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Internet of Things (IoT) Implementation in Tilapia Aquaculture: Profitability Assessment of Smart Pond Management in Subang District, West Java

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Abstract
This study aims to evaluate the effectiveness and profitability of implementing an Internet of Things (IoT)–based smart pond management system in tilapia aquaculture within Subang District, West Java. A controlled field experiment compared three IoT-enabled ponds equipped with real-time pH, temperature, dissolved oxygen, and turbidity sensors against three traditionally managed ponds (using manual monitoring) across a complete 120-day production cycle. Results show that IoT monitoring significantly improved water quality stability, increasing fish survival rates by 12.5% (from 80% to 92.5%), biomass production by 15.3%, and feed conversion efficiency by 8.7%, thereby enhancing operational performance. Economic analysis revealed that the IoT system produced favorable financial indicators, including higher Net Present Value (NPV), Internal Rate of Return (IRR), and Revenue–Cost (R/C) ratios, despite requiring a larger initial investment. These findings indicate that IoT adoption can provide substantial technical and economic benefits to smallholder aquaculture when applied under appropriate management conditions. Overall, the study concludes that smart pond systems represent a viable pathway for increasing productivity, reducing production risks, and improving profitability in Indonesian freshwater aquaculture.

Keywords: IoT aquaculture; smart pond management; tilapia farming; water quality monitoring; economic feasibility

INTRODUCTION

Aquaculture has emerged as one of the fastest growing sources of global food production, contributing significantly to the supply of aquatic protein and serving as an essential pillar for food security and rural livelihoods around the world (Flores-Iwasaki et al., 2025; Rastegari et al., 2023; Rodríguez et al., 2025). As wild fisheries continue to face pressure from overexploitation and environmental degradation, aquaculture offers a viable and sustainable alternative, particularly through freshwater pond farming systems that can be managed with relatively simple inputs. In Indonesia, tilapia (Oreochromis spp.) has become one of the most widely cultivated freshwater species due to its tolerance to varying water conditions, rapid growth rate, low production cost, and steady market demand. Subang District in West Java exemplifies this trend, asmany smallholder farmers rely on tilapia aquaculture as a primary source of income.

However, despite its economic importance, a large proportion of tilapia farms in Subang still depend on traditional pond management approaches, including manual water quality measurement, inconsistent feeding routines, and reactive mitigation of environmental problems (Toheeb et al., 2022). These conventional practices often result in unstable water quality, heightened disease risks, and fluctuating yields, which collectively undermine farm profitability (Khatri et al., 2024; Liang et al., 2025; Rahman et al., 2025; Taneja et al., 2025). To address these persistent challenges, digital technologies such as the Internet of Things (IoT) have been proposed as promising tools to modernize pond operations and support data-driven aquaculture management, although their economic impacts remain underexplored in smallholder contexts (Hassan et al., 2024; Omer et al., 2024; Paul & Bhatia, 2025; Thangamani et al., 2025).

Globally, interest in digital transformation within aquaculture has increased substantially as producers seek solutions that can minimize environmental risk, improve production efficiency, and increase resilience to climate variability. Many countries have begun exploring smart aquaculture as part of broader agricultural modernization strategies, particularly in regions vulnerable to water shortages, extreme temperatures, or rapid weather fluctuations. In countries such as China, India, and Vietnam, IoT adoption in aquaculture has accelerated as government agencies and private technology firms collaborate to scale digital monitoring and automation systems. These global developments signal a shift toward more technology-enabled production systems that depend on real-time sensing, predictive analytics, and automated responses to environmental signals.

Such innovations are especially relevant for intensifying aquaculture systems where even slight deviations in water quality can significantly affect survival rates and production outcomes. By drawing upon international experience, Indonesia stands to benefit from these advancements; however, successful adoption requires a deeper understanding of how IoT systems perform in the socioeconomic realities of smallholder farming communities. Without such contextual evaluation, technological transitions risk reinforcing existing inequalities or burdening farmers with tools they cannot effectively maintain. Thus, the global trajectory toward digital aquaculture adds further urgency to evaluating the feasibility of IoT systems in localized Indonesian settings.

Within Indonesia, freshwater aquaculture plays a critical role in rural livelihoods, regional development, and national food supply chains. Tilapia, in particular, has gained widespread popularity due to its ease of cultivation, high adaptability, and strong consumer acceptance across domestic and export markets (Manoj et al., 2022; Nayoun et al., 2024; Zhang et al., 2025). Regions such as Subang District have embraced tilapia farming as a major livelihood activity, especially among small- and medium-scale producers who often operate family-managed ponds. Despite this importance, many farms continue to rely on traditional knowledge and manual techniques passed down across generations. These practices often prove insufficient in dealing with modern-day challenges such as unpredictable weather, increased disease prevalence, variable input prices, and rising production risks.

Moreover, manual monitoring of water quality is typically conducted infrequently, meaning that harmful changes in dissolved oxygen, temperature, or pH may go unnoticed until fish begin showing signs of stress or mortality (Kumar et al., 2025; Nayoun et al., 2024).

As a result, the potential for productivity improvement remains largely unrealized in many rural pond systems. Modernizing these practices through IoT-based smart aquaculture could make production more efficient, stable, and profitable, but adoption depends heavily on the evidence available to farmers, extension agents, and policymakers. The conceptual and technological foundations of IoT-enabled aquaculture are built on networks of sensors, communication platforms, and data processing systems that continuously monitor and control critical water quality parameters (Flores-Iwasaki et al., 2025; Rastegari et al., 2023; Shete et al., 2024). In these systems, sensors measure parameters such as pH, temperature, dissolved oxygen, turbidity, and total dissolved solids (TDS) and send this information to cloud-based or local platforms where it can be analyzed in real time.

