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Smart Fisheries: Real-Time Water Quality Management and Automated Feeding System Design for Tilapia Farming using ESP32 Micro Controller

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ABSTRAK

Sektor perikanan di Desa Jinengdalem, Buleleng, Bali memiliki potensi yang cukup besar tetapi terus menghadapi tantangan terkait efisiensi operasional dan hasil produksi yang tidak stabil. Studi ini mengusulkan solusi inovatif melalui Perikanan Cerdas: IoT Bertenaga AI dalam Perikanan Cerdas, sistem akuakultur cerdas yang didukung oleh Kecerdasan Buatan (AI) dan Internet of Things (IoT). Sistem ini dirancang untuk melakukan pemantauan parameter air secara real-time, mengotomatiskan proses pemberian pakan, dan menganalisis pertumbuhan ikan untuk meningkatkan produktivitas dan keberlanjutan akuakultur. Metodologi penelitian mengikuti kerangka kerja Penelitian dan Pengembangan (R&D), memanfaatkan model ADDIE (Analisis, Desain, Pengembangan, Implementasi, Evaluasi). Hasil awal menunjukkan bahwa sistem ini menyediakan data lingkungan yang akurat dan mendukung pengambilan keputusan berbasis data dalam pengelolaan perikanan. Proyek ini diharapkan dapat menjadi model yang dapat direplikasi untuk menerapkan teknologi akuakultur digital di wilayah serupa.

ABSTRACT

The fisheries sector in Jinengdalem Village, Buleleng, Bali holds considerable potential but continues to face challenges related to operational efficiency and unstable production outcomes. This study proposes an innovative solution through Smart Fisheries: The AI-Powered IoT in Smart Fisheries, an intelligent aquaculture system powered by Artificial Intelligence (AI) and the Internet of Things (IoT). The system is designed to perform real-time monitoring of water parameters, automate feeding processes, and analyze fish growth in order to enhance aquaculture productivity and sustainability. The research methodology follows a Research and Development (R&D) framework, utilizing the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). Preliminary results indicate that the system provides accurate environmental data and supports data-driven decision-making in fishery management. This project is expected to serve as a replicable model for implementing digital aquaculture technologies in similar regions.

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1. BACKGROUND

Jinengdalem Village possesses substantial aquatic resource potential for aquaculture development, particularly in the cultivation of Nile tilapia. However, traditional issues such as market price fluctuations, unstable water quality, and reliance on conventional methods pose barriers to increased productivity. The evolution of digital technology offers strategic opportunities to build more efficient and precise aquaculture systems through the integration of IoT and AI [1]. The implementation of the Smart Fisheries system offers a substantial contribution in addressing longstanding challenges in the aquaculture sector, particularly within the context of small-scale fisheries in coastal regions such as Jinengdalem Village. A key strength of this system lies in its ability to deliver real-time environmental data, enabling rapid, accurate and data-driven decision-making [2]. Critical operational adjustments such as water temperature regulation, pH balancing, and automated feeding can be executed with minimal manual intervention, thereby reducing delays in responding to rapidly changing environmental conditions [3].

Recent studies affirm the effectiveness of AI- and IoT-based smart systems in improving aquaculture efficiency and mitigating environmental risks [4]. Therefore, this research aims to design, construct, and implement a smart fisheries system that can be directly adopted by local communities using accessible and cost-effective technologies. This study aims to determine the final results of this project with several questions such as how can the Smart Fisheries system be designed to integrate IoT and AI technologies in the context of smart fisheries? How effective is the system in improving the efficiency of fish pond management? and what are the results of the evaluation and testing of Smart Fisheries performance in increasing the productivity of tilapia aquaculture?

From this research will pursue three final objectives such as designing and developing a Smart Fisheries system that combines IoT and AI technologies, implementing and testing the system in a real aquaculture environment, and evaluating the system performance based on water quality and fish growth metrics [5]. It is expected that this project will make a major contribution in the theoretical field by enriching the academic literature on smart aquaculture by introducing a new framework for the integration of AI and IoT in small-scale fisheries and a practical contribution to the Smart Fisheries system that can be adopted by local communities to improve fish farming efficiency and serve as a replicable model for other aquaculture areas[6].

