Engagement:
Jurnal Pengabdian kepada Masyarakat
Vol. 10, No. 01, February, 2026, pp. 179 – 192
ISSN: 2579-8375 (Print), ISSN: 2579-8391 (Online)
https://engagement.fkdp.or.id/index.php/engagement

OPEN ACCESS

Smart Aquaculture Model for the Empowerment of Fisheries Micro, Small, and Medium Enterprises (MSMEs) through Digitalized Fish Farming Using an Automatic Feeding System

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ABSTRACT

Background: This study addresses a common challenge in ornamental fish keeping, which offers aesthetic and psychological benefits but is hindered by inconsistent feeding practices. The issues of malnutrition, stunted growth, and poor water quality resulting from manual feeding inefficiencies are the core focus. The research develops an automated solution to support both hobbyists and small-scale aquaculture.
Purpose of the Study: The purpose of the study is to design and evaluate an IoT-based automatic fish feeding system. The objectives are to ensure consistent and precise feeding, enable remote monitoring and control, and assess the system's accuracy, connectivity, and reliability in operation.
Methods: The study employed an experimental method. The system was built using an LDR sensor, a DC motor, and a NodeMCU ESP8266 microcontroller, integrated with a mobile application and the Adafruit IO cloud platform. Testing focused on feed timing accuracy, system connectivity, and operational performance.
Results: The system demonstrated high reliability, delivering consistent feeding with an average delay of only three minutes. It successfully enabled remote control and real-time monitoring via the mobile application. The research provides a practical automated feeding solution that enhances fish care and supports digital adoption in small-scale aquaculture businesses.

Keywords
Automatic Fish Feeder, ESP8266, DC Motor, Adafruit.

Article History:
Received: Aug 19th 2025
Revised: Dec 23rh 2025
Accepted: Feb 28th 2026

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Introduction

The rapid advancement of digital technology has profoundly transformed various aspects of human life, including industrial production, governance, and domestic activities. Among the most transformative innovations in this digital era is the Internet of Things (IoT). This paradigm connects physical devices into intelligent networks capable of real-time communication, data exchange, and automated control. Recent studies indicate that IoT devices are proliferating rapidly due to declining sensor costs, improved wireless connectivity, and the growing demand for automation across industries. (Abdullah et al., 2024; Flores-Iwasaki et al., 2025; Rodríguez et al., 2025)

In the aquaculture sector, the integration of IoT represents a major step toward modernizing traditional production systems. (Rastegari et al., 2023; Shete et al., 2024) IoT applications have enabled continuous monitoring of water quality, feed management, and system performance, significantly improving operational efficiency and sustainability. (Olanubi et al., 2024; Mohd Jais et al., 2024; Zuhaer et al., 2026). Compared to other agricultural industries, aquaculture has been relatively slow in adopting automation; however, research demonstrates that IoT sensor networks can provide farmers with real-time environmental insights to support decision-making and reduce human error. (Flores-Iwasaki et al., 2025; Sobri & Topiq, 2024).

Indonesia, as one of the world's largest producers and exporters of ornamental fish, possesses vast potential for technological innovation in this domain. According to the World Integrated Trade Solution (WITS) and the Ministry of Marine Affairs, Indonesia accounted for approximately 8.65% of global ornamental fish exports in 2021, with freshwater species such as Guppy (Poecilia reticulata) and Betta sp. dominating trade. (Tarihoran et al., 2023; Marlianingrum et al., 2022). This industry is primarily supported by micro, small, and medium enterprises (MSMEs) that play a vital role in local economies, particularly in Lampung and Java. In Bandar Lampung, MSMEs such as Sabda Aquatic, which produces ornamental fish for domestic and export markets, still rely heavily on manual feeding and environmental monitoring systems.

Figure 1. The field location of Sabda Aquatic MSME

A preliminary assessment conducted in May 2025 identified several inefficiencies in the aquaculture management system. Observations were made through direct field visits, production log analysis, and operator surveys. The main findings are summarized in Table 1.