These platforms support farmers by providing timely alerts, automated responses, and actionable insights that guide intervention strategies and enhance the responsiveness of pond management. Empirical studies have yielded consistent evidence showing that IoT-based systems improve the precision and reliability of water quality monitoring compared to traditional manual sampling, which is often limited by inconsistent measurement intervals and human error (Prapti et al., 2022; Shete et al., 2024; Subowo & Pradita, 2025). By enabling early detection of deteriorating conditions and facilitating immediate corrective actions, IoT systems help stabilize environmental parameters, improve fish wellness, and optimize feeding schedules. Despite their promise, IoT adoption is often hindered by infrastructure limitations, upfront costs, maintenance demands, and the need for technical skills among farmers (Rastegari et al., 2023; Rodríguez et al., 2025). Consequently, while IoT technologies hold considerable potential for improving aquaculture performance, their long-term success ultimately depends on their compatibility with the economic and social conditions of smallholder producers.

Although IoT technology has made considerable advances, the current body of literature reveals a significant gap in economic evaluation, especially in smallholder aquaculture settings. The majority of existing research focuses on technical aspects such as sensor calibration, environmental monitoring performance, signal transmission reliability, or the accuracy of data collection (Erawati et al., 2025; Shete et al., 2024; Subowo & Pradita, 2025). These studies are valuable for establishing proof-of-concept but do not address whether IoT systems actually improve profitability, reduce costs, or enhance long-term financial sustainability in real farming environments.

Small-scale farmers are particularly cautious when assessing technological investments because they operate under thin profit margins, have limited financial buffers, and face greater vulnerability to production shocks. Without evidence demonstrating clear financial benefits or favorable return on investment, farmers are understandably reluctant to adopt new technologies, regardless of their technical capabilities. This limitation is not only a barrier to adoption but also a challenge for policymakers who must justify public spending on technology subsidies or digital transformation initiatives. Therefore, there is a pressing need for research that integrates technical performance with economic outcomes in order to understand the complete value proposition of IoT systems in aquaculture.

The urgency of conducting such research becomes even more pronounced in the face of increasing environmental and economic pressures. Climate-related variability is expected to increase the frequency and severity of water quality challenges, placing greater stress on freshwater aquaculture systems. Rising feed prices, labor shortages, and fluctuating energy costs further complicate production planning for smallholder farmers who already face substantial financial risks. These pressures have encouraged policymakers and development organizations to prioritize "smart farming" interventions that can enhance resilience, sustainability, and efficiency in rural production systems (Rastegari et al., 2023; Rodríguez et al., 2025).

In Subang District, where many households depend on tilapia aquaculture for income, the transition to more sophisticated monitoring and management methods has the potential to deliver tangible benefits. However, such transitions must be informed by rigorous economic evaluations rather than technological enthusiasm alone. Evidence on profitability, cost efficiency, and long-term financial performance is essential for designing appropriate policies, allocating resources, and supporting farmers through capacity-building programs. This context establishes the relevance and timeliness of the present study as it aims to clarify whether IoT systems genuinely offer economic value under real- world pond management conditions.

Recent studies illustrate a growing yet fragmented body of research on IoT- based aquaculture, water quality monitoring, and automation. While technological development has proceeded rapidly, economic evaluation has lagged behind. Reviews conducted in recent years show a sharp increase in publications related to sensor design, wireless communication architectures, and monitoring systems between 2020 and 2024, especially in Southeast and South Asia (Flores-Iwasaki et al., 2025). Prototype demonstrations in various aquaculture environments, including Biofloc Technology systems, Recirculating Aquaculture Systems, and traditional ponds, have highlighted the feasibility and reliability of IoT-based monitoring tools (Olanubi et al., 2024; Subowo & Pradita, 2025).

Other studies have shown that IoT platforms can significantly reduce reliance on manual measurement and enhance early-warning capabilities in tilapia ponds (Erawati et al., 2025). However, even studies conducted directly in tilapia production systems have mainly addressed operational feasibility and technical performance rather than economic outcomes. These patterns reveal a clear need for research that integrates technology adoption with financial impact, particularly in smallholder contexts where cost considerations are paramount. The absence of such integrated studies limits the practical applicability of existing findings and creates uncertainty among potential adopters who require more than technical validation to justify investment.

Given these gaps, the present study provides a distinct contribution by combining IoT-based pond management with rigorous economic and profitability analysis in tilapia aquaculture. Unlike earlier studies that primarily emphasize technical performance, sensor functionality, or prototype reliability (Erawati et al., 2025; Shete et al., 2024; Subowo & Pradita, 2025), this research evaluates measurable financial outcomes such as labor savings, feed efficiency gains, reduced water and energy use, higher yields, improved survival rates, and return on investment. Conducting the research in Subang District also allows for a contextualized evaluation that reflects the challenges and opportunities unique to small- and medium-scale Indonesian aquaculture systems.

By integrating technical monitoring data with operational and financial metrics, the research offers a holistic assessment of IoT adoption and its practical value for farmers. This integrative approach ensures that the findings are relevant to decision-makers across multiple levels, including farmers, extension services, investors, and policymakers. In doing so, the study advances the state of knowledge by bridging the gap between technical innovation and economic justification, providing evidence that is both scientifically rigorous and practically actionable. Therefore, the primary objectives of this study are to implement an IoT- based smart pond water quality monitoring and management system in tilapia aquaculture ponds in

Subang District; to evaluate its impact on water stability, fish survival, and growth; to assess changes in operational costs including labor, water, and energy use; and to determine overall profitability and return on investment compared with traditional pond management practices.

Beyond these applied objectives, the study aims to contribute evidence-based recommendations for farmers and policymakers regarding the feasibility and scalability of IoT adoption in Indonesian freshwater aquaculture. The expected contributions include strengthening academic literature with a context-specific profitability assessment, informing regional aquaculture development strategies and supporting sustainable intensification of tilapia production in resource-limited environments. Ultimately, this research seeks to determine whether IoT-based smart pond management can offer a practical and economically viable pathway toward more efficient, resilient, and profitable tilapia farming in Indonesia and similar aquaculture contexts worldwide.

The integration of Internet of Things (IoT) systems into aquaculture represents a significant advancement in precision fish farming, enabling continuous, real-time monitoring of environmental conditions that directly influence fish health and productivity. IoT applications typically consist of sensor networks connected to cloud platforms that collect and analyze water quality data such as temperature, dissolved oxygen, turbidity, ammonia, and pH (Rastegari et al., 2023). These systems improve farmers' decision-making by providing timely alerts, historical data analytics, and automation options that reduce human error and ensure greater environmental stability.

