



Smart IoT-Based Feeding System with Solar Panel Integration as an Efficient Solution for Freshwater Fish Farming

Mardiana¹, Idham Kamil², Tuti Adi Tama Nasution¹, Fera Damayanti³ and Al Qadry²

¹Department of Electrical Engineering, Politeknik Negeri Medan, Medan, Sumatera Utara, Indonesia

²Department of Mechanical Engineering, Politeknik Negeri Medan, Medan, Sumatera Utara, Indonesia

³Department of Computer Engineering, Politeknik Negeri Medan, Medan, Sumatera Utara, Indonesia

*Corresponding Author: mardiana@polmed.ac.id

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ABSTRACT

Freshwater aquaculture plays a crucial role in supporting food security and economic growth; however, manual feeding practices often lead to irregular schedules, inefficient feed utilization, and increased labor requirements. This study proposes an Internet of Things (IoT)-based automatic fish feeding system integrated with a solar energy supply to improve operational efficiency and sustainability. The system employs an ESP32 microcontroller, an ultrasonic sensor for feed level detection, and a servo motor as the feeding actuator. Remote monitoring and control are implemented through the Blynk application, enabling real-time scheduling and notification. The system is powered by a solar panel combined with battery storage to ensure continuous operation in outdoor aquaculture environments. Experimental results show that the system achieves a sensor error of 3.56%, a feeding delay of 2–4 seconds, and a response time of less than 2 seconds, indicating reliable real-time performance. The proposed system improves feeding accuracy, reduces feed waste, and minimizes labor dependency. In addition, integrating solar energy enhances system sustainability and enables deployment in off-grid aquaculture areas. Therefore, this system provides an efficient, reliable, and scalable solution for modern aquaculture management.

Keywords: Internet of Things (IoT), Automatic Fish Feeder, ESP32, Solar Energy, Aquaculture, Real-Time Monitoring

ABSTRAK

Akuakultur air tawar memiliki peran penting dalam mendukung ketahanan pangan dan pertumbuhan ekonomi; namun, praktik pemberian pakan secara manual sering kali menyebabkan jadwal yang tidak teratur, pemanfaatan pakan yang tidak efisien, serta meningkatnya kebutuhan tenaga kerja. Penelitian ini mengusulkan sistem pemberi pakan ikan otomatis berbasis Internet of Things (IoT) yang terintegrasi dengan sumber energi surya untuk meningkatkan efisiensi operasional dan keberlanjutan. Sistem ini menggunakan mikrokontroler ESP32, sensor ultrasonik untuk mendeteksi ketinggian pakan, serta motor servo sebagai aktuator pemberi pakan. Pemantauan dan pengendalian jarak jauh diimplementasikan melalui aplikasi Blynk, yang memungkinkan penjadwalan dan pemberian notifikasi secara real-time. Sistem ini didukung oleh panel surya yang dikombinasikan dengan penyimpanan energi berupa baterai untuk memastikan operasi berkelanjutan pada lingkungan akuakultur luar ruangan. Hasil pengujian menunjukkan bahwa sistem mencapai tingkat kesalahan sensor sebesar 3,56%, keterlambatan pemberian pakan sekitar 2–4 detik, serta waktu respons kurang dari 2 detik, yang menunjukkan kinerja real-time yang andal. Sistem yang diusulkan mampu meningkatkan akurasi pemberian pakan, mengurangi pemborosan pakan, serta meminimalkan ketergantungan pada tenaga kerja. Selain itu, integrasi memungkinkan penerapan pada area akuakultur yang tidak terjangkau jaringan listrik. Oleh karena itu, sistem ini memberikan solusi yang efisien, andal, dan skalabel untuk pengelolaan akuakultur modern.

Kata kunci: Internet of Things (IoT), Pemberi Pakan Ikan Otomatis, ESP32, Energi Surya, Akuakultur, Pemantauan Real-Time.