Table 1. Summary of Preliminary Findings on Aquaculture System Inefficiencies

Variable	Indicator / Key Findings	Data Source (May 2025)	Description / Main Impact
Feeding schedule	Deviation of 3–4 hours between actual and optimal feeding time	Field observation	Decreases feeding efficiency and disrupts fish growth synchronization

Feed quantity consistency	Variation of 30–70 grams per tank per day, with up to 18% feed waste	Field observation	Causes operational inefficiency and increased feed costs
Fish mortality rate	Mortality reached 15–20% during peak production season	Production logbook	Attributed to poor water quality and overfeeding
Digital literacy of operators	Over 70% of operators are unfamiliar with IoT-based systems	Operator survey	Indicates low adoption of automation and digital monitoring tools

The assessment indicates that inconsistent feeding practices, high mortality rates, and limited digital literacy among operators collectively reduce efficiency and sustainability. These findings emphasize the need for IoT-based automation to optimize feeding schedules, monitor water quality, and improve production outcomes.

These challenges were corroborated through field observations and interviews with the owner and workers, revealing that labor inefficiency and limited access to digital training remain major institutional barriers to modernization. Overfeeding leads to increased ammonia levels (>1.5 mg/L), reducing dissolved oxygen and degrading water quality, whereas underfeeding slows fish growth and affects marketability (Rastegari et al., 2023; Shete et al., 2024). These challenges become even more critical when owners travel or have limited time for daily feeding. Therefore, there is a pressing need for automation technologies capable of delivering precise, scheduled, and remotely controlled feeding processes that also monitor environmental parameters in real time. (Olanubi et al., 2024; Mohd Jais et al., 2024; Rathy & Jenefer, 2024).

Quantitative monitoring confirmed that the enterprise used an average of 2.5 kilograms of feed per day across 70 ponds, with production losses exceeding 10% per cycle. Qualitatively, the lack of exposure to digital systems and the absence of systematic data recording hindered effective decision-making. These findings clearly illustrate a socio-technical gap. The community has strong production potential but lacks access to affordable technology and digital skills to manage it effectively.

Hence, the rationale for this community engagement program is to introduce an IoT-based automated feeding and monitoring system tailored for small-scale ornamental fish enterprises, addressing both technical and socio-economic constraints. This intervention is expected to improve production consistency, lower feed costs, and strengthen MSME competitiveness in the digital economy. (Sobri & Topiq, 2024; Mohamed et al., 2024).

To address these issues, this study proposes an IoT-based Automatic Fish Feeder Monitoring Application designed for MSMEs in the ornamental fishery sector. The system utilizes NodeMCU ESP8266 as the primary microcontroller, integrated with Light Dependent Resistor (LDR) sensors for feed-level detection, DHT11 sensors for temperature monitoring, and motor driver modules for automated feed dispensing. The data are transmitted to a cloud platform (Adafruit IO), which provides real-time visualization, remote control, and notifications via a user-friendly mobile interface. The design prioritizes low-cost hardware, precision control, and ease of use, enabling scalability for household and commercial fish farmers alike. (Sobri & Topiq, 2024; Rathy & Jenefer, 2024; P et al., 2024).

In summary, the Smart Aquaculture project offers a sustainable, scalable, and community-driven approach to enhance the productivity of ornamental fish farming in Indonesia. It bridges the gap between technological innovation and local economic empowerment, transforming conventional fishery practices into data-driven, digitally managed ecosystems that improve efficiency, reduce feed waste, and promote environmental stewardship (Rastegari et al., 2023; Abdullah et al., 2024; Flores-Iwasaki et al., 2025; Rodríguez et al., 2025).

Method

Research Method

This study, titled "Smart Aquaculture Model for the Empowerment of Fisheries Micro, Small, and Medium Enterprises (MSMEs) through Digitalized Fish Farming Using an Automatic Feeding System", adopts the Waterfall method as the main development model.

The Waterfall method is a sequential software development model consisting of several structured stages: analysis, design, programming, testing, and maintenance. Each stage must be completed before proceeding to the next, ensuring system reliability and minimizing integration errors during development. This structured approach is suitable for implementing IoT-based smart aquaculture systems where precision and stability are essential. (Vo et al., 2021).

