ammonia, which is broken down by beneficial bacteria into nitrates. These nitrates serve as nutrients for plants, while the plants filter and clean the water before it is recirculated back to the fish tank. This closed-loop system eliminates the need for artificial fertilizers and reduces water consumption compared to traditional farming

methods. However, maintaining optimal water conditions is crucial for the health of both fish and plants. Factors like pH level, temperature, dissolved oxygen, and water level must be continuously monitored and adjusted to ensure maximum productivity [2][3].

The integration of IoT technology into aquaponics introduces real-time monitoring and automation, allowing farmers to remotely track and control system parameters using sensors and cloud-based applications. Sensors placed in the fish tank and hydroponic system collect data on pH, temperature, water level, and nutrient concentration. This data is processed by a control board and transmitted to a user interface, such as an LCD display or a mobile application. The IoT-based system can automatically trigger pumps, aerators, and heaters to maintain optimal conditions, reducing manual intervention and human error. Additionally, real-time alerts and predictive analytics help farmers prevent potential failures, such as water contamination or oxygen depletion, enhancing overall system efficiency [3].

One of the primary advantages of IoT-enabled aquaponics is its potential for resource optimization and sustainability. Traditional farming methods consume large amounts of water and rely heavily on chemical fertilizers, which contribute to soil degradation and pollution. In contrast, aquaponics requires 90% less water than soil-based agriculture since the same water is continuously reused. The waste produced by fish is naturally converted into plant nutrients, eliminating the need for synthetic fertilizers. Additionally, IoT-based automation minimizes energy wastage by optimizing pump usage and aeration cycles, making the system cost-effective and environmentally friendly [4][5].

Despite its numerous benefits, IoT-based aquaponics faces certain challenges that must be addressed for widespread adoption. The initial setup cost of sensors, controllers, and IoT infrastructure can be high, making it less accessible for small-scale farmers. Additionally, continuous internet connectivity and power supply are required for uninterrupted operation, which may be a limitation in rural areas with limited infrastructure. Technical expertise is also needed to manage and troubleshoot the IoT system, creating a learning curve for users who are unfamiliar with smart farming technologies. However, with advancements in wireless connectivity, low-cost sensors, and renewable energy integration, these challenges can be mitigated, making IoT-based aquaponics a viable solution for both urban and rural agriculture [5].

The application of machine learning and artificial intelligence (AI) in IoT-based aquaponics can further enhance its efficiency by predicting water quality fluctuations, optimizing nutrient supply, and detecting anomalies in fish behavior. AI-powered algorithms can analyze historical data to provide insights and recommendations for improving crop yield and fish health. Blockchain technology can also be incorporated to ensure food traceability and quality control, building consumer trust in aquaponic produce. These advancements position IoT-based aquaponics as a future-ready solution for addressing global food production challenges in a sustainable manner [5].

IoT-based aquaponics presents a revolutionary approach to modern farming by combining technology with sustainable agricultural practices. By leveraging IoT for real-time monitoring, automation, and data-driven decision-making, aquaponics systems can achieve higher productivity, lower environmental impact, and greater scalability. While challenges such as high initial costs and technical expertise remain, ongoing innovations in sensor technology, AI, and renewable energy can further enhance the feasibility of IoT-driven smart farming. As the world moves towards climate-resilient and resource-efficient agricultural systems, IoT-based aquaponics stands out as a promising solution for ensuring food security and environmental sustainability.

PROBLEM IDENTIFICATION

1. **Water Scarcity** – Traditional agriculture consumes excessive water, leading to depletion of freshwater resources. Aquaponics, although water-efficient, requires precise water management.
2. **Nutrient Imbalance** – Maintaining the correct balance of ammonia, nitrates, and pH levels is critical for both fish and plant health. Any imbalance can lead to poor growth or system failure.
3. **System Maintenance** – Regular monitoring and maintenance are required to prevent clogging, pump failures, and biofilter inefficiencies, which can disrupt the entire ecosystem.
4. **High Initial Cost** – Setting up an IoT-based aquaponics system involves expenses for sensors, controllers, pumps, and automation infrastructure, making it costly for small-scale farmers.
5. **Technical Expertise** – Farmers need knowledge of IoT, aquaponics, and water chemistry to efficiently operate and troubleshoot the system.
6. **Power and Connectivity Dependency** – Continuous operation depends on an uninterrupted power supply and stable internet connectivity, which may not be available in rural areas.

7. Data Management and Security – IoT-based systems generate large amounts of data that require secure storage and processing for real-time monitoring and decision-making.

