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# Implementation of Internet of Things (IoT) and Renewable Energy Technologies in Aquaponic Systems for Food and Energy Independence

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ABSTRACT

Food and energy availability have become strategic issues amid population growth and environmental crises, necessitating innovations in more efficient, adaptive, and sustainable aquaculture systems. This study focuses on the development of an integrated aquaponics system that combines fish and plant cultivation within a closed ecosystem, enhanced by Internet of Things (IoT) technology and the use of solar panels as the primary energy source. The developed system is designed to monitor environmental parameters in real time, including pH, TDS, temperature, humidity, and light intensity, as well as to track the performance of solar panel power output as part of the system's energy management. The research methodology includes hardware and software design and integration, prototype development, functional testing, and performance analysis based on energy efficiency and aquaculture productivity. The results show that the resulting smart aquaponics prototype is energy-efficient, adaptive to environmental changes, and user-friendly, demonstrating potential to support food and energy independence at both household and community scales.

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## INTRODUCTION

Food and energy availability have become increasingly urgent strategic challenges amid population growth, land-use changes, and rising environmental pressures. These conditions demand food production systems that are not only efficient and resource-saving but also capable of operating independently in terms of energy. Aquaponics, as an integrated cultivation system combining fish and plant production within a closed ecosystem, offers a sustainable solution by minimizing water usage, reducing waste, and increasing productivity in limited spaces.

However, the success of aquaponic systems is highly dependent on the stability of environmental parameters such as pH, temperature, TDS levels, humidity, and light intensity. Manual monitoring, which requires significant time, effort, and precision, often becomes a constraint, especially for long-term operations. Therefore, technology capable of real-time environmental monitoring and automatic system adjustments is essential to maintain the stability of the aquaponic ecosystem. In this context, the Internet of Things (IoT) serves as a key technology, enabling the integration of sensors, microcontrollers, and actuators so that the system can be monitored and controlled remotely via a smartphone application or directly on-site.

Beyond monitoring and control, energy requirements are a critical component, as IoT devices need a stable power supply. The use of solar panels as the primary energy source provides a strategic solution to enhance system independence, reduce reliance on the electricity grid, and support the implementation of aquaponics in areas with limited access to electricity. Integrating renewable energy technology with IoT systems not only improves operational efficiency but also reinforces the sustainability concept in modern food production.

This study develops an integrated aquaponics system that utilizes IoT for real-time monitoring of environmental parameters and solar panels as the main energy source. The system is designed to manage water circulation and nutrient distribution automatically based on sensor data, with additional manual control options via a smartphone. This approach is expected to overcome the limitations of conventional aquaponic systems, enhance operational reliability, and contribute significantly to a self-sufficient and sustainable model of food and energy production at both household and community scales.

## LITERATURE REVIEW

Meeting the demands for food and energy has become a critical issue that requires modern aquaculture approaches that are efficient, adaptive, and capable of operating independently. One rapidly developing technology to address these challenges is aquaponics, an integrated cultivation system that combines fish and plant production within a closed-loop ecosystem. The effectiveness of aquaponics can be significantly enhanced through the implementation of the Internet of Things (IoT) for real-time monitoring of environmental parameters, supported by solar panels as the system's primary energy source. The integration of these three components—aquaponics, IoT, and renewable energy—forms the core foundation of this research to establish an efficient cultivation model that supports food and energy independence.

### A. Basic Concept of Aquaponics

Aquaponics is a food production system that combines aquaculture (fish cultivation) and hydroponics (plant cultivation in water) within a closed-loop ecosystem. Metabolic waste from fish, rich in ammonia, is converted by nitrifying bacteria into nitrate, which is then utilized by plants as a nutrient source. The plants absorb excess nutrients while simultaneously purifying the water before it is returned to the fish pond. This system offers several advantages, such as efficient water usage, minimal waste production, and the ability to be implemented in limited spaces, whether in urban areas, rural regions, or locations with scarce natural resources. In the context of this study, aquaponics serves as the primary platform optimized through IoT and renewable energy technologies to achieve a stable, efficient, and sustainable cultivation system.