The implementation of Smart Fisheries demonstrates that IoT and AI-based systems can provide more efficient and adaptive pond management [7]. Real-time sensors monitor crucial environmental parameters such as pH and temperature, triggering actuators via relays to maintain optimal conditions. The data is transmitted to a cloud server and visualized through the Blynk application, allowing farmers to remotely monitor and respond to environmental changes promptly. The integration of hardware components (ESP32 microcontroller, pH, TDS, and temperature sensors) with cloud-based software platforms (Blynk, Firebase) demonstrates the feasibility of leveraging open-source technologies to develop intelligent systems that are both cost-effective and high-performing [8]. The availability of a real-time dashboard allows fish farmers even those without technical backgrounds to monitor essential pond parameters anytime and anywhere. This fosters technological inclusivity and strengthens the resilience of local aquaculture production systems [9].

One of the key advantages of the system is its integration with AI algorithms, enabling predictive modeling of fish growth and dynamic adjustment of feeding schedules [10]. AI-based forecasting can significantly improve productivity while reducing the risk of fish diseases [11]. Monitoring Water Quality is also one of the deciding factors for the fish growth and survival rate. In addition, the system reduces operational costs through automation and optimized resource usage particularly feed and water [12]. This supports a more sustainable, inclusive, and data-driven approach to aquaculture [13]. The Smart Fisheries platform not only acts as a monitoring tool but also as a decision support system (DSS), capable of recommending actions based on historical data and trend analysis powered by AI, and Transformer-based time series models [14]. As such, this innovation empowers small-scale farmers with intelligent tools to compete in the digital era, offering real-time analytics, reduced manual labor, and improved ecological impact. The system also opens future research opportunities, including blockchain integration for transparent supply chains and digital twins for aquaculture simulation environments.

From a sustainability perspective, Our proposed design facilitates environmentally conscious aquaculture practices. Data collected by the system indicates notable improvements in water quality within equipped ponds, as interventions such as aeration, filtration, and pH adjustments are executed based on actual needs rather than estimations. This reduces nitrogen and phosphate emissions into surrounding ecosystems, substances commonly associated with eutrophication in natural water bodies [15].

2. METHODS

This study adopted a Research and Development (R&D) approach, guided by the ADDIE model:

a. Analysis by identifying required hardware, environmental factors, and relevant literature.
b. Design with developing a system architecture including an ESP32 microcontroller, sensors for pH, temperature, TDS, and a Blynk-based dashboard.
c. Development by building a Smart Fishery prototype and test pond for real-world application.
d. Implementation with conducting field testing in a real aquaculture environment.
e. Evaluation in assessing system performance in terms of water quality, fish growth rate, and operational efficiency based on collected data.

3. RESULT AND DISCUSSIONS

The architecture of the ESP32-based Smart Fisheries system for real-time monitoring and management of water quality in tilapia biofloc ponds. This system consists of three ESP32 units that act as data acquisition nodes, logic processing, and user interfaces. Including AI support decisions here to make the project more comprehensive.

3.1. System's Design

This system design strategically divides tasks among three ESP32 units to ensure efficient, modular, and scalable operation. By delegating sensor data collection to the first ESP32, fuzzy logic-based water quality assessment and control to the second, and data visualization, logging, and communication to the third, the system avoids processing overload and improves overall reliability. The use of ESP-NOW protocol ensures low-latency, peer-to-peer communication without requiring Wi-Fi infrastructure. Integrating fuzzy logic allows nuanced decision-making for water quality control, while automated drainage and refilling mechanisms maintain optimal aquatic conditions. The third unit's role in data display, logging, and real-time notifications ensures transparency and ease of monitoring, supported by a real-time clock for scheduled operations. Additionally, the inclusion of an automated feeding system with feed level monitoring helps maintain fish health and reduces labor dependency. Overall, this distributed, IoT-based approach maximizes operational efficiency, reduces fish mortality from water degradation or feeding issues, and supports sustainable aquaculture management.

