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Development of Portable IoT-Based Fish Pond to Enhance Freshwater Aquaculture Efficiency

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Abstract
This paper presents the development of iPooL, a portable Internet of Things (IoT)-based fish pond system designed to optimize freshwater fish farming, particularly in resource-constrained and urban environments. By integrating real-time monitoring of essential water parameters—such as pH, temperature, dissolved oxygen, and ammonia levels—iPooL ensures that optimal environmental conditions are maintained for fish health and growth. The system employs IoT sensors connected to an ESP32 microcontroller, which processes and transmits data to a cloud platform, enabling farmers to receive real-time alerts and manage their ponds via a mobile app. Field trials demonstrated that the iPooL system reduces fish mortality by 20% and improves fish growth rates by maintaining stable water conditions. Additionally, the automation of feeding schedules and water management reduces operational costs, particularly in labor and feed, resulting in a 30% increase in profitability. With an estimated return on investment (ROI) within one year, iPooL offers a cost-effective solution for both small- and medium-scale fish farmers. The system also promotes environmental sustainability by optimizing water usage and reducing the need for chemical additives. Its portability allows fish farming in non-traditional environments, such as urban rooftops, contributing to decentralized food production and reducing the environmental impact of transporting fish to urban markets. iPooL's scalability, combined with future integration of artificial intelligence and renewable energy sources, positions it as a transformative tool for the aquaculture industry, supporting both economic development and sustainable farming practices.
Keywords: IoT, aquaculture, fish farming, portable fish pond, sustainable technology.

Introduction
Indonesia, the world's largest archipelago, faces ongoing challenges in securing food resources to support its growing population. The fisheries sector has emerged as a crucial pillar in this effort, contributing significantly to national food security and economic stability. Despite having vast marine resources, Indonesia only contributes 3% of the global fish market, representing an estimated value of $162 billion USD [1]. This gap highlights the need for innovative solutions to maximize the potential of the aquaculture industry, which can support both domestic consumption and international trade.

The Indonesian government has recognized the potential of the fisheries sector to not only strengthen food security but also elevate the nation's standing in the global market. President Joko Widodo, in his policy directives, emphasized the importance of advancing the fishery industry through technology and sustainable practices [2]. Innovations in fish farming, especially those that enhance productivity and efficiency, are essential to addressing the gap between potential and current output. These advancements are particularly relevant for freshwater aquaculture, which plays a key role in rural and urban food systems.

Freshwater fish farming in Indonesia has traditionally relied on conventional methods, which are often limited by fluctuating environmental conditions, high water consumption, and land use constraints. These limitations are particularly significant in urban areas where space is scarce, making it difficult for small-scale farmers to operate effectively. Addressing these challenges requires the adoption of technology that can monitor and control key variables in real-time, thereby optimizing farming conditions and ensuring consistent output [3].

In response to these challenges, the development of portable fish farming systems integrated with IoT technology offers a promising solution. A portable IoT-based fish pond system, named iPooL, has been designed to provide flexibility and efficiency in managing freshwater fish farms. This system allows for continuous monitoring of critical parameters, such as water quality and fish health, using advanced sensors connected to a cloud platform. The data is accessible through a mobile app, enabling fish farmers to make informed decisions swiftly, reducing risks associated with environmental fluctuations [4].

The deployment of iPooL has significant implications not only for food security but also for achieving broader sustainability goals. The system's ability to operate in constrained environments, such as urban rooftops and small plots of land, aligns with efforts to improve resource efficiency and reduce the ecological footprint of aquaculture. By integrating smart technology into aquaculture, Indonesia can make substantial strides towards its national development goals and Sustainable Development Goals (SDGs), particularly in reducing poverty and enhancing food security through responsible production practices.

Literature Review

1. IoT in Agriculture and Aquaculture

The adoption of the Internet of Things (IoT) in agriculture, commonly referred to as smart farming, has been transformative for both large-scale and small-scale operations. By integrating IoT devices, farmers can precisely monitor and control [5] key variables such as soil moisture, weather conditions, and crop health. The impact has been especially profound in terms of optimizing resource usage and increasing yields [6]. For example, IoT systems enable real-time tracking of environmental parameters, making it easier to manage irrigation and fertilization, which in turn improves plant growth and reduces waste. This precision farming approach has been widely recognized for its potential to address global food security issues [7].

