Solar-Powered IoT-Based Smart Aquaponic System for Sustainable Agriculture

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Abstract

This paper introduces a groundbreaking smart aquaponics system designed to address the limitations of conventional setups. The system leverages IoT technology, renewable energy, and automation to achieve real-time monitoring and environmental control. Key innovations include slidable grow beds for optimal sunlight exposure, solar tracking mechanisms for efficient energy utilization, and automated fish feeding using Real Time Clock (RTC) modules. The system demonstrated 90% water efficiency, significant energy savings, and streamlined resource management in prototype testing. With its modular and scalable design, this solution is ideal for urban farming and sustainable agriculture.

Keywords: Aquaponic, Internet of Things, Solar

1. Introduction

Aquaponics is the symbiotic combination of aquaculture (fish farming) with hydroponics (plant growth without soil) [1]. It is a sustainable food production method that could replace conventional agriculture [2]. According to the engineering design, aquaponics systems can be broadly categorized into couple and decoupled systems [3]. A coupled Aquaponics system is an ordinary Aquaponics system in which the aquaculture units and the hydroponics unit are interconnected in a loop. The water is directly pumped from the fish tank to the hydronic unit and then back to the fish tank. Decoupled systems are disposed of in different loops of fish tanks and hydroponics and water is pumped back to the corresponding units [4]. The system can also be categorized according to the location and size of the production, which includes indoor and outdoor Aquaponics systems and small-scale home/hobby systems for self-consumption food production for local use in contrast to industrial/commercial Aquaponics [5]. An indoor system is established within a building to ensure that all the required environmental conditions such as artificial light are available for the system, and this becomes common in urban lifestyle [6]. Outdoor systems employ controlled conditions such as greenhouses to favor the growth of fish and plants. In this case, the system can be even more sustainable by using solar energy to power the entire system [7], [8]. The closed-loop principle can be applied for domestic purposes or demonstration only. Closed loop coupled systems pay more attention to the biological–chemical part of the process water. The undigested particles in the fish waste increase the nutrient value of the water as well as the digestive bacteria. Integrated systems perform better than individual Aquaponics systems [9].

Since the increased urbanization, agricultural land resources have decreased. Rapid population growth has also raised the demand for food. Traditional plant cultivation techniques involve vast amounts of area, time, and labour. Consequently, there is a growing concern for safe and sustainable food sources, demanding the development of innovative agricultural practices [10]. Therefore, conventional agriculture alone cannot address food security; the pursuit of contemporary vertical agriculture is vital. Moreover, the rising need for fish, water, and fertilizer for crop development, as well as environmental and health issues, motivate the development of aquaponics as a viable method for sustainable fish and crop production [11]. In the context of the present food and environmental crises, aquaponics farming offers a means to increase agricultural output. Aquaponics is described as the symbiotic cultivation of aquatic organisms and plants. Aquaponics is gaining popularity due to its capacity to conserve resources, great efficiency, and low usage. Aquaponics have become the current trend in agricultural growth [12].

This paper presents a smart aquaponics system that addresses the limitations of traditional setups by integrating IoT technology, renewable energy, and automation. The system is designed to minimize manual labor, optimize resource usage, and enhance operational efficiency. The rest of this paper is structured as follows: Section 2 outlines the research methodology; Section 3 reports the results of the research; and Section 4 highlights some important conclusions.

2. Methodology

The proposed smart aquaponics system integrates five main modules designed to automate environmental monitoring and system control. These include the structural design of the system, which includes a data acquisition unit, a system rectification unit, IoT integration, and an energy management system. Together, these modules enable real-time monitoring, automated adjustments, and energy-efficient operation. All these five modules are described in details in the following paragraphs.

The physical framework of the system is constructed using durable aluminium profiles, providing lightweight yet sturdy support for all essential components. The design accommodates three sliding grow beds, a central aquarium tank, and a solar panel mounted on a dynamic tracking mechanism. The grow beds are engineered to adjust their position based on sunlight intensity, as measured by Light Dependent Resistor (LDR) sensors. This feature optimises sunlight exposure, enhancing plant growth while reducing energy dependence. Flexible piping connects the aquarium and grow beds, enabling efficient water flow throughout the system. The solar panel, integrated into the structure, is designed to dynamically track sunlight, ensuring maximum energy capture. The structural design of the system is illustrated in Fig. 1.