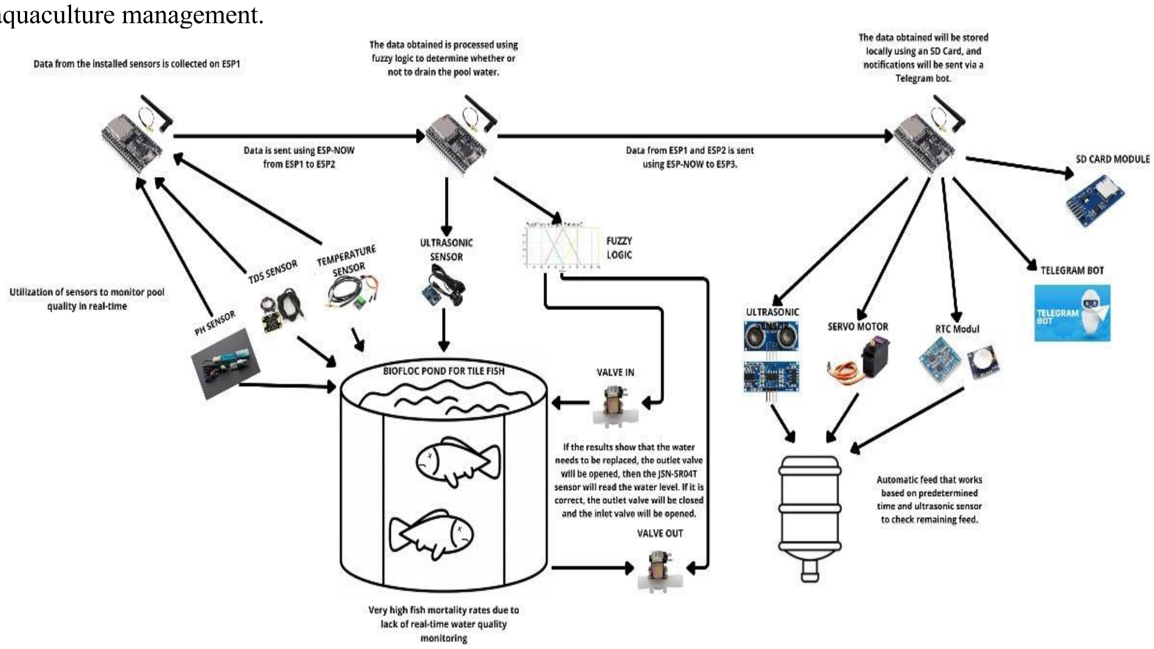

Figure 1. System's Design of Smart Fisheries

The first ESP32 is responsible for collecting data from three main sensors: temperature sensor (DS18B20), pH sensor (SEN0161), and TDS sensor (SEN0244). The obtained environmental data is sent wirelessly using the ESP-NOW protocol to the second ESP32. The second unit runs a fuzzy logic algorithm to evaluate water quality. If the water is declared unfit, the system will activate the drain valve and use an ultrasonic sensor (JSN-SR04T) to monitor the decrease in water level by up to 10 cm. After that, the filling valve is opened to refill the water until it reaches the initial height. Furthermore, data from the first and second ESP32 are sent to the third ESP32. This unit displays water quality parameters on the LCD screen, saves them to the SD Card, and sends notifications automatically via Telegram Bot. This process is controlled by the RTC module as a timer. In addition, this system also manages fish feeding automatically using servo motors and ultrasonic sensors to monitor remaining feed. If the amount of feed is running low, the system will send a notification to Telegram Bot. Overall, this system integrates measurement, water quality control, and feed management in one IoT-based automated platform to increase efficiency and reduce fish mortality rates due to poor water quality.