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1. Introduction

Freshwater fish farming is one of the key sectors in Indonesia's aquaculture industry due to its high economic value, relatively short production cycles, and consistently stable market demand year-round. Commodities such as catfish, tilapia, and gourami serve as the backbone of national aquaculture production because they are relatively easy to cultivate and widely consumed by the community. This sector not only plays a vital role in meeting animal protein requirements but also significantly improves community welfare, particularly in rural and inland water areas. Furthermore, freshwater aquaculture plays a strategic role in supporting national food security programs and reducing poverty by creating jobs and developing new business opportunities. According to the Food and Agriculture Organization (FAO), aquaculture continues to grow rapidly and contributes significantly to global fish production and food supply [1]. This growth is driven by the increasing demand for animal protein, the limitations of capture fisheries, and technological advancements in aquaculture systems [2].

However, despite its significant potential, freshwater aquaculture faces several challenges, one of the most critical being feed management. Feed is the largest cost component in aquaculture operations, accounting for 60–70% of total production costs. Therefore, efficient feed management is a key factor in determining the success and profitability of aquaculture practices. In reality, most feeding activities are still performed manually. Manual feeding often leads to irregular feeding schedules, delays, and inaccurate feed portions. These issues not only hinder optimal fish growth but also increase the feed conversion ratio (FCR) and result in feed wastage, ultimately raising operational costs [3]. Moreover, overfeeding can deteriorate water quality due to the accumulation of uneaten feed, which may trigger disease outbreaks and reduce fish survival rates [4].

In response to these challenges, various studies have explored the application of automation technologies in aquaculture systems. Previous research has developed automatic feeding systems based on microcontrollers and sensors to improve feeding efficiency and accuracy. For instance, Internet of Things (IoT)-based aquaculture monitoring systems have been introduced to automate feeding processes while simultaneously monitoring environmental parameters such as temperature, pH, and dissolved oxygen levels [5]. These technologies enable the integration of multiple sensors and actuators into a unified system that operates automatically under predefined conditions. Furthermore, several studies have investigated the use of Artificial Intelligence (AI) to optimize feeding strategies by analyzing fish behavior and environmental conditions [6].

Despite these technological advancements, several limitations remain. Many existing systems are still limited to local monitoring via LCD displays or simple interfaces, requiring users to be on-site to access system information. Additionally, some systems require additional communication modules, such as separate Wi-Fi or GSM units, which increase system complexity and implementation costs [7]. Another significant limitation is the lack of integration between feeding systems, environmental monitoring, and energy management, resulting in systems that are not fully efficient or autonomous [8]. These constraints highlight the need for more integrated, cost-effective, and user-friendly solutions, particularly for small- and medium-scale fish farmers.

With the rapid advancement of Internet of Things (IoT) technology, new opportunities have emerged to enhance the efficiency and effectiveness of aquaculture systems. IoT-based solutions enable real-time data acquisition, remote device control, and instant notifications delivered directly to users via mobile devices. Additionally, IoT platforms facilitate the integration of historical data for further analysis, enabling more accurate and data-driven decision-making [9]. The use of mobile-based IoT applications also allows users to monitor and control aquaculture systems anytime and anywhere, thereby improving operational flexibility and management efficiency [10].

On the other hand, sustainability has become an essential consideration in modern aquaculture development. The reliance on conventional electricity sources often presents challenges, particularly in remote areas with limited grid access. Therefore, integrating renewable energy sources, such as solar panels, offers a promising way to enhance energy independence in aquaculture systems. Solar energy is environmentally friendly, reduces long-term operational costs, and improves system reliability during power outages or emergency conditions [11]. The application of renewable energy in IoT-based systems has also been widely studied and proven to support sustainable and continuous system operations [12].

Based on these challenges and opportunities, this study proposes developing an IoT-based automatic fish-feeding system integrated with solar panel technology. The system uses an ESP32 microcontroller with built-in Wi-Fi, eliminating the need for additional communication modules. A servo motor is employed as an actuator to precisely control feed distribution, while an ultrasonic sensor is used to monitor feed availability within the container in real time. The system is integrated with the Blynk application, enabling users to schedule feeding times, monitor feed conditions, and receive notifications when feed stock is running low.