Data Collection

To obtain relevant and valid data, several data collection techniques were applied throughout this research. The first technique involved a literature review to build a strong theoretical foundation and identify prior research on IoT-based fish feeding automation and smart aquaculture systems. Previous studies provided important insights into the development of intelligent aquaculture technologies. For instance, Vo et al., (2021) offered a broad overview of smart aquaculture systems employing automation and computer vision, while Megantoro et al., (2024) developed an IoT-based telemetry monitoring system for aquaculture environments. Similarly, Indrawati et al., (2025) implemented a fuzzy logic–based automatic fish feeder integrated with IoT for water quality control, and Silalahi et al., (2023) demonstrated the effectiveness of IoT-enabled automatic feeding and monitoring systems to support small-scale fish farming. These studies collectively served as valuable references for the system design and experimental framework of the present research.

In addition to the literature review, field observation was conducted at Sabda Aquatic, located on Jl. Untung Suropati, Labuhan Ratu, Kedaton District, Bandar Lampung City, Indonesia. The observation focused on understanding fish feeding habits, feeding frequency, and environmental conditions to ensure that the system design reflected the real-world challenges faced by MSME fish farmers. The on-site assessment provided essential insights into how environmental and human factors influence feeding consistency and efficiency.

Figure 2. Field observation conducted at Sabda Aquatic MSME

Furthermore, interviews were carried out with the owner and operators of Sabda Aquatic to explore the main operational problems in fish feeding management, including irregular feeding schedules and significant feed waste. The interview data helped identify the functional requirements of the automatic feeding system and ensured the prototype would be both practical and beneficial for MSME fish farmers.

Figure 3. Interview with the owner of Sabda Aquatic MSME

Lastly, the experimental method was applied to design, construct, and test the IoT-based automatic fish feeding device integrated into the smart aquaculture model. The experimental process involved system design and integration of sensors, servo motors, and the ESP8266 microcontroller; preparation of materials and components compatible with Adafruit IO and Wi-Fi communication; prototype assembly following the schematic design; and iterative testing and evaluation to measure system accuracy, feed timing, and notification reliability.

Experimental Method

The experimental method was used to design, construct, and test the IoT-based automatic fish-feeding device integrated into the smart aquaculture model. The process began with system design, which involved planning the integration of sensors, servo motors, and the ESP8266 microcontroller to ensure seamless data communication and control. After the design stage, appropriate materials and components were selected for compatibility with Adafruit IO and Wi-Fi connectivity, enabling real-time monitoring and remote operation. Once the materials were prepared, the prototype was assembled according in the schematic diagram, integrating mechanical and electronic components into a functional system. The completed prototype was then tested and evaluated through repeated trials to assess its performance in terms of feeding accuracy, timing precision, and notification reliability. These tests ensured that the developed device met the functional requirements of a smart aquaculture system designed for MSME fish farmers.

These experiments were aligned with Indrawati et al., (2025) who tested IoT-based feeding and water quality systems, and Megantoro et al., (2024) who validated IoT telemetry for aquaculture. Experimental data were used to evaluate the device's effectiveness in improving feeding precision and efficiency.

Type of Data

This study uses primary data collected through observation, interviews, and prototype testing. The primary data include system response time, feeding accuracy, and real-time monitoring performance recorded through the Adafruit IO dashboard. Primary data collection ensures that the system's performance reflects real-world aquaculture operations.

System Flowchart

System operation begins with an initialization process, followed by verification of the internet connection to ensure stable communication between the device and the Adafruit IO platform. Once the connection is successfully established, the device performs an automatic check on feed availability within the container. If the feed is detected as empty, the system immediately sends a notification to the user via the Adafruit IO interface, prompting manual refilling.

Conversely, if sufficient feed is available, the system remains in standby mode, awaiting either a manual activation command from the user or an automated feeding schedule trigger based on the predefined program.