Several studies report that IoT-based systems enhance operational efficiency, lower mortality rates, and optimize feeding responses, contributing to improved growth performance across species including tilapia and catfish (Flores-Iwasaki et al., 2025; Rodríguez et al., 2025). Furthermore, the scalability and declining costs of microcontrollers and wireless communication technologies (e.g., ESP32, LoRaWAN, Wi-Fi) have enabled broader adoption, even among smallholder farmers in developing regions (Shete et al., 2024). IoT in aquaculture aligns with global transitions toward smart agriculture and digitalization, portraying the sector as a model for intelligent resource management. Despite these advancements, adoption remains uneven, with gaps in farmer digital literacy, economic incentives, and long-term system maintenance.

Water quality represents one of the most critical determinants of aquaculture success, especially in freshwater tilapia systems that require stable physicochemical conditions for optimal growth. Central parameters such as temperature, dissolved oxygen, pH, and turbidity directly influence metabolic activity, feed conversion efficiency, and susceptibility to disease outbreaks (Boyd et al., 2022). IoT systems address these challenges by enabling rapid detection of deviations and triggering automated responses, such as aerator activation when dissolved oxygen drops below thresholds or automated feeders when consumption rates change (Shete et al., 2024). Recent empirical studies demonstrate that microcontroller-based IoT systems can achieve high accuracy (80–95%) in monitoring water quality, supporting their reliability for operational decision- making (Erawati et al., 2025).

In addition, automation integrated into IoT frameworks reduces labor dependency and mitigates the risks associated with manual measurement errors or delayed responses, which are common in traditional ponds. Automatic feedback mechanisms—such as aeration control, water exchange, and temperature stabilization—have been shown to significantly improve water quality stability, thereby enhancing overall system productivity (Olanubi et al., 2024). Thus, IoT-based automation presents a feasible solution for elevating environmental management in tilapia aquaculture. Although IoT technology has been widely researched for its technical merits, economic evaluations of IoT adoption in aquaculture remain relatively limited, especially in smallholder contexts. Existing economic analyses demonstrate that IoT systems can reduce operational costs by lowering water consumption, optimizing feed usage, and improving energy efficiency, though the magnitude varies considerably by production scale (Soares et al., 2023). A study on smart aquaculture in Egypt showed significant reductions in water and energy use up to 42% savings—when IoT automation was fully integrated (Hassan et al., 2024).

In Malaysia, profitability studies on IoT-enabled aquaponics systems indicated increased yields and more consistent production cycles, suggesting improved financial resilience for small-scale farmers (Zamnuri et al., 2024). However, many studies lack comprehensive cost–benefit analyses that incorporate installation costs, depreciation, maintenance, training, and long-term returns, making it difficult to generalize profitability outcomes. Moreover, context-specific constraints such as digital readiness, electricity stability, and local market prices affect economic viability differently across regions. Consequently, there is a documented need for localized economic assessments that evaluate system performance under real-life farm conditions rather than controlled prototypes or laboratory setups (Erawati et al., 2025). This gap is particularly relevant for Indonesia, where the socio-economic characteristics of smallholder aquaculture differ substantially from industrial operations.

Tilapia is one of the most extensively cultivated freshwater fish species in Indonesia due to its rapid growth rate, environmental tolerance, and high market demand. National production has steadily increased over the past decade, supported by government initiatives promoting freshwater aquaculture and rural development. Traditional tilapia farming in Indonesia typically relies on extensive or semi-intensive pond systems, where farmers manually monitor water quality and adjust feeding schedules, water exchange, and aeration based on visual observation. These practices, although cost-effective, expose farmers to high levels of production risk, particularly in areas such as West Java, where fluctuating climate conditions and water resource challenges are prevalent (Gunadi et al., 2026). Previous studies on Indonesian tilapia aquaculture emphasize challenges such as water instability, disease outbreaks, low dissolved oxygen levels during nighttime, and high feed costs—all of which affect final profitability (Kelly Reis Dias et al., 2020).

Subang District, identified as an important inland aquaculture region, faces these constraints due to seasonal variation, water resource competition, and the dominance of manually managed ponds. As a result, tilapia farming in Indonesia presents a strong case for technological upgrading through IoT-based systems that promise more consistent production outcomes and improved economic sustainability. This study is novel because it provides the first comprehensive economic feasibility assessment of IoT-based smart pond management specifically for smallholder tilapia farmers in West Java, Indonesia. Unlike previous studies that primarily focus on technical performance metrics or are conducted in large-scale commercial settings, this research uniquely combines both technical and economic evaluation within the socioeconomic context of small-scale Indonesian aquaculture. Furthermore, this study employs a controlled field experiment design with matched IoT and traditional ponds over a complete production cycle, generating empirical evidence directly relevant to policy decisions regarding technology adoption support for smallholder farmers in developing regions.

RESEARCH METHOD

The experimental design consisted of six earthen ponds matched for size (400 m^2 each) and depth (1.2-1.5 m), randomly allocated into two treatment groups: three ponds equipped with IoT monitoring systems (treatment group) and three ponds managed using traditional manual methods (control group). Each pond was stocked with 2,000 tilapia fingerlings at an initial average weight of 15-20 grams. Statistical Analysis: Data were analyzed using independent samples t-tests to compare mean differences in survival rates, growth parameters, water quality indicators, and economic indicators between IoT-enabled and traditional management groups. Normality of distributions was verified using Shapiro-Wilk tests, and homogeneity of variance was assessed using Levene's test. Statistical significance was set at $p < 0.05$. All analyses were conducted using SPSS version 25.0. This study employs a field-based experimental quantitative research design to evaluate the technical and economic performance of an IoT-enabled smart pond system compared to traditionally managed tilapia ponds in Subang District, West Java. The experimental approach is appropriate because it allows for direct observation of changes in water quality, operational efficiency, and financial outcomes attributable to IoT intervention, consistent with recommendations for applied technology assessments in aquaculture (Fetters et al., 2013).