2. Method

2.1. Hardware Design

The proposed system consists of a solar-powered energy subsystem, a sensing subsystem, a control unit, and an actuation mechanism, designed to operate in an integrated and autonomous manner. The primary power source is a 50–100 Wp solar panel connected to a Maximum Power Point Tracking (MPPT) charge controller to optimize energy harvesting under varying irradiance conditions. MPPT technology ensures the solar panel operates at its optimal voltage and current, maximizing energy conversion efficiency even under partial shading or fluctuating sunlight intensity. The electrical energy generated is stored in a 12V battery to ensure continuous operation, particularly during low-light conditions or at night. The integration of solar energy into aquaculture systems has been shown to improve sustainability, enhance energy independence, and reduce reliance on conventional power sources, especially in remote or off-grid aquaculture locations. In addition, solar-powered systems have been reported to significantly reduce operational costs over time while maintaining reliable performance for IoT-based applications. The experimental setup is given in Figure 1.



Figure 1. Experimental setup of the solar-powered IoT-based automatic fish feeding system

A voltage regulation system is implemented to stabilize fluctuations during transient loads, such as when the servo motor is activated. Transient load conditions can cause voltage instability, which may affect the performance of sensitive electronic components. Therefore, a stable power management approach is required to ensure reliable system operation. The supplied energy is regulated by a buck converter to provide a stable, efficient voltage suitable for the ESP32 microcontroller and its peripheral components across various operating conditions. The use of DC-DC converters in embedded systems is essential for maintaining voltage stability, improving energy efficiency, and preventing potential damage from overvoltage or undervoltage conditions. The block diagram is given in Figure 2.

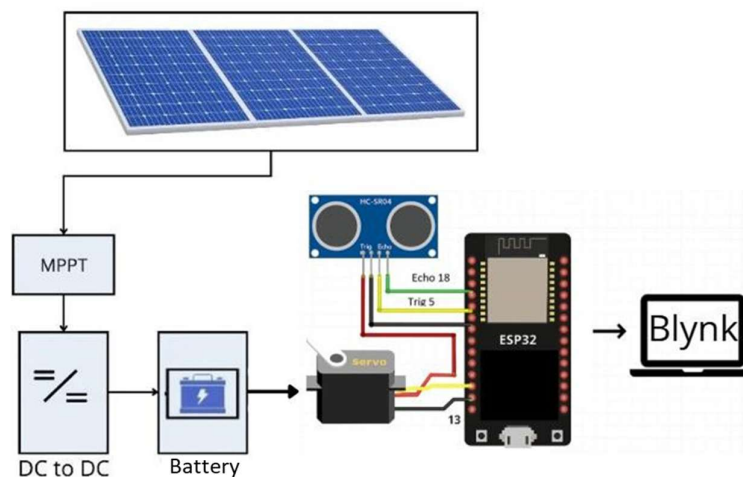


Figure 2. Block diagram of the solar-powered IoT-based automatic fish feeding system.

The proposed system operates as an integrated energy and control architecture that combines a solar power source with IoT-based monitoring and automation. Electrical energy generated from the solar panel is first processed through a Maximum Power Point Tracking (MPPT) module to optimize energy harvesting under varying irradiance conditions. The regulated output is then converted using a DC-DC converter to ensure a

stable voltage level before being stored in the battery. This stored energy serves as the primary power supply for the entire system, including the control unit, sensors, and actuator, enabling continuous operation even under fluctuating environmental conditions.

The core control unit of the system is based on the ESP32 microcontroller, which manages data acquisition, processing, and communication. The ESP32 receives input signals from the connected sensors and processes them in real time to determine the system's response. Its built-in Wi-Fi capability enables seamless data transmission to the cloud platform, allowing users to monitor system parameters and control feeding operations remotely. Due to its low power consumption, high processing power, and integrated communication capabilities, the ESP32 is well-suited for IoT-based monitoring and control applications. The feeding mechanism is driven by a servo motor, controlled by the ESP32 via a PWM signal to precisely regulate the opening and closing of the feed container.

Feed level monitoring is achieved using an ultrasonic sensor positioned at the top of the feed container. The sensor continuously measures the distance between the feed surface and the sensor, and the obtained data is processed by the ESP32 to determine the availability of feed. This measurement approach enables the system to perform non-contact sensing, ensuring consistent performance regardless of feed characteristics. The use of ultrasonic sensors in such applications is well established due to their reliability, simplicity, and effectiveness across diverse operating conditions.