### B. Working Principle of the Internet of Things (IoT) in Aquaponics Systems

The Internet of Things (IoT) is a concept that integrates physical devices such as sensors, microcontrollers, communication modules, and actuators, which are interconnected via networks to exchange data and perform automatic control. In aquaponic systems, IoT enables real-time monitoring and control of environmental parameters through smartphone devices. IoT sensors are used to measure critical parameters such as pH, TDS, water temperature, ambient humidity, light intensity, and energy performance data such as solar panel voltage and current. This information is sent to a microcontroller (e.g., ESP32) for processing and used to automatically control water pumps, aeration, and nutrient circulation. In addition to automation, the system provides manual control options via the IoT-based application. The implementation of IoT makes the system more precise, responsive to environmental changes, and operationally efficient, aligning with the research objective to create an adaptive and user-friendly aquaponics system.

### C. Renewable Energy Technology (Solar Panels)

Solar panels are photovoltaic devices that convert sunlight into electrical energy. The generated energy can be stored in batteries or used directly to operate system components such as sensors, IoT controllers, water pumps, and actuators. In this study, solar panels are used as the primary energy source to support the independence of the aquaponic system from conventional electricity grids. This approach not only reduces long-term operational costs but also enables the system to operate in areas with limited electrical infrastructure. The integration of solar panels with IoT creates an energy-efficient cultivation system that operates sustainably and provides real-time energy performance data for analysis and optimization purposes.

## METHODOLOGY

The research methodology in the study of the Implementation of the Internet of Things (IoT) and Renewable Energy Technology in Aquaponic Systems for Food and Energy Independence was conducted through several stages, including the design, development, integration, and testing of an IoT-based aquaponic system prototype powered by solar energy. The study began with hardware design, which involved the mechanical construction of the aquaponic system and the selection of electronic components such as pH, TDS, temperature, humidity, light intensity sensors, and solar panel performance sensors. Microcontrollers—such as the ESP32—were programmed to read sensor data, control pumps, and manage other actuators. The energy system was designed using solar panels connected to a charge controller and batteries to ensure a stable and independent power supply.

The next stage involved software development, including microcontroller programming, automation algorithms, and the creation of an IoT application for real-time monitoring and manual control via smartphones. Following this, integration was carried out between the aquaponic system, IoT modules, and the solar panel circuit so that all components functioned as a cohesive, supportive ecosystem. The integrated prototype was then subjected to functional testing to evaluate sensor reading accuracy, data transmission stability to the IoT application, and automatic and manual control responses to environmental conditions. Additionally, energy performance analysis was conducted by measuring solar panel output, system energy consumption, and battery capacity to maintain operation during low light intensity. This comprehensive methodology was designed to produce an intelligent aquaponic system that is efficient, adaptive, and capable of sustainable operation to support food and energy independence.

### A. Research Design

The research design to be carried out can be seen in the Overall System Design Diagram below:

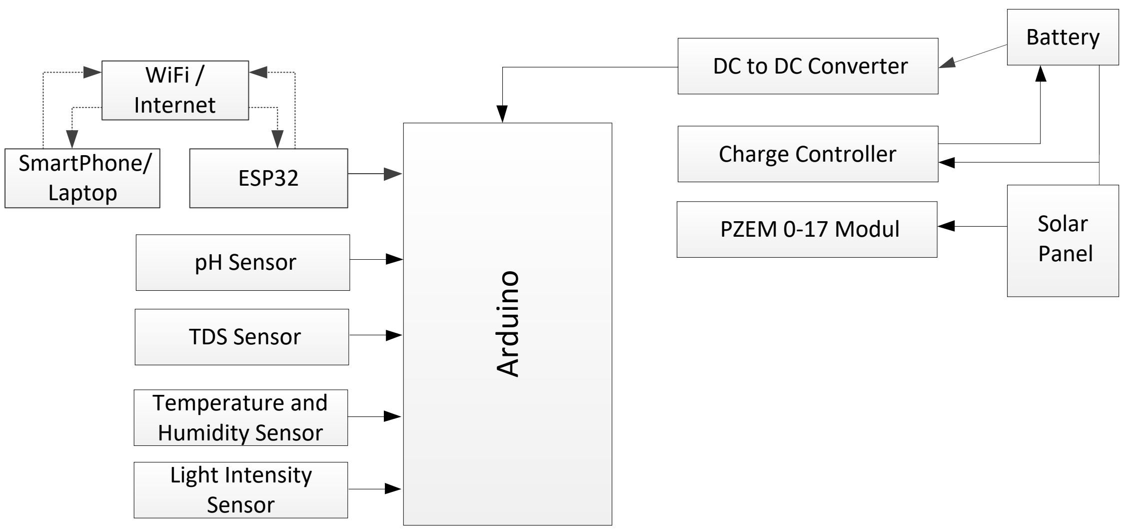


Figure 1. Overall System Design Diagram

Based on the block diagram above, it illustrates the design of an IoT-based monitoring and automation system integrated with renewable energy sources to support energy independence in aquaponic or tilapia farming systems. All sensors—including pH, TDS, temperature and humidity, as well as light intensity sensors—are connected to an Arduino, which serves as the central data processing unit, continuously measuring each water quality and environmental parameter. The collected data is then transmitted to an ESP32 module, which acts as a bridge to the WiFi or internet network, allowing real-time monitoring via smartphones or laptops. Meanwhile, the system's power supply utilizes solar panels connected to a PZEM-017 module to monitor energy consumption, then routed through a charge controller to charge the batteries, and subsequently stabilized via a DC-to-DC converter before being supplied to electronic devices. The integration of IoT and renewable energy technology enables the system to operate automatically, energy-efficiently, and be remotely monitored, in line with the research objective of enhancing the efficiency and sustainability of aquaponic systems.

**RESEARCH RESULT**

The results and discussion in the study on the Implementation of the Internet of Things (IoT) and Renewable Energy Technology in Aquaponic Systems for Food and Energy Independence consist of five tests, namely: testing the DHT11 sensor for temperature and humidity detection, testing the performance of the pH sensor within the system, testing the performance of the TDS sensor within the system, testing the performance of the light sensor and RTC module, and testing the solar panel as part of the integrated IoT monitoring system.

**A. Testing of the DHT11 Sensor for Temperature and Humidity Detection**

This test was conducted to determine the accuracy of temperature and humidity detection using the DHT11 sensor. The test results are presented in Table 1 below.

**Table 1. DHT11 Sensor Data for Temperature and Humidity Detection**

| No. | Sensor Measurement DHT 11 | | Hygrometer Measurement | | Error Percentage (%) | |
|---|---|---|---|---|---|---|
| | Temperature (°C) | Humidity (%) | Temperature (°C) | Humidity (%) | Temperature (°C) | Humidity (%) |
| 1 | 30,6 | 72,4 | 29,3 | 1 | 30,6 | 72,4 |
| 2 | 30,1 | 70,2 | 28,9 | 2 | 30,1 | 70,2 |
| 3 | 29,8 | 71,7 | 28,7 | 3 | 29,8 | 71,7 |
| 4 | 28,9 | 76,9 | 27,6 | 4 | 28,9 | 76,9 |
| 5 | 28,5 | 78,1 | 27,2 | 5 | 28,5 | 78,1 |

Based on Table 1 above, it shows the comparison between the readings of the DHT11 sensor and the reference hygrometer in the solar-powered IoT-based aquaponic system. In general, the temperature and humidity values recorded by the DHT11 follow the same pattern as the reference instrument, although they still exhibit a certain deviation consistent with the sensor's characteristics. The temperature error percentage ranges from 3.8% to 4.8%, while the humidity error ranges from 5.8% to 6.4%. These results confirm that the DHT11 sensor is sufficiently reliable for monitoring the aquaponic environment, particularly for real-time monitoring functions, even though it is not as precise as laboratory instruments. Overall, the sensor performs stably and is suitable for use as part of a renewable energy-based IoT automation and monitoring system.