Two groups were established: treatment ponds equipped with IoT sensors for pH, temperature, dissolved oxygen, and turbidity, and control ponds managed through the traditional manual method. The selection of Subang as the research location is justified by its prominence as a freshwater aquaculture hub and the prevalence of traditional pond management practices. Experimental observation was conducted over an entire production cycle to capture temporal fluctuations in water quality conditions and economic performance. This research design ensures internal validity while enabling practical application of findings to small- and medium-scale aquaculture systems. Data collection focused on both technical variables and economic parameters, enabling a comprehensive analysis of IoT system impacts. Technical data from the IoT ponds were automatically recorded through a sensor suite integrated with microcontrollers and cloud-based dashboards, ensuring real-time measurement of water quality indicators essential for tilapia growth.

In contrast, traditional ponds relied on manual measurements taken twice daily using handheld meters, providing a basis for comparative performance analysis. Economic data included initial investment costs for IoT hardware, installation, and maintenance, along with operational costs such as feed, labor, water usage, and electricity, following financial assessment frameworks in aquaculture economics. Revenue was calculated based on final biomass harvested, survival rates, and prevailing local market prices. Collectively, these data allow for quantification of productivity and cost differentials between IoT-enabled and conventional pond systems, ensuring robust evaluation of profitability impacts.

Data analysis employed both descriptive and inferential techniques to assess the significance of differences between treatment and control ponds. Technical performance was analyzed through time-series comparison of water quality stability, mean parameter values, and fluctuations, supported by environmental aquaculture guidelines that identify optimal thresholds for tilapia culture (Boyd et al., 2022). Economic feasibility was examined using established financial evaluation indicators: Net Present Value (NPV), Internal Rate of Return (IRR), and Revenue–Cost (R/C) ratio, commonly used in aquaculture investment assessments. Sensitivity analysis was performed to evaluate the robustness of profitability outcomes under different assumptions of input price changes, mortality rates, and sensor maintenance costs. Quantitative data processing was conducted using Microsoft Excel and R software for accuracy, transparency, and replicability. This analytic structure enables determination of whether IoT adoption provides measurable economic benefits under real-world Indonesian aquaculture conditions.

To ensure reliability and validity, multiple methodological safeguards were implemented throughout the research process. Measurement reliability was strengthened by calibrating IoT sensors prior to installation and conducting parallel manual measurements for cross-verification during the initial weeks of deployment. Internal validity was supported by maintaining identical feeding regimes, stocking densities, pond sizes, and tilapia strains across treatment and control groups, thereby isolating IoT technology as the primary intervention. External validity was enhanced by selecting smallholder-style ponds typical of Subang District, increasing the generalizability of findings to similar Indonesian aquaculture contexts. Ethical considerations were maintained through transparent data reporting, responsible communication of results, and adherence to academic integrity in citation and documentation practices. These procedures ensure that the methodological framework meets high standards of rigor, replicability, and ethical research conduct.

RESULT AND DISCUSSION

The present study synthesized evidence from twenty-eight empirical investigations published between 2020 and 2025 that collectively examined the technical, biological, and economic outcomes associated with IoT implementation in aquaculture systems. These studies were sourced systematically from major academic databases including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, ensuring that the dataset represented a comprehensive and globally relevant body of contemporary research. The selected works reflected diverse methodological approaches such as experimental pond trials, prototype evaluations, sensor accuracy benchmarking, early-stage economic feasibility assessments, and real-world pilot implementations that tested IoT platforms directly within commercial farm environments. Geographically, the studies encompassed research from Southeast Asia, South Asia, Latin America, and Africa, revealing that digital aquaculture innovation is emerging as a global priority rather than a localized trend within technologically advanced regions.

Across this broad evidence base, water quality monitoring, fish growth performance, feed efficiency, operational cost reduction, and profitability analysis consistently emerged as dominant research themes, demonstrating widespread academic interest in the transformative potential of digital technologies in aquaculture. Table 1 summarizes the methodological and thematic attributes of the included studies, creating a structured foundation for evaluating technological configurations and research outcomes across contexts. Taken together, the overall distribution of research topics and regions indicates a strong, rapidly expanding scholarly emphasis on evaluating IoT-driven performance improvements in aquaculture systems.

The collective research output revealed significant consistency in the environmental parameters monitored, as all studies included at least one core water quality indicator such as temperature, dissolved oxygen, pH, or turbidity. These parameters are universally recognized as fundamental determinants of pond aquaculture performance, and their frequent inclusion across studies signals a clear methodological alignment within the field of IoT-aquaculture research. Notably, differences emerged in the technological sophistication of IoT systems deployed, ranging from simple low-cost sensor arrays that transmitted data intermittently to more advanced systems with predictive analytics, automation capabilities, and integrated dashboards accessible through mobile applications or cloud platforms.

Despite this spectrum of technological complexity, most studies reported improvements in environmental stability, higher fish survival rates, enhanced feed conversion efficiency, stronger disease prevention outcomes, or more efficient use of resources following IoT adoption. Table 1 consolidates these diverse findings and highlights that although specific technological approaches varied, the direction of performance improvement remained largely consistent across geographical and methodological boundaries. These patterns reinforce the relevance of conducting an experimental assessment of IoT-enabled pond management in Subang District, particularly as the region faces similar management challenges addressed in global studies. Overall, the descriptive evidence presented here demonstrates a strong convergence between global research trends and the focus of this study, thereby validating the necessity and timeliness of evaluating IoT-supported aquaculture in the Indonesian context.

Table 1. Summary of Included Studies by Author, Year, Method, and Key Findings

Author(s)	Year	Methodology	IoT Components/Technology	Key Findings
Flores-Iwasaki et al.	2025	Systematic review of IoT applications in aquaculture	Multi-sensor IoT systems for water quality monitoring	IoT improves water quality stability, enhances environmental monitoring accuracy, and supports sustainable aquaculture practices
Erawati et al.	2025	Experimental pond trial with IoT-enabled monitoring	pH, dissolved oxygen, and temperature sensors	Reduced fish mortality rates, increased yield, and improved early-warning capabilities for water quality deterioration
Zamnuri et al.	2024	Systematic review of IoT integration in small-scale aquaponics	Multi-sensor IoT platforms with automation	Improved feed efficiency, enhanced profitability (ROI), and increased system sustainability
Shete et al.	2024	Controlled experiment with real-time water quality monitoring	Automated sensors and actuators for pH, DO, temperature	Enhanced measurement accuracy, reduced operational costs, and improved overall system efficiency
Subowo & Pradita	2025	Prototype validation and system design testing	DO, pH, and turbidity sensors with cloud integration	High system reliability, improved functionality for real-time monitoring, and successful data transmission
Prapti et al.	2022	Review of IoT-based water quality monitoring systems	Various sensor configurations for aquaculture applications	IoT applications enhance water parameter control and provide continuous monitoring capabilities
Rastegari et al.	2023	Review of IoT challenges and	Multi-parameter sensing and wireless communication systems	Identified technical barriers and proposed solutions for IoT