Furthermore, integrating sensing, control, and communication components into a unified IoT platform enables automated, real-time system operation. Data collected from the sensors is transmitted to a cloud-based interface, allowing users to monitor system status, schedule feeding times, and execute manual control when necessary. This integrated approach enhances operational efficiency, reduces human intervention, and improves feeding accuracy. The implementation of IoT-based systems in aquaculture has demonstrated significant advantages, including real-time monitoring, data-driven decision-making, and the automation of routine processes. Consequently, the developed system provides a scalable and efficient solution that supports sustainable freshwater fish farming by leveraging renewable energy and smart technology.

2.2. Software Design

The software is developed using the Arduino IDE and deployed on the ESP32 microcontroller, enabling continuous data acquisition, processing, and real-time decision-making. The system periodically reads input data from the ultrasonic sensor to evaluate the feed level inside the container and determine the overall system status. The acquired data are processed to control the feeding mechanism and to update system information for remote monitoring.

Feeding schedules are configured through the Blynk mobile application, which communicates with the ESP32 via Wi-Fi. The use of IoT platforms such as Blynk enables remote monitoring, real-time control, and notification systems in aquaculture applications. The system automatically actuates the servo motor according to predefined feeding schedules and allows users to manually trigger feeding via the application interface when necessary.

To ensure accurate and reliable feed-level detection, a predefined threshold is set based on the measured distance between the ultrasonic sensor and the feed surface. In this study, the maximum measurable distance of the feed container is approximately 25 cm. A low feed level condition is defined when the measured distance is greater than or equal to 20 cm (≥ 20 cm), indicating that the feed volume has significantly decreased and requires replenishment. A normal condition is defined when the distance is less than or equal to 10 cm (≤ 10 cm), representing sufficient feed availability. Meanwhile, distances of 10-20 cm are categorized as moderate, indicating that the feed is still available but should be monitored. These threshold values are determined through experimental calibration and are consistent with typical container dimensions used in small-scale aquaculture systems.

When the measured distance exceeds the predefined threshold (≥ 20 cm), the system classifies the feed level as low and automatically sends a notification to the user via the mobile application. This approach enhances operational efficiency, reduces the need for manual inspection, and minimizes the risk of feed shortages in aquaculture operations.

The threshold parameters presented in Table 1 define the classification of feed levels based on the measured distance obtained from the ultrasonic sensor. These ranges are used to determine the system response, including normal operation, monitoring conditions, and refill notifications. By establishing clear threshold values, the system can perform accurate decision-making and ensure timely feeding management in aquaculture operations.

Table 1. Feed Level Threshold Parameters

Parameter Range	Condition Level	Description
Distance \leq 10 cm	Full	Feed is sufficient (normal condition)
10 cm < Distance < 20 cm	Moderate	Feed is available but requires monitoring
Distance \geq 20 cm	Low	Feed is insufficient (refill required)
Maximum Distance	\approx 25 cm	Total container height capacity

The system operation begins with an initialization stage, in which all input and output (I/O) peripherals are configured, including the ultrasonic sensor, servo motor, and communication interface. During this phase, the ESP32 microcontroller establishes a stable Wi-Fi connection to the Blynk platform to enable real-time data exchange and remote control. Once the connection is successfully established, the system enters a continuous monitoring loop.

In the monitoring phase, the ultrasonic sensor periodically measures the distance between the sensor and the feed surface to determine the feed level within the container. The acquired data are processed by the ESP32 and subsequently transmitted to the Blynk application, allowing users to observe the system status in real time. The system then evaluates the measured feed level against predefined threshold conditions to determine whether sufficient feed is available.

If the feed level is within the acceptable range, the system remains in standby while continuously updating the feed status on the Blynk platform. However, if the feed level falls below the defined threshold, the system proceeds to the decision-making stage. In this stage, the ESP32 checks for feeding triggers, which may originate from either predefined automatic schedules or manual commands issued through the Blynk application interface. This dual-mode operation ensures flexibility by supporting both autonomous and user-controlled feeding mechanisms.