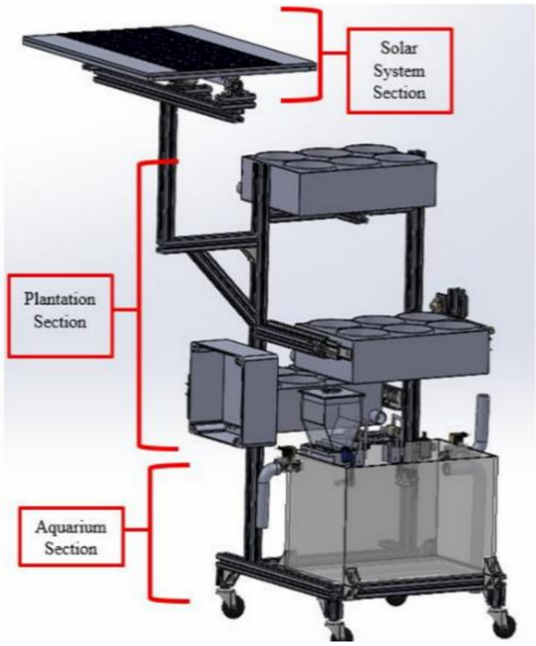

Fig.1 Structural design of the system.

The data acquisition unit plays a pivotal role in maintaining the delicate balance required for aquaponics. It employs a network of sensors to monitor critical environmental parameters. A pH sensor ensures the water's acidity remains within the optimal range of 6.5 to 7.5, critical for both plant and fish health. The DS18B20 waterproof temperature sensor provides precise readings, maintaining stable water temperatures conducive to a thriving ecosystem. An ultrasonic sensor measures water levels, preventing overflow or underfill conditions. These sensors continuously transmit real-time data to the system's central processing unit for analysis and subsequent action. The integration of these sensors ensures the aquaponics environment remains stable, automated, and responsive to dynamic conditions. Fig. 2 illustrates the flow chart for the data acquisition system.

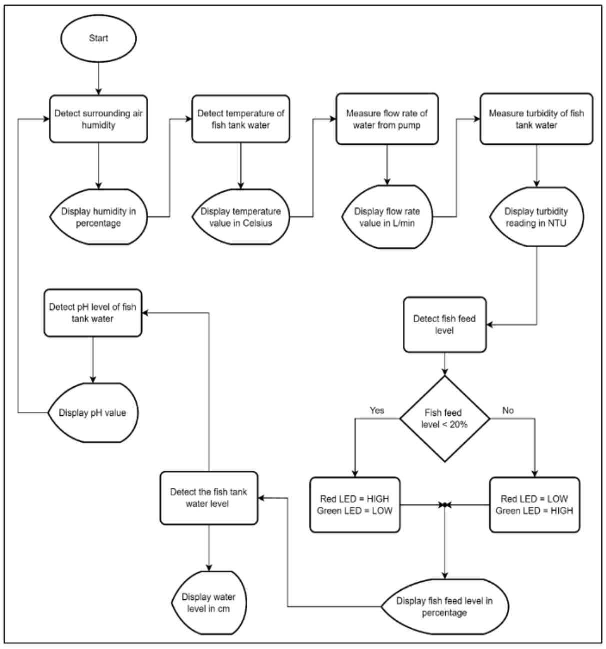

Fig.2 Data acquisition system flow chart

The system incorporates a sophisticated rectification unit to address anomalies detected by the sensors. This includes an automated fish feeder that operates on a Real-Time Clock (RTC) module, dispensing feed at precise intervals to ensure consistent care for the aquaculture. Water flow management is achieved using solenoid valves that regulate the flow between the aquarium and grow beds, maintaining a consistent and nutrient-rich circulation. Grow bed adjustments are facilitated by servo motors, which dynamically position the beds based on sunlight availability. The sliding mechanism for the grow beds ensures optimal exposure during the day while retracting them at night to protect the plants. The rectification unit enhances operational efficiency by automating critical interventions, reducing the need for manual oversight. The water flow management flow chart is shown in Fig. 3.