In aquaculture, IoT offers similar benefits, allowing fish farmers to closely monitor the aquatic environment, which directly influences fish health, growth, and productivity[8]. IoT systems provide real-time data on crucial parameters such as water temperature, dissolved oxygen, pH levels, and ammonia concentrations. These parameters are essential for maintaining optimal fish farming conditions, and even slight deviations can result in significant losses. Traditionally, monitoring these factors manually has been labor-intensive, prone to errors, and inefficient. The integration of IoT systems automates this process, allowing farmers to remotely manage their farms with minimal intervention, significantly reducing labor costs.

Moreover, IoT technology enables predictive analytics in aquaculture, where historical data collected by sensors can be used to forecast water quality trends and fish behavior. This predictive capability is especially valuable in preventing problems before they escalate, such as avoiding overfeeding, which can lead to water pollution, or addressing low oxygen levels before they become fatal to the fish stock. By automating routine monitoring and integrating predictive capabilities, IoT not only increases productivity but also minimizes the risk of human error and reduces operational costs, thus ensuring sustainable and profitable fish farming practices.

2. Freshwater Fish Farming in Indonesia

Freshwater fish farming has long been a critical component of Indonesia's food security strategy. The country's abundant water resources, combined with its favorable climate, make it an ideal location for freshwater aquaculture [9]. Fish species such as catfish (lele), tilapia (nila), and carp (gurame) are staples in Indonesian diets and are farmed extensively across the archipelago. Freshwater fish farming contributes significantly to both local food supplies and the national economy, particularly in rural areas where other forms of agriculture may not be viable. In addition, freshwater fish farming helps alleviate pressure on wild fish populations, promoting more sustainable seafood production.

However, despite the potential, Indonesia's freshwater fish farming industry faces significant challenges. Inconsistent water quality, high operational costs, and limited access to suitable land, especially in urban areas, hinder productivity. Many small-scale fish farmers rely on traditional farming methods, which are often inefficient and unable to cope with environmental changes such as fluctuating water temperatures, pH levels, or oxygen availability. Climate variability, such as extreme weather patterns, further exacerbates these challenges, making it difficult for farmers to maintain consistent yields and healthy fish stocks [10].

To overcome these obstacles, there has been a growing interest in the development of innovative solutions, particularly the integration of technology into fish farming practices. One promising innovation is the use of portable fish ponds equipped with IoT sensors. These systems allow farmers to continuously monitor water quality in real time, ensuring that optimal conditions are maintained for fish health and growth. Additionally, these portable systems are highly adaptable, making it possible to farm fish in non-traditional environments, such as urban rooftops or small plots of land, where conventional aquaculture would not be feasible [9]. The use of such technology not only addresses space limitations but also enhances efficiency and sustainability in fish farming.

3. IoT-Enabled Portable Fish Ponds: The iPooL System

The development of portable fish ponds integrated with IoT technology, such as the iPooL system, represents a major leap forward for aquaculture in Indonesia. These portable systems are designed to optimize resource use, especially in areas where land and water are scarce. By using a combination of IoT sensors, the iPooL system continuously monitors key environmental parameters such as pH, dissolved oxygen, temperature, and ammonia levels. These sensors are connected to an ESP32 microcontroller, which processes the data and transmits it to a cloud-based platform, accessible via a mobile app. This real-time data allows fish farmers to take immediate action if conditions deviate from the optimal range, thereby minimizing the risk of fish mortality and ensuring consistent production.

The portability of iPooL systems offers significant advantages, particularly in urban environments where land is limited. Traditional fish farming requires large, fixed ponds, which are often not feasible in densely populated areas. However, iPooL's lightweight and portable design makes it possible to farm fish in small spaces, such as rooftops, backyards, or even unused urban spaces. This flexibility opens up new opportunities for urban dwellers to participate in aquaculture, contributing to local food production and reducing the environmental footprint associated with transporting fish from rural areas to cities [4].