When a valid feeding condition is detected, the ESP32 generates a control signal to activate the servo motor. The servo motor then performs a controlled rotation to open the feed container and dispense an appropriate amount of feed. After feeding is complete, the servo motor returns to its initial position to close the container, ensuring controlled, repeatable operation.

Following the execution phase, the system updates the operational status and transmits the latest information back to the Blynk platform. This includes feed-level status and system activity, which the user can access remotely. The system then returns to the monitoring loop, enabling continuous operation, real-time responsiveness, and efficient feed management.

Overall, the implemented flowchart reflects a closed-loop control system that integrates sensing, decision-making, actuation, and communication processes. This architecture enhances system reliability, reduces the need for manual intervention, and ensures consistent feeding operations, making it highly suitable for smart aquaculture applications.

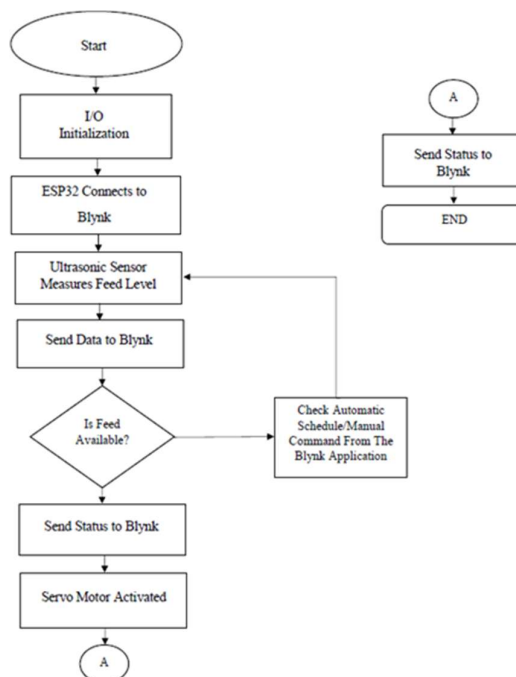


Figure 3. Flowchart of the solar-powered IoT-based automatic fish feeding system.

2.3. System Testing and Data Collection

System performance is evaluated through a series of experimental tests, including sensor calibration, feeding-time accuracy, and system response-time analysis. These evaluations are conducted to assess the accuracy, reliability, and responsiveness of the proposed system under real operating conditions. The experimental setup and measurement parameters are given in Table 2.

Table 2. Experimental Setup and Measurement Parameters

Parameter	Description
Measurement Tool	Calibrated ruler (mm precision)
Sensor Calibration Points	Full, medium, and low feed levels
Fish Type	Freshwater fish (e.g., tilapia or catfish)
Number of Fish	Approximately 50–100 fish
Feeding Schedule	2–3 times per day (morning and afternoon)
Response Time Scenario	Stable Wi-Fi and moderate latency conditions
Data Recording Method	System log timestamp from ESP32

Sensor calibration is performed by comparing the ultrasonic sensor's distance measurements with reference values obtained via manual measurements. The manual measurements are taken with a calibrated ruler to millimeter precision, directly from the ultrasonic sensor position to the surface of the feed inside the container. Multiple measurement points are taken at different feed levels (full, medium, and low) to ensure consistency and accuracy across the entire operating range. The deviation between the sensor readings and the manual measurements is then used to calculate the measurement error and identify any systematic bias in the sensor output. The calibration results are further analyzed to ensure the sensor provides stable, consistent, and reliable data for feed-level detection.

Feeding time accuracy is evaluated under controlled experimental conditions by scheduling multiple feeding events at predefined time intervals. The test is conducted in a freshwater aquaculture setup consisting of a small-scale fish pond containing approximately 50–100 freshwater fish (e.g., tilapia or catfish), which represent commonly cultivated species in aquaculture systems. The system is configured to dispense feed at specific times (e.g., morning and afternoon feeding schedules), and the actual execution time of the servo motor activation is recorded in the system log as a timestamp. The deviation between the programmed schedule and the actual execution time is calculated to assess the precision and reliability of the system's timing mechanism.