**B. Testing the Performance of the pH Sensor in the System**

This test was conducted to evaluate the effectiveness of the pH sensor used to detect pH levels in the aquaponic system. The test results are presented in Table 2 below.

**Table 2. pH Sensor Data in the System**

| No. | pH Input Value | Measured pH Sensor Value | System Status | |
|---|---|---|---|---|
| | | | Notification | Buzzer |
| 1 | 7.0 | 5.8 | Notification Sent | On |
| 2 | 7.0 | 7.3 | No Notification | Off |
| 3 | 7.0 | 6.7 | No Notification | Off |
| 4 | 7.0 | 8.6 | Notification Sent | On |

Based on Table 2 above, it shows the pH sensor readings in the aquaponic system compared to the ideal pH setpoint value (7.0). When the pH reading falls outside the safe range of 6.5–7.5, the IoT system automatically sends a notification to the user and activates a buzzer as a local alert. Conversely, if the sensor reading remains within the safe range, the system does not send any notification and the buzzer remains inactive. This test demonstrates that the pH detection system operates responsively and accurately in maintaining stable water quality in the solar-powered autonomous aquaponic system.

**C. Testing the Performance of the TDS Sensor in the System**

This test was conducted to evaluate the effectiveness of the TDS sensor used to detect the concentration levels in the nutrient solution for plant cultivation within the aquaponic system. The test results are presented in Table 3 below.

**Table 3. Performance Test of the TDS Sensor in the System**

| No. | Input Value (ppm) | Measured TDS Sensor Value (ppm) | System Status | |
|---|---|---|---|---|
| | | | Additional Solution Pump | Neutral Water Pump |
| 1 | 1200 | 1050 | On | Off |
| 2 | 1200 | 1185 | Off | Off |
| 3 | 1200 | 1240 | Off | Off |
| 4 | 1200 | 1380 | Off | On |

Based on Table 3 above, this table illustrates how the IoT system controls TDS balance in the aquaponic system. When the TDS value is read below the setpoint (e.g., 1050 ppm), the system automatically activates the nutrient solution pump to increase the concentration. If the value remains within the safe range (±5–10%), both pumps remain inactive. Conversely, when the TDS value exceeds the upper limit (e.g., 1380 ppm), the system activates the neutral water pump to reduce the concentration. These results indicate that the automation system can respond accurately to changes in water quality, supporting nutrient stability for both fish and plants in the solar-powered aquaponic system.

**D. Testing the Performance of the Light Sensor and RTC Module**

This test was conducted to evaluate the effectiveness of the light sensor and RTC (Real-Time Clock) module, which are used to control the nutrient pump and lighting system. The test results are presented in Table 4 below.

**Table 4. Test Results of the Light Sensor and RTC Module Performance**

| No. | Light Sensor | Time | System Status | |
|---|---|---|---|---|
| | | | Main Nutrient Pump | Lighting Lamp |
| 1 | Bright | 13.00 | On | Off |
| 2 | Dark | 10.30 | On | On |
| 3 | Dark | 21.15 | Off | On |
| 4 | Bright | 17.20 | On | Off |

Based on Table 6 above, the testing of the light sensor and RTC module indicates that the system can automatically regulate the operation of the nutrient pump and lighting based on light–dark conditions and the programmed schedule. During daylight conditions, the lighting remains off because natural light is sufficient, while the nutrient pump continues to operate according to the schedule. When darkness occurs in the morning or afternoon, the lights automatically turn on to meet the plants' lighting needs. At night, the nutrient pump stops according to the operational schedule, whereas the lights remain on until the predetermined lighting period ends. These results demonstrate that the integration of the light sensor and RTC module effectively supports energy efficiency and promotes stable plant growth in the IoT- and renewable energy-based aquaponic system.