OBJECTIVES

1. Automated Monitoring – Implement real-time monitoring of water temperature, pH, and water levels using IoT sensors.
2. Reduced Human Intervention – Minimize manual effort by automating system adjustments and alerts.
3. Enhanced Productivity – Improve fish health and plant growth for higher yield compared to traditional aquaponics.
4. Efficient Resource Management – Optimize water flow, nutrient circulation, and aeration through machine learning algorithms.
5. Sustainable Operation – Ensure long-term system stability with remote supervision and reduced failure risks.

LITERATURE REVIEW

1. Al-Kodmany, K. (2018), This study explores the integration of IoT in aquaponics to enhance system efficiency and sustainability. The author highlights how IoT-enabled sensors monitor crucial parameters such as water temperature, pH levels, and nutrient concentrations in real-time. By automating water circulation and aeration, energy and resource efficiency improve significantly. The study finds that IoT-based aquaponics leads to increased fish growth rates and plant yields compared to conventional systems. Additionally, predictive analytics help in early disease detection, reducing losses. However, challenges such as initial high costs and technical expertise requirements are noted. The research concludes that IoT-powered aquaponics presents a viable, sustainable agricultural model for urban and rural settings.

2. Somerville, C. et al. (2014), This study presents an in-depth analysis of small-scale aquaponics as a sustainable farming method. The authors highlight how fish waste provides essential nutrients for plant growth while plants act as bio-filters, purifying water for fish. The research finds that aquaponics significantly reduces the need for chemical fertilizers, making it an environmentally friendly alternative. Additionally, the study emphasizes the role of system design, including water flow rates and biological filtration, in optimizing production efficiency. While aquaponics proves to be resource-efficient, the study identifies technical challenges, such as maintaining stable pH levels and preventing fish diseases. The findings suggest that with proper system management and IoT automation, small-

scale aquaponics can be a cost-effective and sustainable solution for food security.

3. Rakocy, J. E. (2012), This research discusses the integration of hydroponics and recirculating aquaculture to create an efficient food production system. The study emphasizes that nutrient cycling is crucial in maintaining system stability. Fish waste serves as a natural fertilizer, reducing the dependency on synthetic nutrients. The author identifies challenges such as biofiltration efficiency, system scalability, and the need for consistent monitoring of water quality parameters. Experimental results indicate that aquaponic systems improve overall resource utilization by recycling nutrients effectively. The study also highlights that automation through IoT-based monitoring can optimize production and reduce labor-intensive maintenance. Overall, Rakocy's research establishes aquaponics as a promising approach for sustainable food production, provided that system monitoring and management are effectively implemented.

4. Love, D. C. et al. (2015), This study presents a global survey of aquaponics practitioners to evaluate system efficiency, challenges, and best practices. The research finds that aquaponics is widely adopted in urban and rural settings due to its ability to produce food with minimal water usage. However, the study highlights common challenges such as high initial investment costs, energy consumption, and technical knowledge barriers. The findings suggest that integrating IoT technology can enhance system performance by automating monitoring and control processes. Additionally, the research points out the need for policy support and incentives to encourage widespread adoption. The study concludes that aquaponics has significant potential for sustainable food production but requires technological advancements for scalability.

5. Goddek, S. et al. (2019), This study explores technological advancements in aquaponics, particularly focusing on automation through IoT and artificial intelligence (AI). The authors demonstrate that integrating smart sensors with AI-based predictive models significantly improves system efficiency. By continuously monitoring environmental parameters such as water levels, nutrient composition, and fish health, IoT-enabled systems can automatically adjust aeration, feeding, and filtration processes. The research finds that AI-driven decision-making reduces operational costs while increasing crop and fish yield. However, the study acknowledges challenges such as data

integration complexities and reliance on power sources. The findings suggest that future aquaponic systems should incorporate renewable energy sources to further enhance sustainability. The study concludes that IoT and AI-powered aquaponics represent the future of precision agriculture, optimizing food production while conserving natural resources.

6. Graber, A., & Junge, R. (2009), This study investigates how aquaponics can enhance nutrient recycling by utilizing fish wastewater for vegetable production. The authors demonstrate that aquaponic systems efficiently convert fish waste into plant nutrients, reducing environmental pollution while increasing agricultural productivity. The research finds that compared to conventional hydroponics, aquaponics requires fewer chemical inputs and enhances water conservation. However, maintaining a balanced nitrogen cycle remains a challenge, as excessive ammonia levels can be toxic to fish and plants. The study emphasizes the importance of biofiltration and microbial activity in stabilizing nutrient availability. The research concludes that aquaponics is a viable alternative to traditional farming, particularly in water-scarce regions, but requires precise system management to prevent nutrient imbalances.