In addition, system response time is analyzed by measuring the delay between user-issued commands in the Blynk application and the servo motor's corresponding actuation. This test is conducted under various network conditions, including stable Wi-Fi connectivity and moderate network latency, to evaluate the robustness of the communication system. The response time includes both data transmission delay and processing time within the ESP32 microcontroller, providing a comprehensive assessment of system performance in real-time operation.

Similar evaluation approaches have been widely adopted in prior IoT-based aquaculture studies to assess system performance with respect to accuracy, responsiveness, and operational reliability [13,14].

2.4. Data Analysis

The collected data are analyzed quantitatively using statistical methods, including calculating mean values and percentage errors to evaluate system performance. The average values represent the system's overall behavior during experimental testing, while error percentages measure the deviation between observed and reference values.

Sensor accuracy is assessed by calculating the deviation between the ultrasonic sensor's measured values and the corresponding actual values determined by manual measurement. This analysis allows identification of measurement consistency and the sensor's precision in detecting feed levels.

Furthermore, system responsiveness is evaluated using time-delay measurements, specifically by calculating the latency between input commands and the resulting system actuation. This includes both communication delays and processing time within the microcontroller. The response time analysis is essential for determining the system's capability to operate under real-time conditions and ensuring the timely execution of feeding operations.

These evaluation metrics are widely adopted in IoT-based aquaculture systems to ensure reliable performance, accuracy, and operational effectiveness under real-world conditions.

3. Results and Discussion

3.1. Sensor Calibration Results

The sensor calibration test was conducted to evaluate the ultrasonic sensor's accuracy in measuring the feed level. The results are given in Table 3. The comparison between the sensor readings and manual measurements shows an average error of 3.56%. This result indicates that the sensor has a relatively high level of accuracy, exceeding 95%.

The observed error may be influenced by several factors, including the surface shape and density of the feed, as well as signal reflection characteristics of the ultrasonic waves. Similar studies have reported that ultrasonic sensors in IoT-based monitoring systems typically exhibit error rates of 3%-5%, depending on environmental conditions and object properties [15,16]. Therefore, the obtained result is still within an acceptable range and suitable for practical implementation in aquaculture systems.

Table 3. Result of sensor calibration

No	Actual Distance (cm)	Detected Distance (cm)	Error (%)
1	5	5.2	4.0
2	10	10.3	3.0
3	15	15.5	3.3
4	20	20.7	3.5
5	25	26.0	4.0
Average Error			3.56

3.2. Feeding Time Accuracy

The feeding time accuracy test was performed by comparing the scheduled feeding time with the actual execution time. The results (Table 4) show a time difference ranging from 2 to 4 seconds, with an average delay of approximately 3 seconds. Despite this slight delay, all feeding events were successfully executed within the acceptable time tolerance, categorized as "on time."

The delay can be attributed to system processing time, network latency, and communication between the ESP32 microcontroller and the IoT platform. Previous studies have reported similar delays in IoT-based control systems, where response times are influenced by network conditions and cloud-based communication. Therefore, the system demonstrates reliable scheduling performance for real-time feeding applications.

Table 4. Result of automatic feeding monitoring

Schedule	Actual Time	Response Time	Difference (Second)
08:00	08:00:03	3	On Time
12:00	12:00:02	2	On Time
17:00	17:00:04	4	On Time

3.3. System Response Time

The system response time was evaluated based on the delay between user commands and system execution. Table 5 shows that the response time for manual feed activation (ON) is approximately 1.2 seconds, and for deactivation (OFF) is approximately 1.1 seconds. Additionally, the notification for low feed levels is successfully delivered in less than one second. These results indicate that the system operates in real time with an average response delay of less than 2 seconds. The observed delay is primarily influenced by communication latency between the ESP32 microcontroller and the IoT platform, as well as processing time within the system. In IoT-based systems, communication latency is commonly affected by network conditions, data transmission protocols, and cloud processing time, which can introduce delays in real-time control applications [17]. Similar studies on IoT-based aquaculture systems have reported response times ranging from 1 to 3 seconds, depending on network conditions and system architecture [13,14]. Therefore, the performance of the developed system is reliable and suitable for real-time fish-feeding applications.