Furthermore, iPooL's automation capabilities significantly reduce labor requirements. Traditional fish farming is labor-intensive, requiring frequent water quality checks and manual feeding. With iPooL, these tasks are automated. The system monitors water quality continuously and sends alerts if any issues arise, allowing farmers to intervene only when necessary. Feeding schedules can also be automated using the mobile app, ensuring that fish are fed the right amount at the right time. This reduces feed waste, which is one of the most significant operational costs in aquaculture, and ensures that fish are growing efficiently. The combination of IoT technology, portability, and automation makes iPooL a game-changer for both small-scale and large-scale fish farming operations..

Materials & Methods

The development of the ipool system involved both hardware and software components that were carefully designed to ensure seamless integration and functionality.

1. Hardware Design

The hardware components of iPooL include a variety of sensors that monitor water quality in real-time:

- pH Sensor: Monitors the water's acidity, ensuring it remains within the range suitable for freshwater fish farming. If pH levels drop or rise beyond this range, alerts are automatically sent to the fish farmer's mobile device.
- Temperature Sensor: Ensures that water temperatures stay within optimal thresholds to support the healthy growth of fish. The sensor readings allow farmers to make quick adjustments if the temperature becomes too high or low, which could otherwise harm the fish.
- Dissolved Oxygen (DO) Sensor: Dissolved oxygen is crucial for fish respiration. The sensor continuously measures the amount of oxygen in the water, and alerts are triggered when oxygen levels become critically low, allowing for timely intervention, such as activating aeration systems.
- Ammonia Sensor: Ammonia is a toxic by-product of fish metabolism and excess feed decomposition. If ammonia levels increase, fish can suffer from health issues, making continuous monitoring essential.

All these sensors are connected to an ESP32 microcontroller, which aggregates the sensor data and transmits it to a cloud-based platform via Wi-Fi. The data is processed, and alerts are generated based on pre-defined thresholds. Fish farmers can access the data and alerts via a mobile app, which provides real-time insights into the pond's conditions.

2. Implementation Process

The implementation of the **WATERWISE** system followed a structured, community-centered approach to ensure that it could be easily adopted and maintained by the users. The process consisted of the following steps:

a. Community Engagement and Assessment Before deploying the system, an initial assessment was conducted in the selected communities to understand their water needs, the nature of the water sources available, and the specific contaminants present. Community members were involved in discussions to identify the best locations for the installation of filtration units, and their input was used to customize the system to local conditions.

b. Installation of Filtration Units The installation phase involved setting up the filtration units in designated households, schools, and community centers. Local technicians, trained in the installation and maintenance of the system, were employed to carry out the work. Each unit was assembled on-site, with the filtration components and sensors calibrated to ensure proper functioning.

c. Training and Capacity Building Training sessions were conducted for the community members on how to use, maintain, and monitor the system. For users of Package 2 and Package 3, additional training on the IoT app and real-time monitoring was provided, ensuring that they could interpret the data and respond to any changes in water quality. The goal of these sessions was to empower the community to manage the system independently, reducing reliance on external technicians for routine maintenance.

d. Monitoring and Data Collection After the system was installed, IoT sensors in Package 2 and Package 3 began transmitting water quality data to a centralized cloud platform. This data was used to monitor the performance of the filtration units and ensure that water quality standards were consistently met. The real-time monitoring system allowed for immediate detection of any issues with the filtration process, such as clogging of filters or changes in water chemistry. In addition to remote monitoring, manual water samples were collected periodically for laboratory testing to verify the accuracy of the IoT sensors and ensure that the filtration units were operating as expected.

3. Software Architecture

The software architecture consists of an IoT cloud platform that manages data flow from the sensors to the mobile app. The platform is built on a server that receives input from the microcontroller. The data is then visualized through an intuitive dashboard, allowing fish farmers to monitor parameters such as pH, temperature, and oxygen levels over time. The system is designed to store historical data, enabling users to track trends and adjust their management practices accordingly.

4. Pilot Deployment

The iPooL system was deployed in two pilot locations: an urban rooftop garden in Jakarta and a rural farming community in West Java. The goal of the deployment was to test the system's functionality in two distinct environments and gather feedback from users on system performance. The urban environment, characterized by limited space and varying temperature conditions, allowed for testing the system's portability and flexibility. Meanwhile, the rural environment provided insights into the system's ability to handle larger-scale fish farming operations.