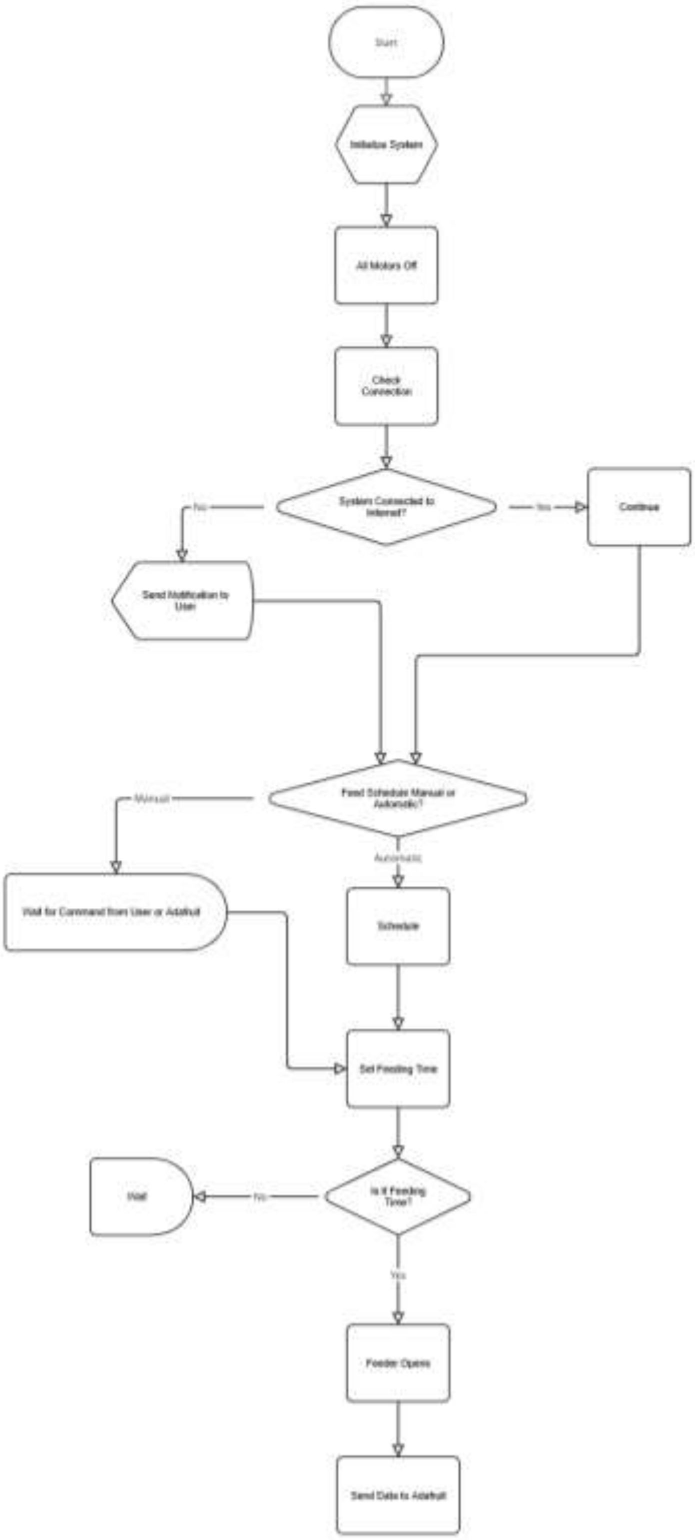

Figure 4. System Flowchart

In manual mode, the servo motor opens the feed valve immediately. In scheduled mode, the system automatically activates the motor based on preset feeding times. This process ensures consistent, efficient feeding, reducing human dependency (Silalahi et al., 2023).