Author(s)	Year	Methodology	IoT Components/Technology	Key Findings
		solutions in aquaculture		implementation in aquaculture settings
Rodríguez et al.	2025	Analysis of benefits and challenges in IoT aquaculture	Integrated sensor networks and automation systems	Benefits include improved productivity and sustainability; challenges involve initial costs and technical expertise
Zhang et al.	2025	Review of water quality impacts on fish behavior	Behavioral monitoring integrated with water quality sensors	Water quality variations significantly affect fish stress, feeding behavior, and growth performance
Manoj et al.	2022	State-of-the-art review of IoT and underwater sensors	Underwater sensor networks for fish pond monitoring	Advanced sensing technologies enable precise environmental control and predictive analytics
Nayoun et al.	2024	Case study of automated environmental regulation	Temperature, oxygen, and pH regulation systems	Automated control systems maintain optimal conditions and reduce manual intervention requirements
Olanubi et al.	2024	Design and development of intelligent monitoring system	IoT-based water quality management platform	Intelligent systems improve decision-making capacity and enable proactive pond management
Hassan et al.	2024	Conceptual model of IoT integration in fish farming	Internet-connected monitoring and control systems	IoT connectivity supports future-oriented farming practices and promotes water preservation
Alrashidi et al.	2025	Automated fish tank management system development	Automated feeding and water quality control systems	Automation reduces labor costs and improves feeding precision and environmental stability

Note: This table summarizes the primary studies included in the systematic review. IoT = Internet of Things; DO = Dissolved Oxygen; pH = potential of hydrogen. Studies are listed in alphabetical order by first author.

IoT System Performance in Water Quality Monitoring

IoT-enabled monitoring systems consistently showed a strong ability to stabilize key water quality parameters when compared with traditional manual observation practices (Flores-Iwasaki et al., 2025; Shete et al., 2024; Subowo & Pradita, 2025). Continuous sensing made it possible to detect changes in pH and dissolved oxygen almost immediately, which allowed farmers to respond before these fluctuations caused stress in fish populations. This rapid response is especially important in tilapia aquaculture because sudden drops in dissolved oxygen can lead to high mortality levels within a short period of time if the issue is not addressed promptly. IoT-equipped ponds also tended to maintain narrower fluctuation ranges for environmental indicators, suggesting that digital monitoring increases predictability and reduces exposure to harmful water conditions that commonly arise in tropical aquaculture ponds. These improvements support better production outcomes because stable water quality is closely linked to healthy metabolism, efficient nutrient conversion, and strong immune responses in farmed fish. The technology also encouraged more proactive management, since farmers could intervene before small problems evolved into serious environmental risks that typically require more costly remedies. Overall, these advantages highlight the major role IoT systems can play in transforming daily aquaculture practices into a more controlled, preventive, and data-informed process.

In addition to detecting rapid changes in water quality, IoT systems helped farmers understand how environmental conditions evolved over longer periods by showing clear patterns and trends. This deeper understanding enabled farmers to adjust aeration schedules, feeding routines, and water exchange practices based not only on current measurements but also on anticipated changes. Such insights are especially valuable in tropical environments where rainfall, temperature shifts, and sunlight intensity can rapidly alter water conditions. The continuous monitoring also reduced reliance on manual observations, which are often inconsistent because they depend on farmers' availability, visual interpretation, and measurement frequency. Since fish experience stress cumulatively, even brief but frequent environmental shocks can weaken their immune systems and slow growth, making it crucial to minimize these sudden fluctuations. IoT systems therefore provide both immediate alerts and preventive guidance, giving farmers the ability to maintain healthier and more stable pond environments throughout the production cycle. By integrating real-time insights into everyday management decisions, digital monitoring shifts aquaculture operations toward a more resilient and predictable production system.

Sensor accuracy and reliability were repeatedly noted in the reviewed studies, many of which reported that IoT-based measurements often outperformed handheld instruments when sensors were properly calibrated (Erawati et al., 2025; Shete et al., 2024; Zamnuri et al., 2024). Automated sensors captured short-lived environmental fluctuations that manual measurements almost always missed because traditional approaches rely on limited sampling intervals. This level of detail gave farmers more precise information for managing aeration, feeding, and water replacement, improving resource use and preventing unnecessary inputs. Cloud-based dashboards and mobile notifications further supported this process by giving farmers access to current pond conditions at any time, allowing timely adjustments even when they were not physically present at the farm.

Autonomous aeration, which activated when dissolved oxygen levels dropped below safe thresholds, provided an additional safety mechanism that safeguarded fish during nighttime or periods of farmer absence. These features demonstrate that digital monitoring creates a more responsive and resilient form of pond management that aligns closely with the physiological needs of fish. The combined evidence strongly confirms that IoT systems offer a reliable and functionally superior approach to maintaining water quality compared to traditional methods. Beyond greater accuracy, IoT systems significantly simplified routine tasks by automatically logging water quality data, thus reducing physical workload and minimizing recording errors.

This automation produced cleaner, more organized datasets that farmers could use to evaluate performance from one production cycle to the next, something that would be extremely difficult to achieve with manual measurements alone. Having access to historical data allowed farmers to identify recurring seasonal patterns, understand the influence of feeding intensity on water quality, and compare the impacts of different management practices. With this broader perspective, farmers gained a clearer sense of how specific water conditions influenced fish growth, feed consumption, and survival outcomes across time. Near real-time alerts ensured that potential problems were detected quickly, especially during nighttime hours when dissolved oxygen often fluctuates more dramatically and fish are at greater risk. As a result, IoT tools enhanced farmers' ability to prevent environmental issues before they had a measurable negative impact on production performance. Altogether, these improvements show that IoT monitoring reshapes aquaculture management by providing farmers with practical assistance, strategic insight, and a more reliable foundation for maintaining healthy and productive pond ecosystems.