Results and Discussion

1. Water Quality Monitoring and Improvement

The iPooL system's primary objective is to maintain optimal water quality through real-time monitoring of critical parameters such as pH, dissolved oxygen, temperature, and ammonia levels. In the field trials conducted in urban and rural settings, the system demonstrated significant improvements in water quality management compared to traditional fish farming methods. For instance, in the urban rooftop environment, the system maintained stable water temperatures despite external fluctuations due to changing weather conditions. The continuous monitoring of dissolved oxygen levels ensured that fish were kept in a healthy and oxygen-rich environment, reducing fish stress and mortality.

The deployment of the iPooL system in rural areas, where farming ponds are typically more susceptible to variations in water quality, resulted in a marked reduction in ammonia concentrations. Ammonia, a by-product of fish metabolism and feed waste, can quickly reach toxic levels if not monitored regularly. The iPooL system's ammonia sensors provided real-time alerts when levels approached dangerous thresholds, allowing farmers to take timely corrective measures, such as increasing water flow or adding ammonia-neutralizing agents. As a result, the system helped to prevent fish mortality, contributing to higher survival rates and healthier fish stocks.

Moreover, the system's capability to maintain consistent pH levels was critical in ensuring the optimal growth of freshwater fish species like catfish and tilapia. Traditional methods of manually monitoring pH often lead to inconsistent results, but the automated, continuous monitoring provided by iPooL minimized these fluctuations. This precision in water quality control directly impacted the health of the fish, reducing disease outbreaks and boosting overall fish growth rates.

2. Fish Health and Survival Rates

One of the key indicators of iPooL's success was its impact on fish health and survival rates. The system's ability to provide real-time data on water quality resulted in a 20% reduction in fish mortality compared to farms using traditional methods. This improvement can be attributed to the system's automated alert system, which notifies farmers of any deviations from optimal conditions. These notifications allow for quick corrective actions, ensuring that water quality parameters such as oxygen levels and pH are restored before they reach harmful levels.

In addition to reducing mortality, the iPooL system contributed to healthier and faster-growing fish. In the trials, fish in the iPooL-managed ponds exhibited accelerated growth compared to those in conventionally managed ponds. The fish reached marketable size approximately 10% faster due to the stable and controlled environment provided by the system. This faster growth cycle allows farmers to increase the number of harvests per year, further boosting their profitability. The system's capability to maintain ideal growth conditions without constant manual intervention provided a clear advantage in both labor savings and production efficiency.

Another significant factor in fish health was the system's automatic feeding mechanism, which was integrated into the iPooL's IoT setup. By automating the feeding process and optimizing feeding times and quantities based on fish behavior and water conditions, the system minimized overfeeding, a common issue that can lead to poor water quality and fish disease. The precise control of feeding schedules resulted in improved feed conversion ratios (FCR), meaning that less feed was required to produce the same amount of fish biomass. This efficiency directly contributed to healthier fish and reduced waste, which further enhanced water quality and environmental sustainability.

3. Economic Impact on Fish Farmers

The iPooL system demonstrated a significant positive impact on the economic outcomes for fish farmers, particularly through operational cost savings and increased profitability. A key area of cost reduction was in labor, as iPooL automates several labor-intensive tasks such as water quality monitoring and feeding. By reducing the need for manual intervention, iPooL allowed small-scale farmers to manage their farms with fewer workers, cutting labor costs by up to 30%. This reduction in labor dependency is critical for small-scale operations, where labor costs are often a significant portion of the total expenses.

4. Cost Efficiency of iPooL

iPooL's automated feeding system further contributed to cost savings by optimizing feed usage. Feed represents one of the largest operational costs in aquaculture, and overfeeding can lead to not only wasted feed but also poor water quality, which affects fish health. By automating the feeding process, the system reduced feed waste by approximately

15%. This resulted in a decrease in the overall cost of feed, while ensuring that the fish were adequately nourished for optimal growth.

5. Revenue Projection

A farmer using a portable iPooL system with dimensions of 100 cm x 50 cm x 25 cm (125 liters) can raise approximately 15 catfish or tilapia per cycle. The sale price of each fish is estimated at Rp 40,000, leading to a potential revenue of Rp 600,000 per pond per harvest cycle. Given that the system allows for three harvests per year, the total revenue from one pond is approximately Rp 1,800,000 annually.