7. Danaher, J. J. et al. (2013), This study evaluates the co-cultivation of tilapia and lettuce in an aquaponic system and its impact on yield and sustainability. The research finds that aquaponics provides optimal growing conditions for both fish and plants by ensuring a continuous nutrient cycle. The authors highlight that while tilapia thrive in recirculating water systems, proper aeration and waste removal are essential to prevent ammonia buildup. Experimental results reveal that lettuce grown in aquaponic systems exhibits higher nutrient uptake and faster growth compared to soil-based cultivation. However, the study identifies challenges such as temperature regulation and system scaling for commercial production. The findings suggest that integrating automated monitoring systems can enhance efficiency, making aquaponics a promising solution for sustainable food production.

8. Yep, B., & Zheng, Y. (2019), This review paper provides an overview of global trends in aquaponic research and identifies key challenges hindering widespread adoption. The authors find that aquaponics significantly reduces water and fertilizer usage, making it a sustainable alternative to conventional agriculture. The study discusses various system designs, including media-based,

nutrient film, and deep water culture, highlighting their advantages and limitations. One major challenge identified is the complexity of system maintenance, as balancing nutrient levels requires continuous monitoring. The authors suggest that integrating IoT technology can automate system regulation, improving efficiency. The research concludes that while aquaponics holds great potential for sustainable agriculture, further innovations in automation and energy efficiency are needed to enhance scalability and commercial viability.

9. Palm, H. W. et al. (2018), This study examines the transition of aquaponics from small-scale research models to commercial-scale production. The authors discuss various system designs, nutrient cycling efficiencies, and water quality management techniques. The research finds that commercial aquaponics faces challenges such as high initial investment costs, strict food safety regulations, and the need for skilled labor. However, technological advancements, including IoT-based monitoring and automated nutrient dosing, have improved system efficiency and reduced labor requirements. The study highlights that integrating renewable energy sources can further enhance sustainability. The authors conclude that with proper regulatory frameworks and technological innovations, commercial aquaponics has the potential to revolutionize sustainable food production, particularly in urban environments.

10. Goddek, S., & Keesman, K. J. (2020), This study explores the role of dynamic modeling in optimizing aquaponic systems for maximum productivity and sustainability. The authors highlight that real-time data collection using IoT sensors enables predictive analytics, allowing for more precise system adjustments. The research finds that by modeling nutrient flows, water temperature, and microbial activity, aquaponic systems can achieve higher efficiency and stability. One key finding is that AI-based automation can significantly reduce resource wastage and improve fish and plant health. However, the study acknowledges challenges such as data integration complexities and the high costs of implementing smart technologies. The research concludes that AI and IoT-driven aquaponics will play a crucial role in future sustainable agriculture, reducing environmental impact while increasing food production efficiency.

Research Gap

Extensive research on aquaponic systems, several gaps remain in optimizing their efficiency,

scalability, and commercial viability. Many studies focus on nutrient recycling and water conservation but fail to address the long-term sustainability of large-scale aquaponic farms. Additionally, most research is conducted under controlled laboratory conditions, with limited real-world implementation data. The integration of IoT and AI for real-time monitoring and automation is still in its early stages, with challenges in data accuracy, system adaptability, and affordability. Furthermore, studies often overlook the economic feasibility of aquaponics, including high initial investment costs and maintenance requirements. There is also a lack of standardized guidelines for system design, water quality management, and regulatory compliance. Addressing these gaps through interdisciplinary research, field experiments, and technological advancements will be crucial in making aquaponics

a more viable and widely adopted agricultural practice.

- Despite advancements in IoT-based aquaponics, several research gaps remain. Most studies focus on monitoring water parameters, but limited research exists on predictive maintenance and early fault detection using AI.
- The integration of renewable energy sources for sustainable power remains underexplored. While automation has improved efficiency, optimizing nutrient delivery based on real-time plant and fish health data requires further investigation.
- Scalability and cost-effectiveness of IoT-based aquaponics for large-scale farming need more analysis. Lastly, security concerns related to cloud-based monitoring systems lack comprehensive study.
- Addressing these gaps can enhance the reliability and sustainability of smart aquaponics systems.

METHODOLOGY

Proposed System

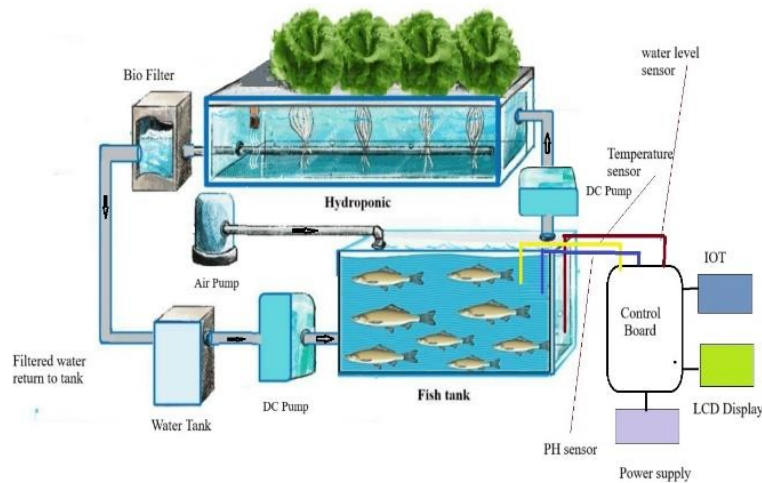


Fig. 1. Diagram of the Aquaponics system for enhanced crop yield and fish health

Working of IoT-Based Aquaponics System

Fish Tank & Waste Generation:

- The aquaponics system starts with the fish tank, where fish are kept and nurtured.
- As the fish consume food, they produce waste, which contains ammonia-rich compounds.
- If accumulated, this waste becomes toxic for the fish, requiring a proper filtration mechanism to maintain water quality.

Bio-Filter for Nitrification:

- The water containing fish waste is pumped from the fish tank into a bio-filter.
- In this filter, nitrifying bacteria convert toxic ammonia into nitrites and then into nitrates.

- These nitrates serve as natural fertilizers, essential for plant growth in the hydroponic section.
- This process, known as nitrification, ensures that harmful ammonia is converted into useful nutrients, making the system sustainable.

Hydroponic Plant Growth:

- The nitrate-rich water is directed into the hydroponic grow bed, where plants absorb the nutrients for growth.
- Since hydroponics eliminates soil, plant roots directly access water and nutrients, enhancing growth efficiency.
- As plants absorb the nitrates, they naturally filter and purify the water.

- This creates a mutually beneficial system—fish provide nutrients for plants, and plants clean the water for fish.

Water Circulation & Filtration:

- Once the plants absorb the required nutrients, the purified water is filtered and recirculated back into the fish tank.
- A DC pump ensures continuous water circulation, maintaining a balanced and self-sustaining closed-loop system.
- Additional water filtration mechanisms, such as mechanical filters, may be included to remove solid waste before returning water to the tank.

Sensor-Based Monitoring & IoT Control:

- To maintain optimal water quality, pH sensors, temperature sensors, and water level sensors continuously monitor the system's parameters.
- The control board processes this data and transmits it to an IoT module for remote monitoring and automation.
- If any abnormality (e.g., high ammonia, low water level, or temperature fluctuations) is detected, the system can automatically adjust settings, such as turning on a water pump or activating an aeration system to increase oxygen levels.

User Interface & Alerts:

- The collected data is displayed on an LCD screen and sent to a connected IoT device, such as a smartphone or computer.
- Users receive real-time alerts in case of any system malfunctions, allowing for quick intervention and maintenance.
- This automated IoT-based monitoring minimizes manual labor, optimizes fish health, and enhances plant yield, making the aquaponics system more efficient and sustainable.
- This intelligent, sensor-driven aquaponics system ensures a self-sustaining, resource-efficient method of food production, combining fish farming and hydroponic plant growth in a single ecosystem.

Components Used

- Fish Tank
- Frame
- Power Supply Unit
- Arduino Controller
- IOT Module
- LCD display
- PH sensor
- Water level sensor
- Temperature sensor

- Relay Board
- DC Pump
- Water Filter
- Air Pump
- Others.

ADVANTAGES

- Efficient Resource Utilization – Reduces water and nutrient wastage by continuously recycling water.
- Automated Monitoring – IoT sensors track water parameters, reducing manual intervention.
- Sustainable System – Utilizes fish waste as nutrients for plants, promoting eco-friendly farming.
- Higher Productivity – Ensures optimal conditions for fish and plants, leading to increased yield.
- Reduced Chemical Usage – Minimizes the need for fertilizers and pesticides.

APPLICATIONS

- Urban Farming – Used in cities to grow fresh vegetables and fish in limited space.
- Sustainable Agriculture – Helps in eco-friendly food production with minimal environmental impact.
- Commercial Fish Farming – Enhances fish health and productivity with automated monitoring.
- Research & Education – Used for studying aquaponics and smart farming techniques.
- Rural Development – Provides a sustainable food production system in remote areas.

CONCLUSION

The IoT-based aquaponics system presents a transformative solution for sustainable agriculture by integrating fish farming and hydroponic plant growth into a single, efficient ecosystem. By leveraging real-time monitoring through IoT sensors, the system ensures optimal water level, temperature, and pH levels, creating a self-sustaining and automated farming environment. This smart approach minimizes human intervention while improving efficiency, productivity, and resource utilization.

Overall, this IoT-powered aquaponics system offers a promising, technology-driven approach to modern agriculture. By improving food production efficiency while conserving natural resources, it provides a sustainable, eco-friendly, and innovative solution to meet the growing global demand for food security and environmental conservation.

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