Table 5. Result of automatic control

Status	System Condition	System Response	Response Time (s)
Manual Feed ON	Motor ON	Feed valve opens	1.2
Manual Feed OFF	Motor OFF	Feed valve closes	1.1
Low Feed Notification	Detected by the sensor	“Refill Needed” alert	<1

2.3. Solar Power System Performance

The integration of a solar power system plays a crucial role in ensuring energy sustainability and system autonomy. The use of a solar panel, an MPPT charge controller, and battery storage enables the system to operate independently of conventional power sources. In this study, the system utilizes a 20 W photovoltaic panel and a 12 V, 7 Ah battery, yielding a total energy capacity of approximately 84 Wh, as calculated using Equation (1).

$$E = V \times Ah \quad (1)$$

To evaluate operational capability, the system's total power consumption is estimated from its main components. The ESP32 microcontroller operates at an average power consumption of approximately 1–1.5 W, while peripheral components such as the ultrasonic sensor and communication module contribute an additional 0.5–1 W. The servo motor, which operates intermittently during feeding cycles, contributes a peak power of approximately 2–3 W, but its average contribution is significantly lower due to its short duty cycle. As a result, the overall average system power consumption is approximately 3–5 W.

Based on this configuration, the system can operate continuously for approximately 16.8 to 28 hours without solar input, depending on operating conditions and the servo motor's duty cycle. Under typical outdoor conditions with 4–6 peak sun hours per day, the solar panel generates approximately 80–120 Wh/day, sufficient to recharge the battery and sustain continuous system operation. This demonstrates that the system is energetically self-sufficient for daily operation in typical aquaculture environments.

The presence of a supercapacitor helps stabilize voltage during peak loads, while the buck converter ensures a consistent supply voltage to the ESP32 and other components. This configuration enhances system reliability, especially in outdoor aquaculture environments where power availability may be limited.

Previous studies have shown that solar-powered IoT systems can significantly reduce operational costs and improve sustainability in aquaculture applications [18,19]. In addition, the integration of renewable energy systems with IoT-based monitoring platforms has been reported to improve energy efficiency and operational autonomy in smart aquaculture environments [20]. Although detailed long-term performance testing of the solar system was not conducted extensively in this study, the implemented configuration demonstrated stable operation during testing.

2.4. Discussion

Overall, the developed system demonstrates reliable performance in sensor accuracy, feeding-time precision, and response speed. The sensor's 3.56% accuracy indicates that the system can effectively monitor feed levels, which is essential for preventing feed shortages and minimizing waste.

Accurate feeding schedules and fast system response times contribute to improved automation, reducing dependence on manual labor. Compared with traditional feeding methods, this system provides a more consistent and efficient feeding process, thereby improving fish growth and reducing operational costs.

The integration of IoT technology allows remote monitoring and control, enabling users to manage feeding activities more effectively. In addition, the use of solar energy enhances system sustainability and makes it suitable for deployment in remote aquaculture areas with limited access to electricity.

However, several limitations should be noted. The performance of the ultrasonic sensor may be affected by environmental conditions and feed characteristics. In addition, system performance may vary depending on network stability and solar energy availability. Future improvements may include integrating additional sensors, such as water quality sensors (pH, temperature, and dissolved oxygen), and optimizing the power management system to enhance reliability.

Overall, the proposed system provides a practical, efficient, and sustainable solution for modern aquaculture management, aligning with the growing trend of smart farming and IoT-based automation.

4. Conclusion

This study successfully developed and evaluated a solar-powered, IoT-based automatic fish feeding system using an ESP32 microcontroller and the Blynk application. Experimental results confirm the system's high reliability and precision, featuring a low sensor error of 3.56%, a minimal feeding delay of 2–4 seconds, and a response time under 2 seconds. The integration of a solar power subsystem ensures energy autonomy, making

it a scalable and sustainable solution for off-grid aquaculture areas. Although network stability and environmental variables remain challenges, future developments will focus on integrating water-quality sensors (pH, dissolved oxygen, temperature) and optimizing adaptive power-management algorithms for fully automated smart farming.

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