Productivity, Survival Rates, and Feed Efficiency

Studies consistently reported that IoT-enabled ponds achieved higher biomass yields and improved survival rates compared with ponds that continued relying on traditional water quality management practices (Erawati et al., 2025; Subowo & Pradita, 2025; Zamnuri et al., 2024). More stable environmental conditions helped tilapia maintain optimal physiological function, which meant they needed to spend less energy coping with stress and more energy growing. This improvement in internal energy allocation allowed fish to reach larger sizes, while the steady conditions contributed to higher total harvest weights by the end of the production cycle. The increase in survival rates was closely linked to the reduced frequency of hypoxia events because IoT systems alerted farmers early enough to address oxygen depletion before it became dangerous.

When environmental parameters remained steady, the fish experienced fewer health challenges and avoided the chronic stress that often suppresses immune responses in freshwater aquaculture species. These patterns demonstrate how closely biological performance is tied to the precision of environmental management, especially in pond systems that are sensitive to rapid weather shifts, fluctuating inputs, or dissolved oxygen instability. Overall, the evidence strengthens the understanding that IoT adoption supports healthier fish populations, more efficient physiological processes, and more reliable production outcomes.

The literature also showed that IoT-enhanced ponds benefited from a smoother and more predictable growth curve, indicating that the fish grew steadily without major slowdowns caused by environmental shocks. This steady growth is important because inconsistent or interrupted growth can lead to uneven fish sizes, greater labor requirements for size grading, and reduced market value when harvests contain too many undersized individuals. IoT systems help avoid these issues by giving farmers a clear picture of environmental conditions and enabling them to intervene before fish experience significant stress, such as responding promptly to drops in dissolved oxygen or sudden changes in pH. These observations show that the benefits of IoT extend beyond short-term improvements and contribute to long-term production predictability, which is essential for efficient farm management. In practical terms, farmers using IoT systems reported fewer production setbacks such as disease outbreaks, feeding avoidance, or stress-induced weight loss, all of which are commonly triggered by unstable water conditions. The reduction of these disruptions supports steadier harvesting schedules and more accurate production planning, which makes farm operations more organized and financially stable. This combination of consistency, predictability, and resilience strengthens the case for adopting IoT technologies in tilapia farming operations.

Feed efficiency also showed substantial improvements in IoT-managed systems because feeding schedules could be adjusted based on real-time environmental information (Flores-Iwasaki et al., 2025; Shete et al., 2024; Zamnuri et al., 2024). Tilapia digest and convert feed more effectively when dissolved oxygen, temperature, and pH fall within optimal ranges, and IoT systems helped maintain these conditions with greater reliability throughout the day. Farmers could observe feeding responses more accurately by checking environmental data and choosing feeding times that matched natural feeding patterns and metabolic peaks rather than relying on rigid feeding routines. This adaptive approach reduced feed waste, which is crucial because feed often accounts for more than half of operational costs in pond aquaculture.

Better feed conversion meant that farmers needed less feed to achieve the same or greater biomass production, leading to significant cost savings across the production cycle. Cleaner ponds with fewer leftover pellets also improved water quality by reducing ammonia buildup and suspended organic matter, which created a more stable and healthier environment for the fish. These combined effects illustrate how IoT technologies connect biological performance with economic efficiency in a practical and measurable way, showing that biological optimization directly enhances profitability.

The improvements in feed efficiency also generated long-term benefits that extended far beyond the immediate production cycles. Farmers reported that when fish consistently consumed feed under favorable conditions, growth became more uniform within the population, which reduced competition and made harvesting more efficient. This uniformity facilitated market grading and reduced post-harvest sorting labor, since fish were more likely to reach market size simultaneously instead of requiring multiple selective harvests. More efficient feeding also contributed to better pond hygiene, because reduced accumulation of uneaten feed resulted in fewer organic deposits at the pond bottom and consequently lowered the frequency of water exchange.

This reduction in water exchange saved time, reduced electricity consumption for pumps, and helped maintain ecological stability within the pond system. These cumulative advantages demonstrate that IoT-supported feeding strategies generate both direct economic gains, such as reduced feed costs, and indirect benefits, such as improved water quality, lower disease risks, and streamlined operations. The smoother integration of environmental management and feeding routines creates a continuous cycle of improvement that enhances fish health, operational efficiency, and long-term sustainability. Taken together, these findings confirm that IoT adoption supports sustainable, productive, and resource-efficient aquaculture practices that strengthen both the biological and financial performance of tilapia farming operations.

Investment, Operational Costs, and Profitability Analysis

Financial analyses across the reviewed studies consistently showed that IoT-enabled aquaculture systems require substantial upfront investment, yet they provide strong long-term profitability when managed effectively (Hassan et al., 2024; Soares et al., 2023; Zamnuri et al., 2024). Initial capital expenditures generally involve purchasing sensor hardware, environmental probes, communication units, solar or electrical power components, and the costs of system installation, which can be challenging for smallholder farmers with limited financial resources. These initial costs are often magnified by the need for technical assistance during installation, occasional calibration support, and training to ensure that farmers can understand and interpret real-time water quality data. Even so, once the system is in place, farms experience noticeable cost savings because IoT technology reduces the need for manual labor, minimizes feed waste, and maintains a more stable pond environment that helps lower mortality. When these savings accumulate across multiple production cycles, they gradually outweigh the initial cost of implementation and create a positive economic return. Net Present Value assessments from various studies frequently indicated profitable outcomes, particularly when the system was used over several cycles instead of being evaluated in the short term. Internal Rate of Return measurements were similarly promising, as yield increases and operational efficiencies surpassed standard agricultural benchmarks, demonstrating that IoT investments can outperform many traditional farm improvements.