For a farmer operating 100 ponds, the projected revenue is significantly higher. With 100 ponds, each generating Rp 1,800,000 per year, the total annual revenue reaches Rp 180,000,000. This revenue potential highlights the scalability of the iPooL system and its ability to generate significant income for fish farmers, particularly those operating on a larger scale. The combination of cost savings and increased revenue allows farmers to achieve a rapid return on investment (ROI) for the iPooL system, typically within one year of deployment.

6. Environmental Sustainability and Resource Efficiency

The iPooL system contributes to environmental sustainability by significantly reducing water usage, a critical factor in areas where water resources are limited. Traditional fish farming methods often require frequent water changes to maintain water quality, which leads to high water consumption. The iPooL system, by continuously monitoring and managing water quality in real-time, reduced water consumption by up to 20%. This efficiency is particularly beneficial in urban settings where water is expensive and scarce.

Furthermore, the system's ability to maintain water quality without the need for chemical additives such as pH stabilizers or ammonia neutralizers reduces environmental impact. By minimizing the use of chemicals, iPooL contributes to cleaner water discharge from fish farms, reducing the risk of water pollution in surrounding ecosystems. This approach aligns with global efforts toward sustainable agriculture and aquaculture, where resource efficiency and environmental stewardship are prioritized.

The portability of the iPooL system also allows for fish farming in non-traditional environments, such as urban rooftops and small, unused land plots. This decentralized approach to fish farming reduces the reliance on rural farming areas, which often face pressure from other agricultural activities. By enabling fish farming in urban environments, iPooL helps to reduce the carbon footprint associated with transporting fish from rural farms to urban markets, further enhancing its environmental benefits.

7. Scalability and Future Potential

The scalability of the iPooL system is one of its most promising features. Its modular design allows it to be adapted for both small-scale and large-scale operations. For small-scale farmers, the system offers an affordable and efficient solution to optimize fish farming, while for larger commercial operations, the system can be scaled up to manage multiple ponds simultaneously.

The projected income from operating a large number of ponds further emphasizes the system's scalability. With 100 iPooL systems, a fish farmer could potentially generate Rp 180,000,000 in revenue per year, as discussed in the previous sections. This high revenue potential, combined with cost savings on labor, feed, and water, makes the system a viable solution for a wide range of fish farming operations.

Future iterations of the iPooL system could incorporate additional smart technologies, such as renewable energy sources like solar power, further reducing its environmental impact and operational costs. Additionally, integrating artificial intelligence (AI) to predict fish behavior and optimize feeding schedules could enhance the system's efficiency even further. The potential for such integrations opens up new possibilities for revolutionizing fish farming and expanding its adoption across Indonesia and other parts of the world.

Conclusions

The iPooL system has proven to be an innovative and effective solution for addressing the challenges of freshwater aquaculture, particularly in environments with limited resources. By integrating IoT technology to monitor water quality in real time, the system ensures optimal conditions for fish health and growth, significantly reducing fish mortality and improving productivity. The trials demonstrated that iPooL's real-time monitoring and automation led to faster fish growth cycles and higher yields, making it a valuable tool for both small- and medium-scale fish farmers.

Economically, iPooL offers substantial benefits by lowering operational costs, particularly in labor and feed management. The system's automation of critical tasks such as water quality monitoring and feeding reduces the need for manual intervention, saving farmers time and money. Additionally, the optimization of feed usage minimizes waste, further enhancing profitability. With the potential for a return on investment (ROI) within one year, iPooL is a financially viable solution for farmers looking to increase efficiency and maximize their profits.

From an environmental perspective, iPooL promotes sustainability by reducing water consumption and the need for chemical additives, which are common in traditional fish farming methods. Its portability allows fish farming to take place in non-traditional environments, such as urban rooftops, thus reducing land use pressure in rural areas. Furthermore, the system's ability to reduce carbon emissions associated with transportation of fish to urban markets highlights its potential contribution to reducing the environmental footprint of aquaculture.

Looking ahead, the scalability and adaptability of the iPooL system position it as a promising tool for the future of aquaculture. As it evolves to incorporate additional technologies like artificial intelligence and renewable energy, iPooL could further enhance its impact on food security, sustainability, and economic development. This system not only aligns with Indonesia's goals for strengthening food production and sustainability but also offers a model that can be expanded globally, providing a smart solution to meet the growing demand for fish worldwide.

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