3.2. Flowchart System

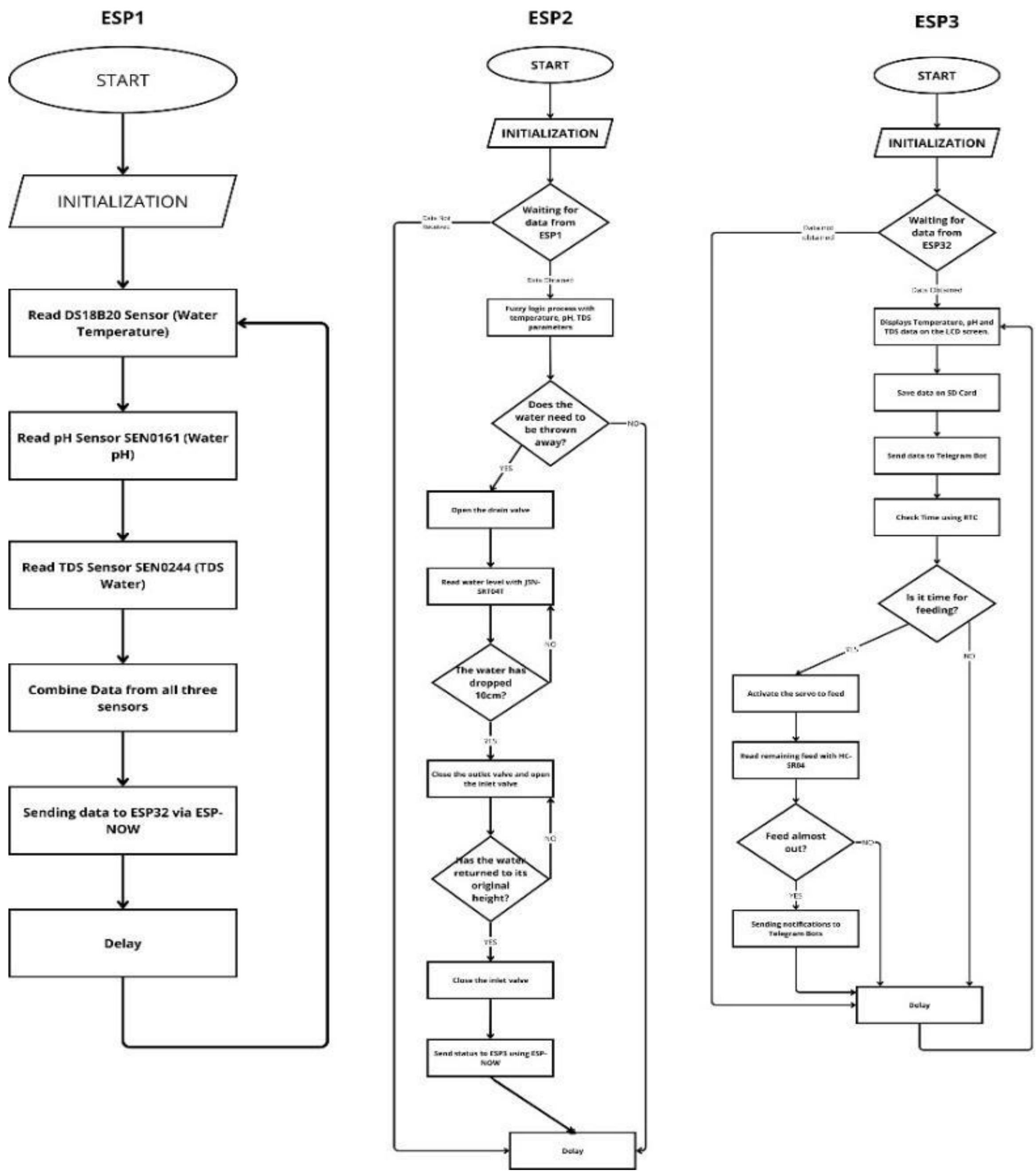

Figure 2. Flowchart of Smart Fisheries Architecture

From the systematic rules embedded within the system design, a comprehensive operational flowchart is constructed to illustrate the entire process, beginning from the initial stages of microcontroller activation.

Each microcontroller, upon receiving power, initiates a self-initialization routine that configures its internal modules and prepares the communication protocols required for interaction with peripheral sensors. Once initialization is completed, the microcontroller proceeds to poll or receive data from each connected environmental sensor deployed in the field such as pH sensors, temperature probes, and TDS meters. These sensors continuously monitor the physical and chemical conditions of the water in the biofloc system, providing real-time data essential for aquaculture health and management. The gathered raw data is then processed locally, including filtering noise, formatting values, and time-stamping each measurement to ensure accurate logging.

Following data acquisition and preliminary processing, the microcontroller transmits the information to a central data logging module. This module can take the form of an SD card or cloud-connected storage platform, depending on the system's configuration. The data logging unit ensures that all sensor readings are securely stored in chronological order for further analysis. This organized collection of data serves as the foundation for subsequent AI-based predictive modeling, enabling intelligent decision-making processes to maintain optimal water quality in the biofloc-based nila cultivation system. The described system design offers a structured and intelligent approach to environmental monitoring in biofloc-based nila cultivation. By embedding systematic rules into the microcontroller operations, the system ensures a reliable and autonomous workflow from initialization to data acquisition, processing, and storage. The key advantages of this design include real-time monitoring of critical water parameters, localized data processing for reduced latency and improved accuracy, and secure chronological data logging for long-term analysis. Additionally, the integration with cloud or centralized storage platforms opens the potential for advanced AI-driven predictive modeling, allowing proactive water quality management. Altogether, this architecture enhances the system's responsiveness, reliability, and scalability ultimately supporting sustainable and efficient aquaculture practices.