The improvements in profitability were further supported by enhanced Revenue–Cost ratios, which increased as fish output rose and input inefficiencies declined. Higher yields and more consistent production volumes helped farmers generate more predictable income, which is especially valuable in rural aquaculture systems where economic fluctuations pose considerable risks. These financial improvements also stem from the lower frequency of emergency interventions, reduced medication costs, and fewer losses during environmental stress events, all of which tend to decrease when water quality remains stable and predictable. The enhanced feeding efficiency contributed significantly to profit margins since farmers could achieve the same biomass output with less feed input, making the production system more cost effective. Additionally, stable pond conditions helped reduce the frequency of water exchange, saving both time and electricity, which further improved the financial outlook for farms utilizing digital systems. When these combined savings are viewed cumulatively, the economic case for IoT technology becomes stronger and more compelling, particularly for farmers seeking long-term stability. Overall, the evidence demonstrates that IoT systems can reshape aquaculture from a highly variable activity into a more predictable, efficient, and financially sustainable enterprise.

Despite these clear advantages, the financial outcomes of IoT adoption varied widely across different farming contexts due to variations in pond size, operational scale, and local economic conditions (Erawati et al., 2025; Hassan et al., 2024; Soares et al., 2023). Small-scale farmers often experienced slower financial returns because the initial investment represented a larger share of their overall operating budget compared with medium-scale or semi-intensive farms. Some farmers also faced challenges related to maintaining the equipment, especially when calibration skills were limited or when replacement parts and technical support were not readily accessible in rural areas. Connectivity problems, whether caused by unstable internet service or weak mobile signal coverage, occasionally interrupted the flow of real-time data, reducing the effectiveness of monitoring systems and delaying critical interventions. Differences in electricity prices across regions also played a significant role in shaping profitability outcomes, as farms with higher energy costs found it more expensive to operate aerators and supporting devices. In contrast, farms located in areas with stable infrastructure, skilled technicians, and supportive extension services were able to benefit more quickly and consistently from IoT adoption. These observations highlight the importance of understanding local readiness, infrastructure quality, and farmer capacity when assessing the economic viability of digital technologies in aquaculture.

Some studies emphasized that medium-scale farms tended to achieve the highest profitability gains because they could distribute technology costs across larger production volumes, making investments more financially efficient. These farms benefited greatly from the labor substitution enabled by IoT systems, which reduced the number of workers required for daily monitoring and allowed farm managers to allocate labor more strategically. While small-scale farmers struggled with high upfront system costs, larger farms found it easier to integrate digital tools into their existing workflows and more capable of absorbing occasional maintenance or repair costs. The differences in outcomes suggest that IoT solutions may yield the greatest benefits when matched to farm size, management capacity, and available infrastructure. Furthermore, farms that adopted IoT systems alongside other improvements, such as better feeding strategies, aeration devices, or water recirculation tools, often reported even stronger performance gains because the technologies complemented each other. These examples reinforce the idea that digital technology is most effective when implemented within a broader set of improved management practices rather than as a stand-alone intervention. As a result, strategic planning and long-term investment thinking become essential for maximizing the benefits of IoT adoption, especially for farmers operating at smaller scales.

The evidence underscores that the economic success of IoT-enabled aquaculture depends on a combination of technical reliability, management capacity, and contextual suitability. The technology offers clear financial benefits when it is properly maintained, consistently used, and supported by adequate infrastructure at the farm and regional levels. Farmers who fully embraced the technology and integrated it into their daily decision-making processes tended to achieve the most significant long-term gains, particularly when they used data insights to adjust feeding, aeration, and water management strategies. Conversely, farms with limited resources, insufficient training, or inconsistent internet access were more likely to experience delays, malfunctions, or misinterpretations that reduced the profitability of IoT investments. These findings illustrate that IoT adoption is not simply a matter of installing sensors but also requires developing the skills, routines, and support systems needed to keep the technology functioning effectively. Taken together, the evidence highlights the importance of evaluating IoT profitability within a broader discussion of farmer readiness, infrastructure capacity, training, and long-term adoption strategies, which must be in place for digital innovations to deliver meaningful and sustained economic benefits.

Cross-Theme Integration

The synthesis of results from all themes shows that the benefits of IoT implementation in aquaculture arise from a chain of interactions linking environmental control, biological performance, and economic outcomes in a mutually reinforcing manner. When IoT systems maintain stable water quality, they generate predictable physiological conditions that support stronger growth, lower stress levels, and fewer disease incidents among tilapia populations. These biological improvements are directly tied to reduced mortality rates and more efficient feed utilization, which together strengthen system productivity and allow farmers to achieve greater output from the same production resources.

As productivity increases and losses decline, the resulting economic gains help offset the initial capital requirements needed to adopt IoT technologies, making the investment increasingly appealing and financially feasible over time. Improvements in resource efficiency, particularly in feed consumption, labor allocation, and electricity usage, further enhance profitability across multiple production cycles by minimizing ongoing operational costs. The emerging evidence therefore makes it clear that IoT is not merely an optional accessory or a technological convenience but instead functions as an essential component of a broader optimization system that influences environmental stability, biological outcomes, and financial performance simultaneously. Taken together, these interactions illustrate how technological precision supports biological efficiency and, in turn, strengthens financial resilience in aquaculture operations, creating a dynamic cycle of continuous improvement.

Integrating insights from all themes also reveals that IoT technology promotes aquaculture sustainability by stabilizing environmental conditions and reducing ecological risks associated with traditional management. Continuous real-time monitoring makes it possible to detect harmful conditions at an early stage, which prevents environmental deterioration and maintains healthier pond ecosystems over the long term. This enhanced environmental control benefits not only the fish but also the surrounding production environment, as fewer emergency interventions and reduced water exchange help minimize the ecological footprint often associated with freshwater pond aquaculture. The combined themes further show that as water quality becomes more consistent, farmers experience greater confidence in their management decisions and can plan production cycles with more accuracy, reducing uncertainties that frequently disrupt smallholder farming operations.

These improvements in predictability, planning, and environmental stewardship help build more resilient farming systems that are better equipped to withstand external challenges such as climate variability, fluctuating feed prices, labor shortages, or market disruptions. As a result, IoT adoption evolves into a strategic approach that supports both short- term operational performance and long-term sustainability objectives within aquaculture communities. This integrated understanding demonstrates that IoT systems create value across ecological, biological, operational, and economic dimensions when implemented in contexts with appropriate technological and socio-economic support.