**E. Solar Panel Testing**

This test was conducted to evaluate the performance of the solar panel in the Implementation of Internet of Things (IoT) and Renewable Energy Technologies in the Aquaponic System for Food and Energy Independence. The test results can be seen in Table 5 below.

Table 5. Solar Panel Testing Data

| Time | Solar Panel | | | Weather Status |
|---|---|---|---|---|
| | Voltage (V) | Current (A) | Power (W) | |
| 08:00 | 17,90 | 0,20 | 3,58 | Cloudy |
| 09:00 | 18,40 | 0,26 | 4,78 | Sunny |
| 10:00 | 18,85 | 0,32 | 6,03 | Sunny |
| 11:00 | 19,20 | 0,48 | 9,21 | Sunny |
| 12:00 | 19,75 | 0,65 | 12,84 | Sunny |
| 13:00 | 20,10 | 0,80 | 16,08 | Sunny |
| 14:00 | 19,10 | 0,72 | 13,75 | Sunny |
| 15:00 | 18,60 | 0,58 | 10,79 | Cloudy |
| 16:00 | 18,30 | 0,40 | 7,32 | Cloudy |
| 17:00 | 18,10 | 0,28 | 5,07 | Cloudy |

From the tests conducted, the results of the solar panel evaluation indicate that solar irradiance significantly affects the power output. During the morning and cloudy conditions, the voltage and current remain relatively low, resulting in minimal power generation. The power increases significantly between 11:00 and 13:00 when the weather is clear and the sun is at an optimal position. In the late afternoon, especially under cloudy conditions, the power output decreases again. These data demonstrate that the solar panel is capable of providing a stable energy supply for the IoT-based aquaponic system, particularly during peak power production hours around 11:00–14:00 WIB.

**F. Monitoring System Testing**

The testing of the integrated Internet of Things (IoT) monitoring system demonstrates how the concept of monitoring using IoT technology can be implemented within the system. Some of these tests are illustrated in Figure 2 below.


Figure 2. Integrated Internet of Things Monitoring System

Based on Figure 1 above, it can be seen that the integrated Internet of Things monitoring system has successfully connected to all sensors, allowing real-time remote monitoring of aquaponic parameters.

## DISCUSSION

This study develops an integrated aquaponic system combining fish and plant cultivation with IoT technology and solar energy to enhance food and energy self-sufficiency. The system enables real-time monitoring of environmental parameters—pH, TDS, temperature, humidity, and light intensity—and solar power performance. Results show the prototype is energy-efficient, adaptive, and user-friendly, offering a sustainable solution for household and community-level food and energy production, with potential for further enhancement in control features.

## CONCLUSIONS AND RECOMMENDATIONS

The conclusion of this study is that the implementation of the Internet of Things (IoT) and renewable energy technology in aquaponic systems has been proven to enhance operational efficiency, sustainability, and self-sufficiency in integrated fish and plant farming. The developed system successfully performs real-time monitoring of environmental parameters—including pH, TDS, temperature, humidity, and light intensity—through the integration of sensors with Arduino and ESP32 connected to the internet, allowing information to be accessed via smartphones. Moreover, the utilization of solar panels as the primary energy source has been proven capable of providing stable and sustainable power, supported by the PZEM energy monitoring module and a charge controller circuit that ensures optimal energy storage and distribution. Test results indicate that this smart aquaponic system prototype is not only energy-efficient but also adaptive and user-friendly, thereby supporting increased productivity while reducing reliance on conventional energy sources. Overall, this study confirms that the integration of IoT with renewable energy technology has significant potential to promote food and energy self-sufficiency, both at household and community scales.

## ADVANCED RESEARCH

This study develops an intelligent aquaponic system integrating IoT and renewable energy to achieve food and energy self-sufficiency. Using high-precision sensors, IoT communication, and solar energy, the system enables real-time monitoring, responsive actuator control, and efficient energy management. The approach supports a sustainable, scalable, and autonomous farming model, particularly suitable for areas with limited electricity, and lays the foundation for AI-driven precision agriculture and smart renewable-powered aquaculture.

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