Working Principle of the Device

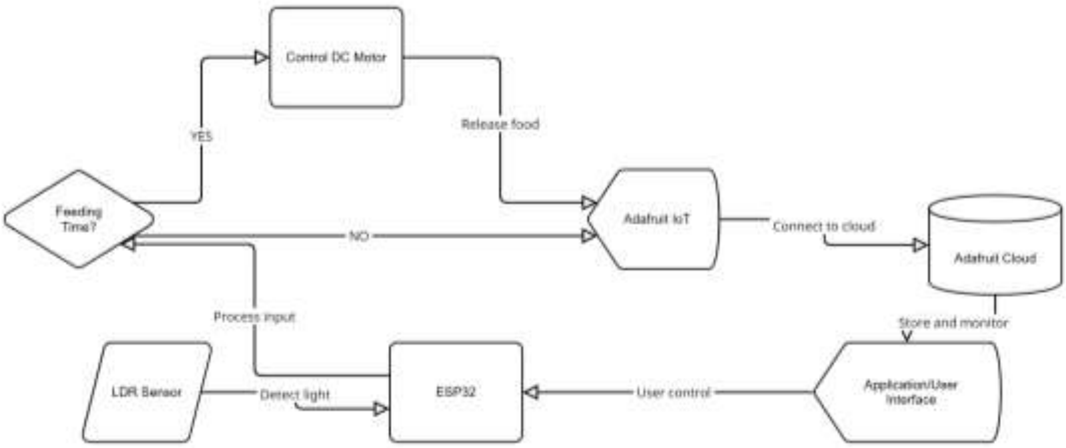

Figure 5. System Design

The device consists of several interconnected modules controlled by the ESP8266 microcontroller. The feed-level sensor detects the remaining feed, while the servo motor regulates feed distribution to the aquarium. All operations are coordinated via Adafruit IO, which allows remote control and real-time monitoring through the internet.

The system architecture integrates several interconnected components designed to ensure efficient automation and real-time monitoring. At its core, the ESP8266 NodeMCU microcontroller serves as the primary unit for data processing and wireless communication, enabling seamless transmission between hardware sensors and the cloud server. The feeding mechanism is driven by a servo motor, which acts as an actuator to dispense fish feed at predetermined intervals with precise control. To maintain continuous operation, a feed-level sensor is installed to detect the remaining stock in the feed container and send alerts when refilling is required. A power supply unit stabilizes the electrical flow to all components, ensuring consistent performance and preventing voltage fluctuations. All data collected from the sensors is transmitted to the Adafruit IO dashboard, which serves as the remote monitoring and control interface. Through this platform, users can visualize feeding schedules, monitor environmental conditions, and adjust system parameters in real time via mobile or web applications.

This configuration supports digitalized aquaculture management, enabling MSME fish farmers to automate feeding schedules, minimize feed waste, and optimize operational efficiency in line with findings by Megantoro et al., (2024) and Vo et al., (2021) who emphasized the benefits of IoT in aquaculture automation.

Result

After the planning stage was completed, the implementation phase was carried out using the designed components. All hardware, including the LDR sensor, L298D motor driver, and DC motor, was connected to the NodeMCU ESP8266 microcontroller to form the complete automatic fish feeder prototype (Figure 6).

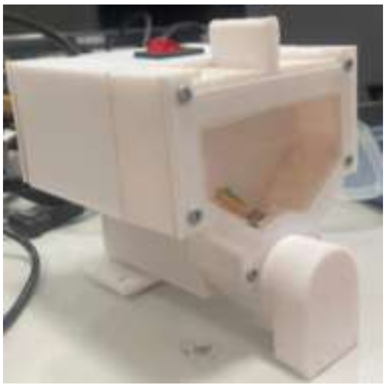

Figure 6. Automatic Fish Feeder

The device was installed and tested at Sabda Aquatic, the assisted MSME partner, to ensure functionality under real operating conditions. During this stage, the research team worked collaboratively with the fish farmers to integrate the tool into their daily feeding routine. Training sessions were conducted to introduce the system operation, application interface, and maintenance procedures.

Application Interface

Figure 7. Application Display

The mobile application interface was developed to display real-time sensor data transmitted from the microcontroller via Adafruit IO. The interface provided users with accessible, clear information on the system's operational status, including feed availability, device connectivity, and temperature conditions. Through this platform, users could monitor feeding activities remotely and adjust feeding schedules as needed.

The introduction of this application marks a behavioral shift among MSME participants from manual to data-driven management, encouraging the use of digital dashboards for operational decisions. (Silalahi et al., 2023).

Connectivity Testing

Connectivity testing verified the Wi-Fi network performance of the ESP8266 module. The results in Table 2 show that the system successfully connected to different SSIDs, ensuring stable data transmission between the hardware and cloud server.

Table 2. Connectivity Test

Description	SSID	Password	IP Address	Status
Test 1	MEKATRONIK UBL	MEKATRONIK123	192.168.12.7	Connected
Test 2	Pasca Sarjana	ublkecee	192.168.7.169	Connected
Test 3	Msas	12345678900	192.168.180.168	Connected

Stable connectivity ensured uninterrupted monitoring and control of feeding schedules. This result is in line with findings by Megantoro et al., (2024), who reported that stable IoT connectivity is critical for the continuous performance of aquaculture automation.