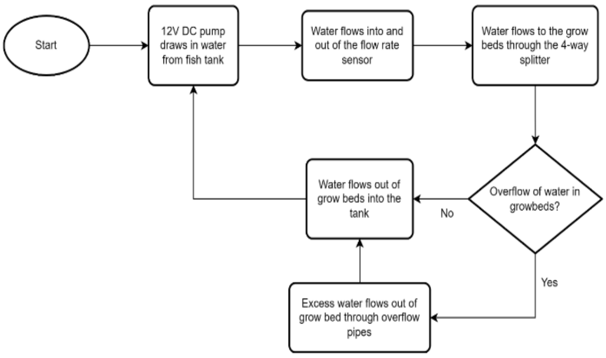

Fig.3 Water flow management flow chart.

IoT integration is at the heart of the system, enabling users to monitor and control its operations remotely. The Arduino IoT Cloud serves as the primary platform for data visualisation and control. Real-time environmental data, including pH levels, temperature, and water flow rates, is displayed on an intuitive dashboard accessible via web or mobile applications. The system is designed to send alerts when parameters deviate from their optimal ranges, allowing users to intervene promptly. The IoT interface also provides a manual override feature, giving users the flexibility to control actuators directly if required.

This integration ensures seamless interaction between users and the system, enhancing reliability and ease of use. The Arduino IoT cloud web dashboard is shown in Fig. 4.

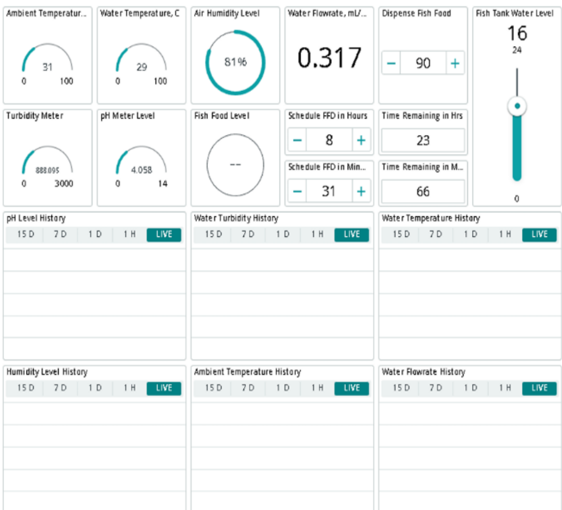

Fig. 4. Arduino IoT cloud web dashboard.

Energy management is a critical aspect of the system, achieved through a hybrid solar power setup. The solar panel is equipped with a tracking mechanism that adjusts its orientation to follow the sun throughout the day, maximizing energy capture. The captured energy is stored in a 12V DC battery, ensuring uninterrupted operation during nighttime or cloudy conditions. In situations where solar energy is insufficient, the system switches to a direct power supply, maintaining continuous functionality. This energy-efficient design significantly reduces operational costs and aligns with the project's sustainability objectives. Fig. 5 illustrates the solar charge controller of the system.

Fig. 5. Solar charge controller.

3. Results and Discussion

Extensive testing was conducted to validate the system's functionality and efficiency. Each sensor was calibrated to ensure high accuracy. The pH sensor maintained an error margin of ±0.1, while the DS18B20 temperature sensor demonstrated an accuracy of ±0.5°C across varying water conditions. The ultrasonic sensor reliably measured water levels, ensuring seamless water circulation. Grow bed actuation was tested under dynamic light conditions, confirming smooth and accurate movement. The solar tracking system was evaluated for energy efficiency, showing a 30% improvement in energy capture compared to fixed panels. Automated fish feeding schedules, managed by the RTC module, consistently dispensed feed at the pre-set times without errors. The final prototype during the system testing and validation process is shown in Fig. 6.


Fig.6 Final prototype system testing and validation

The smart aquaponics system demonstrated impressive performance metrics during prototype testing. The sensors provided accurate and reliable data, with real-time logging and visualization through the IoT dashboard. Users were able to remotely monitor system operations and receive alerts for deviations, showcasing the efficacy of the IoT integration. The system performance on the Arduino IoT cloud web dashboard is shown in Fig. 7.

Fig. 7. System performance monitoring on the Arduino IoT cloud web dashboard

The solar tracking mechanism significantly enhanced energy efficiency, capturing 30% more solar energy than conventional fixed-panel setups. This, combined with the hybrid power system, ensured uninterrupted operation even under low-light conditions. Water circulation was consistent, maintaining a nutrient-rich environment for plants and fish while minimizing wastage. The grow beds, dynamically positioned based on light intensity, achieved optimal sunlight exposure, accelerating plant growth rates.