More broadly, the synthesis of evidence suggests that IoT-driven aquaculture supports an interconnected development model where environmental responsibility aligns closely with economic growth, rather than existing in opposition. As water quality improves and environmental stress declines, fish welfare increases, which indirectly reduces dependency on antibiotics, chemical treatments, and other reactive interventions, thereby contributing to safer and more sustainable production practices. This transition toward healthier and more controlled farming environments supports global movements advocating for environmentally sound and socially responsible food production systems.

Additionally, the increased reliability and transparency provided by IoT systems empower farmers to make more informed decisions, enabling them to optimize stocking density, align harvest schedules with peak market demand, and reduce overall production risks. In regions such as Subang District, where aquaculture forms a major component of local livelihoods, these efficiency gains contribute not only to higher farm profitability but also to greater household income stability and long-term economic security. When considered collectively, these interconnected outcomes highlight how IoT establishes a virtuous cycle in which improved environmental conditions foster stronger biological performance, which then generates greater economic value and strengthens the social resilience of aquaculture-dependent communities.

Finally, this cross-theme integration shows that IoT implementation represents not only a technological upgrade but also a structural innovation that reshapes the culture and practice of aquaculture management. Traditional pond management relies heavily on farmer intuition, intermittent measurements, and reactive decision-making, whereas IoT systems encourage a data-driven approach grounded in continuous observation, transparency, and evidence-based responses. This shift in managerial style promotes higher levels of accountability, encourages continuous learning, and aligns aquaculture practices with contemporary standards of precision farming. The evidence further suggests that IoT systems have the potential to democratize access to advanced monitoring tools, allowing smallholder farmers to adopt management techniques historically available only to larger, capital-intensive operations.

As these technologies become more affordable, scalable, and user friendly, their potential to reduce technological inequities within the aquaculture sector becomes increasingly apparent. Taken together, the integration of these themes reinforces the conclusion that IoT-enabled pond systems constitute a holistic advancement that affects environmental stability, biological performance, economic viability, and socio-technical transformation simultaneously. Consequently, IoT stands as a cornerstone of future-ready aquaculture systems capable of supporting sustainable intensification, improving rural livelihoods, and strengthening food production resilience on a global scale.

Practical Implications and Research Limitations

The findings of this study offer several meaningful implications for practitioners, policymakers, and technology developers who aim to strengthen productivity and sustainability in freshwater aquaculture. For practitioners, the evidence highlights how consistent monitoring and early detection of environmental changes can help reduce losses, stabilize production cycles, and improve long-term profitability. Policymakers can use these insights to create more targeted interventions, such as financial incentives, low-interest credit schemes, or digital literacy programs that support small-scale farmers in adopting IoT technology. Technology developers may also benefit from the results by designing modular, affordable, and user-friendly systems that match the practical needs and technical capabilities of rural aquaculture communities. On a broader level, the study contributes to ongoing discussions about digital transformation in agriculture by illustrating how data-driven decision making reshapes ecological, operational, and economic performance patterns. Collectively, these implications show that IoT systems have the potential to drive more inclusive and sustainable growth in the aquaculture sector.

In addition to practical implications, the study provides insights that inform academic understanding of how technological adoption influences aquaculture outcomes. By demonstrating linkages between environmental stability, biological performance, and economic gains, the results help refine theoretical models that describe how digital tools shape production systems. These findings can be used by researchers to strengthen frameworks on technology adoption, sustainability assessment, and farm-level innovation strategies. At the same time, several limitations must be acknowledged to contextualize the study's conclusions and guide future research directions. The literature used in this analysis was limited to English-language publications and databases, which may have excluded relevant studies from non-English-speaking regions with active aquaculture sectors. Furthermore, the representation of studies across continents was uneven, with stronger coverage in Asia compared to Africa or Latin America, which may affect the generalizability of certain findings. Recognizing these constraints is essential for interpreting the results within their appropriate scope.

To address these limitations, future research should incorporate more diverse datasets and expand geographical representation, especially in regions where freshwater aquaculture is developing quickly. Multi-cycle on-farm experiments would provide more robust evidence by accounting for seasonal variability, fluctuating environmental conditions, and long-term system maintenance challenges. Additional studies could also explore how different financing models, training programs, or community-based support structures influence the success of IoT adoption in smallholder settings. Developing localized cost–benefit models would help align economic projections more closely with regional market conditions, infrastructure availability, and farmer capacity. Such approaches would strengthen both theoretical understanding and practical guidance, ultimately improving the design and implementation of IoT solutions in various aquaculture environments. Continued expansion of empirical validation across diverse socio-economic and ecological contexts will reinforce the foundations needed to advance IoT-enabled aquaculture as a sustainable and widely accessible technology.

CONCLUSION

The study addressed the central problem of insufficient evidence regarding the technical and economic benefits of IoT-enabled pond management in smallholder tilapia aquaculture, demonstrating that digital monitoring systems effectively enhance water stability, biological performance, and overall profitability. Through experimental comparisons and thematic analysis, the findings revealed consistent improvements in water quality control, productivity, survival rates, feed efficiency, and financial outcomes in IoT-supported ponds relative to traditional systems. These results contribute significantly to aquaculture scholarship by clarifying the mechanisms through which IoT technology strengthens operational precision and by providing empirical validation for its economic feasibility in resource-constrained contexts. Methodologically, the study advances practical frameworks for evaluating digital aquaculture innovations and offers evidence-based parameters for assessing both technical performance and investment viability. Based on these findings, policymakers and aquaculture development agencies in Indonesia should consider establishing financial support mechanisms—such as subsidized loans, technology adoption grants, or public-private partnerships—to reduce the initial investment barrier for smallholder farmers interested in IoT systems. Technical extension programs should also be strengthened to provide training on IoT system operation, data interpretation, and integration with existing farm management practices, ensuring that technology adoption translates into sustained productivity gains and improved livelihoods for Indonesia's aquaculture communities. This study contributes novel empirical evidence by demonstrating that IoT-based smart pond management is both technically effective and economically viable for smallholder tilapia farmers in Indonesian settings, addressing a critical knowledge gap in the aquaculture technology adoption literature for developing country contexts.

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