Feeding Time Testing

Table 3. Feeding Time Test

No.	Feeding Session	Scheduled Time	Actual Feeding Time	Time Deviation
1	Morning	08:00	08:03	+3 minutes
2	Evening	17:00	17:02	+2 minutes
3	Morning	09:00	09:03	+3 minutes
4	Afternoon	16:40	16:44	+4 minutes

Testing aimed to measure the accuracy between scheduled and actual feeding times. The average time deviation was calculated as follows:

$$\text{Average delay} = \frac{(3+2+3+4)}{4} = 3 \text{ minutes}$$

The average delay of three minutes indicates that the system operates with high accuracy and reliability. Minor deviations were caused by network latency and temporary synchronization delays on Adafruit IO. These results are consistent with Indrawati et al., (2025) who observed minor response delays in IoT-based feeding systems but confirmed their operational stability and effectiveness.

Community Empowerment and Social Impact

Beyond the technical achievements, this project generated measurable social and institutional impacts through a structured community mentoring process conducted over seven months (May–November 2025). The mentoring program involved the owner and four workers of Sabda Aquatic, combining training, field assistance, and peer learning. All activities were documented through attendance sheets, field notes, and video logs to ensure verifiable evidence of implementation.

Table 4: Implementation Stages and Key Results of the Smart Aquaculture IoT Feeder Program

Stage	**Period**	**Key Activities**	**Main Findings / Results**
Preparation and Planning	May–June 2025	Needs assessment, interviews, and partnership agreement with Sabda Aquatic	70 tarpaulin ponds identified; all feeding/manual monitoring; baseline feed 2.5 kg/day; mortality 17%

Technology Development and Training	June–July 2025	Development of IoT-based feeder (NodeMCU ESP8266, LDR, DHT11, Adafruit IO); two 3-hour training sessions	Pre-training IoT knowledge: 20%; post-training operational competence: 100%
Field Testing and Technical Mentoring	July–August 2025	Pilot testing in 3 ponds (10,000 fish); twice-weekly technical assistance	Feed reduced from 2.5 kg to 1.9 kg/day (↑24% efficiency); ammonia < 1.0 mg/L; mortality dropped from 17%→8%
Implementation and Peer Replication	September–October 2025	MSME operates the system independently, with peer mentoring for 3 neighboring farmers	New adopters achieved 1.5 hours/day time savings; local leadership and peer learning emerged.
Evaluation and Documentation	October–November 2025	Joint evaluation and dissemination preparation	Digital confidence increased from 2.1→4.6 (Likert 5); data and reports published (Engagement Journal, UBL TV)

Summary of Findings

The integration of IoT technology in ornamental-fish farming enhanced feeding efficiency, reduced operational workload, and strengthened MSME digital capacity through sustained mentoring and knowledge sharing.

The implementation of the IoT-based smart aquaculture program produced significant quantitative and qualitative outcomes. Quantitatively, feed waste was successfully reduced by approximately 20–25%, indicating improved feeding accuracy and system efficiency. The fish mortality rate also declined markedly from 17% to 8%, demonstrating better water-quality control and feeding consistency. In addition, the average daily working time of operators decreased by approximately 1.5 hours, reflecting increased operational efficiency from automation. The pre- and post-training surveys further revealed a remarkable 119% improvement in participants' confidence in using digital tools and managing IoT-based systems.

Qualitatively, the participants developed greater independence in operating the automated feeding system and established peer mentoring networks among local fish farmers. This collective engagement fostered a shared awareness of the importance of data-driven aquaculture practices and encouraged continued learning within the community. Overall, these achievements validate the project's initial hypothesis that combining low-cost IoT innovations with participatory mentoring can provide a scalable, sustainable model for digital transformation in small-scale aquaculture. The initiative exemplifies how technological adoption, when integrated with community empowerment, can simultaneously enhance productivity, strengthen digital inclusion, and promote sustainable socio-economic change within MSME ecosystems.

Discussion

The implementation of the Smart Aquaculture Model demonstrates that integrating IoT and automation technologies into small-scale fish farming can significantly improve operational efficiency and empower MSME fish farmers. The findings address the study's objectives by validating that technology-based solutions can enhance productivity while fostering social transformation within local aquaculture communities.