While the system performed well, certain challenges were identified, including occasional connectivity issues with the IoT platform and mechanical wear on the sliding grow beds. These limitations underscore the need for further refinement, such as improving connectivity resilience and enhancing material durability. Nevertheless, the system's modular design and demonstrated performance highlight its potential for scalable applications in urban and commercial farming.

4. Conclusion

The development of the smart aquaponics system demonstrates a significant advancement in sustainable agriculture by integrating IoT technology, renewable energy, and automation. The system effectively combines aquaculture and hydroponics into a self-sustaining unit capable of optimizing resource usage and minimizing human intervention. Key innovations, such as the sliding grow beds for enhanced sunlight exposure, real-time environmental monitoring through IoT dashboards, and a hybrid solar power system, showcase the potential for scalability and adaptability in urban and commercial farming environments. Testing validated the system's high efficiency, achieving a 90% reduction in water usage and a 30% improvement in energy capture. While challenges like connectivity stability and mechanical wear require further refinement, this project provides a scalable framework for addressing food security challenges in resource-constrained settings.

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References

1. Kyaw, Thu Ya, and Andrew Keong Ng. "Smart aquaponics system for urban farming." Energy procedia 143 (2017): 342-347.
2. Mahkeswaran, R., and Andrew Keong Ng. "Smart and sustainable home aquaponics system with feature-rich Internet of things mobile application." In 2020 6th International Conference on Control, Automation and Robotics (ICCAR), pp. 607-611. IEEE, 2020.
3. Chandramenon, Praveen, Amar Aggoun, and Fideline Tchuenbou-Magaia. "Smart approaches to Aquaponics 4.0 with focus on water quality− Comprehensive review." Computers and Electronics in Agriculture 225 (2024): 109256.
4. Monsees, Hendrik, Werner Kloas, and Sven Wuertz. "Comparison of coupled and decoupled aquaponics-Implications for future system design." Abstract from aquaculture Europe (2016).
5. Li, Chunjie, Chew Tin Lee, Yueshu Gao, Haslenda Hashim, Xiaojun Zhang, Wei-Min Wu, and Zhenjia Zhang. "Prospect of aquaponics for the sustainable development of food production in urban." Chemical Engineering Transactions 63 (2018): 475-480.
6. Tomlinson, Lisa. "Indoor Aquaponics in abandoned buildings: a potential solution to food deserts." Sustainable Dev. L. & Pol'y 16 (2015): 16.
7. Nagayo, Analene Montesines, Cesar Mendoza, Eugene Vega, Raad KS Al Izki, and Rodrigo S. Jamisola. "An automated solar-powered aquaponics system towards agricultural sustainability in the Sultanate of Oman." In 2017 IEEE International Conference on Smart Grid and Smart Cities (ICSGSC), pp. 42-49. IEEE, 2017.
8. Khaoula, Taji, Rachida Ait Abdelouahid, Ibtissame Ezzahoui, and Abdelaziz Marzak. "Architecture design of monitoring and controlling of IoT-based aquaponics system powered by solar energy." Procedia Computer Science 191 (2021): 493-498.
9. Goddek, Simon, Alyssa Joyce, Benz Kotzen, and Gavin M. Burnell. Aquaponics food production systems: combined

aquaculture and hydroponic production technologies for the future. Springer Nature, 2019.
10. Haryanto, M. Ulum, A. F. Ibadillah, R. Alfita, K. Aji, and R. Rizkyandi. "Smart aquaponic system based Internet of Things (IoT)." In Journal of Physics: Conference Series, vol. 1211, p. 012047. IOP Publishing, 2019.
11. Vernandhes, Wanda, Nur Sultan Salahuddin, A. Kowanda, and Sri Poernomo Sari. "Smart aquaponic with monitoring and control system based on IoT." In 2017 second international conference on informatics and computing (ICIC), pp. 1-6. IEEE, 2017.
12. Yanes, A. Reyes, P. Martinez, and R. Ahmad. "Towards automated aquaponics: A review on monitoring, IoT, and smart systems." Journal of Cleaner Production 263 (2020): 121571.

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