3.2.1. IoT Architecture

The Smart Fisheries system is built using 3 ESP32 as microprocessors that will perform different processes, where the First ESP will initialize first by reading the Water Temperature (DS18B20 Sensor), Water PH Sensor (SEN0161 Sensor), Water TDS Sensor (SEN0244). After the three sensor data are read by ESP 1, the three sensor data will be combined and sent to the Second ESP32 via ESP-Now. After receiving data from the first ESP32, the second ESP32 will perform a fuzzy logic process with temperature, PH and TDS parameters, when the water needs to be discharged, the discharge valve will be opened, then the water level will be read with KSN-SRT04T, when the water has dropped 10cm, the outlet valve will be closed and the inlet valve will be opened until the water returns to its original height. When these conditions have been met, the status will be sent to the third ESP via ESP Now.

The third ESP32 will perform a process that will later display temperature, pH and TDS data on the LCD screen, after which the data will be stored on the SD Card which will later be sent to the telegram bot. The data sent to the telegram bot is checked for time using RTC. If the time shows the fish feeding schedule, the servo will be active. The remaining fish feed will be read by the HC-SR04 Sensor where when the feed is almost gone, the system will send a notification to the telegram bot.

3.2.2. Artificial Intelligence

The application of Artificial Intelligence (AI) technology in the field of aquaculture is increasingly developing, especially to support real-time water quality monitoring and prediction systems. In the context of tilapia cultivation with a biofloc system, water quality such as pH, temperature, and total dissolved solids (TDS) are critical parameters that must be maintained consistently. Fluctuations in the values of these parameters can have a direct impact on fish health and growth efficiency. Therefore, the development of AI-based predictive models, such as Long Short-Term Memory (LSTM) is able to provide intelligent solutions by analyzing historical patterns of sensor data and predicting future trends in water quality parameters.

AI support not only increases the speed and accuracy of decision making, but also allows the biofloc system to be more adaptive and sustainable. By utilizing a multivariate time series approach, the model can capture complex relationships between parameters, so that predictions become more reliable in dealing with the dynamics of the aquatic environment. This opens up opportunities for precise automation of aeration systems, feeding, or water changes, which ultimately supports the productivity and resilience of sustainable tilapia cultivation efforts.

4. CONCLUSION

This research has successfully designed and implemented Smart Fisheries, an intelligent, integrated system that combines Internet of Things (IoT) and Artificial Intelligence (AI) technologies to optimize the efficiency, sustainability, and productivity of tilapia aquaculture in Jinengdalem Village. The system architecture is thoughtfully structured across multiple ESP32 microcontrollers, each with distinct responsibilities including environmental monitoring, water quality control, data logging, and automated fish feeding—demonstrating a practical implementation of distributed intelligence in a real-world aquaculture setting.

Field evaluations have shown that the system significantly improves water quality stability, which is a critical factor in fish health and growth rates. Through continuous, real-time monitoring of temperature, pH, and total dissolved solids (TDS), the system ensures that water parameters remain within optimal ranges. The integration of a fuzzy logic algorithm enables intelligent decision-making regarding water drainage and refilling, maintaining water quality without human intervention. This automated process reduces the need for frequent manual water checks and changes, resulting in substantial savings in labor and water resources.

In terms of economic impact, the Smart Fisheries system has demonstrated the ability to reduce operational costs while increasing yields. One of the major cost contributors in traditional aquaculture is feed waste, often caused by overfeeding or inefficient feeding schedules. By using behavioral analysis supported by ultrasonic sensors and controlled feeding mechanisms, the system delivers feed precisely when and where it is needed, thereby minimizing waste and ensuring more efficient feed utilization. This alone has the potential to save a considerable portion of operating expenses, which in small- to medium-scale aquaculture operations can account for over 60% of the total cost. Furthermore, the data logging and notification system, powered by SD card storage and a Telegram Bot interface, enables farmers to stay informed in real-time, even remotely. This capability improves decision-making and enhances the responsiveness to changes in pond conditions, further reducing the risk of fish mortality due to undetected water quality degradation or feeding failures.

Importantly, beyond the immediate local benefits, the Smart Fisheries system is highly replicable and scalable. Its modular design, reliance on affordable microcontrollers and sensors, and integration with widely accessible digital platforms make it a viable solution for broader implementation across various aquaculture settings in Indonesia and beyond. In the context of the national agenda for digital transformation and smart agriculture/fisheries, this system aligns closely with government initiatives to modernize the fisheries sector, improve food security, and enhance the livelihoods of fish farmers.

In conclusion, the Smart Fisheries system not only provides a technically robust and economically viable solution for tilapia cultivation in Jinengdalem Village but also represents a scalable model for intelligent aquaculture management that could significantly contribute to the modernization of the fisheries industry at the regional and national levels.

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