From a technical standpoint, the developed system successfully performed its main functions: real-time monitoring, remote control, and automatic feeding. These results align with Silalahi et al., (2023)**,** who emphasized that IoT-based automation improves feeding precision and reduces human error in aquaculture management. However, compared with previous studies, this research extends the application by integrating cloud-based data visualization (Adafruit IO), enabling not only feed control but also performance tracking accessible via mobile devices, representing an advancement in accessibility and usability for MSMEs.

From a community service perspective, the project's participatory approach through workshops, demonstrations, and direct mentoring encouraged active involvement by the assisted community at Sabda Aquatic in Bandar Lampung. The local fish farmers, who initially depended on manual feeding, gradually developed digital literacy and confidence in operating the IoT-based system.

Behavioral change was one of the most visible impacts. Farmers began interpreting sensor readings, adjusting feeding schedules via the application, and relying on real-time data rather than estimates. This shift represents a move from traditional to data-driven aquaculture management, in line with the concept of technological empowerment discussed by Vo et al., (2021). It also demonstrates a micro-level social transformation: from dependency on manual routines toward independent, digitally competent entrepreneurship.

From a theoretical standpoint, these outcomes reinforce Rogers' (2003) Diffusion of Innovations Theory, in which early adopters act as change agents who influence wider community acceptance of new technology. The observed behavioral transformation also corresponds with the Technology Acceptance Model (TAM) proposed by Davis (1989) where perceived usefulness and ease of use directly affect adoption and sustained engagement. As a result, Sabda Aquatic not only benefited from improved operational efficiency but also became a local model of technological diffusion within the fish-farming community.

This combination of technological and social outcomes highlights that community-based IoT innovation can produce dual impacts: (1) measurable improvements in feeding accuracy and time efficiency, and (2) social empowerment through knowledge transfer and behavioral adaptation. These results confirm the notion that digital transformation in MSMEs can lead to long-term sustainability when coupled with participatory learning and contextualized technology design.

In conclusion, the Smart Aquaculture project not only met its engineering and service objectives but also initiated a process of social change and digital empowerment among local fish farmers. Future studies could extend this model to other types of aquaculture or integrate machine learning for predictive feed control, thereby strengthening the role of IoT in achieving sustainable and inclusive digital transformation across Indonesia's MSME sector.

Conclusion

Based on the research conducted, several conclusions can be drawn regarding the development and implementation of an IoT-based automatic fish feeding system using an LDR sensor and a DC motor.

First, from a technical standpoint, the system effectively enables remote and scheduled feeding, providing a practical solution for ornamental fish business owners who travel frequently or are away for extended periods. The integration of IoT technology allows real-time monitoring and control, reducing feeding irregularities and minimizing the risk of overfeeding or underfeeding.

Second, from a community empowerment perspective, the introduction of this system at Sabda Aquatic has increased local MSME awareness of digital technology applications in aquaculture. The farmers have shifted from traditional manual feeding methods to data-driven, automated management, demonstrating clear behavioral change and growing digital literacy.

Third, theoretically, these findings reinforce the principles of technological empowerment and innovation diffusion theory (Rogers, 2003) showing that early exposure to IoT systems within MSMEs can foster wider adoption of digital solutions in small-scale aquaculture. The results also align with the Technology Acceptance Model (Davis, 1989), which posits that perceived usefulness and ease of use influence sustained technological adoption.

As a community service recommendation, the Smart Aquaculture Model can be expanded through collaborative training programs for MSMEs, particularly in other regions of Lampung and Java, to accelerate digital transformation in fisheries.

Future research may focus on integrating machine learning algorithms to optimize feeding prediction, expand sensor functionality for water-quality monitoring, and evaluate the long-term socio-economic impacts of IoT adoption among MSMEs.

Overall, this study not only meets its engineering objectives but also contributes to the broader goal of community digital empowerment, supporting Indonesia's agenda for sustainable and technology-driven economic development.

Acknowledgements

The researcher would like to express sincere gratitude to Universitas Bandar Lampung (UBL) for its continuous support, academic guidance, and facilities provided throughout this community service project.

This program was funded by the Ministry of Education, Science, and Technology (KEMDIKTI SAINTEK) through the BIMA Community Service Grant Scheme. Special appreciation is also extended to the Ministry for its commitment to promoting innovation and applied research in smart aquaculture and community empowerment.

Conflict of Interest

The authors declare **no conflict of interest**.

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