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Precision Aquaculture Integration with IoT Multi-Parameter Water Quality Sensor for Tambak Udang Farmers in Cirebon Coastal Area

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ABSTRACT

Shrimp aquaculture in the coastal tambak areas of Cirebon, West Java, faces persistent challenges related to fluctuating water quality driven by tidal dynamics and estuarine pollution, which frequently result in mass shrimp mortality events that devastate smallholder farmers' livelihoods. This study aimed to design, implement, and evaluate a low-cost IoT multi-parameter water quality monitoring system for vanamei shrimp (Litopenaeus vannamei) tambak farmers in Kecamatan Losari and Gebang, Cirebon. A mixed-methods research design was employed, integrating experimental hardware development, quantitative sensor validation, and qualitative usability assessment through a 30-day field deployment across five active pond units. The system utilized a NodeMCU ESP32 microcontroller integrated with pH, dissolved oxygen (DO), temperature (DS18B20), salinity, and turbidity sensors, transmitting real-time data via WiFi and LoRa to Firebase and ThingsBoard cloud platforms, accessible through an Android mobile application. Results demonstrated strong sensor accuracy across all parameters, pH (MAE ±0.20), DO (MAE ±0.27 mg/L), and temperature (MAE ±0.09°C), with system uptime of 94.7% and mean alert notification latency below five seconds. Farmer usability evaluation yielded a System Usability Scale (SUS) composite score of 78.4 (Grade B=Good). No mass mortality events occurred during the trial period, providing preliminary evidence of tangible aquaculture outcome improvement. The study concludes that affordable, participatory-designed IoT monitoring systems can effectively bridge the technology-adoption gap in smallholder coastal aquaculture, with recommendations for LoRa-primary connectivity, wet-season validation trials, and AI-driven predictive alert integration in future iterations.

INTRODUCTION

Aquaculture has emerged as one of the fastest-growing food production sectors globally, contributing significantly to food security, rural livelihoods, and national economic development across Asia and beyond (Gonzalez Parrao et al., 2021; Mohd & Mushtaq, 2025). Indonesia, as the world's largest archipelagic nation, possesses an estimated 17.91 million hectares of coastal and brackish water land suitable for aquaculture activities, positioning it as one of the leading producers of farmed shrimp in the global market (Gonzalez Parrao et al., 2021). Shrimp farming, particularly the cultivation of Pacific white shrimp (Litopenaeus vannamei), has become a cornerstone of Indonesia's marine sector, with smallholder tambak (traditional ponds) farmers forming the backbone of national production output. However, the productivity of coastal aquaculture systems is inherently susceptible to environmental fluctuations, disease outbreaks, and inadequate farm management practices, which collectively undermine the sustainability and profitability of shrimp cultivation (Arifin et al., 2023). The Cirebon coastal area, situated along the northern coast of West Java, represents one of the country's most active shrimp-farming zones, where hundreds of smallholder farmers operate under conditions shaped by tidal influences, estuarine pollution, and limited access to modern monitoring technologies. Despite its economic significance, this region continues to face persistent challenges in maintaining optimal water quality parameters, including pH, dissolved oxygen (DO), temperature, salinity, and turbidity, that are critical for shrimp survival and growth. Addressing these challenges through technological innovation is thus not merely an agricultural imperative but a socioeconomic necessity that demands systematic, evidence-based intervention.

Water quality management in shrimp aquaculture is grounded in a robust body of scientific knowledge that links specific physicochemical parameters to shrimp physiology, behavior, and mortality rates. Dissolved oxygen, for instance, is widely recognized as the most immediately life-threatening parameter, with levels below 3 mg/L triggering stress responses and mass die-offs in Litopenaeus vannamei within hours (Rahman et al., 2021). Similarly, pH fluctuations outside the optimal range of 7.5–8.5 impair osmoregulation, compromise immune function, and increase susceptibility to bacterial infections, which are endemic in tropical coastal ponds. Temperature exerts pervasive effects on metabolic rates, feed conversion efficiency, and pathogen proliferation, making continuous thermal monitoring an indispensable component of precision aquaculture management. Salinity, a key determinant of osmotic stress, must be maintained within species-specific tolerance limits, particularly during the post-larval and juvenile stages when shrimp are most physiologically vulnerable (Supriyadi et al., 2022). Turbidity, often overlooked in conventional monitoring frameworks, serves as a proxy for suspended organic matter, phytoplankton density, and sedimentation rates, all of which directly influence dissolved oxygen dynamics and disease pressure. The theoretical foundation for integrated, multi-parameter water quality monitoring is therefore well-established in aquaculture science, yet the practical translation of this knowledge into affordable, user-friendly field technologies remains an underexplored domain, particularly for smallholder farmers in developing coastal regions.

Despite significant advances in sensor technology and digital agriculture, the integration of real-time, multi-parameter monitoring systems within smallholder shrimp farming contexts in Indonesia remains critically underdeveloped. The prevailing practice among tambak farmers in the Cirebon coastal area is manual water quality sampling, which is conducted intermittently, typically once or twice daily, using handheld instruments or basic chemical test kits, rendering it incapable of capturing rapid environmental changes that occur during tidal cycles or nocturnal oxygen depressions (Wibowo et al., 2023). This temporal gap between water quality events and farmer response constitutes a systemic vulnerability, as critical deteriorations in DO or pH can reach lethal thresholds within periods shorter than the manual sampling interval. Furthermore, the absence of centralized data infrastructure means that farmers cannot detect recurring patterns, seasonal trends, or cumulative pollution effects that would otherwise inform more strategic pond management decisions. Commercial IoT-based aquaculture monitoring solutions, while technically capable, are predominantly designed for large-scale industrial operations and carry upfront hardware, installation, and subscription costs that far exceed the financial capacity of smallholder operators in regions such as Cirebon. The literature reveals a persistent tension between technological capability and contextual accessibility, with few studies having operationalized low-cost, locally deployable IoT systems that are both technically robust and practically usable by non-technical farmers (C. Kurniawan & Azwir, 2019). This gap, between the theoretical promise of precision aquaculture and the lived reality of coastal smallholder farmers, constitutes the central problematic that this study seeks to address.

The urgency of developing and implementing an affordable IoT-based water quality monitoring system for tambak shrimp farmers in Cirebon is underscored by converging ecological, economic, and policy pressures that make the status quo increasingly untenable. From an ecological standpoint, the northern coast of West Java has experienced accelerating environmental degradation over the past two decades, driven by riverine pollution from upstream agricultural runoff, urban wastewater discharge, and unregulated industrial effluents, all of which compound the natural variability introduced by the Java Sea tidal regime (S. Y. Purnomo et al., 2025). These compounding stressors have resulted in increasingly frequent episodes of acute water quality deterioration, including hypoxic events and harmful algal blooms, that cause mass shrimp mortality events locally known as *kematian massal*, which can eradicate an entire pond's production within a single production cycle. Economically, the financial exposure faced by smallholder farmers during such events is catastrophic, given that shrimp represent a high-value commodity requiring substantial investment in seed, feed, and operational costs, without the safety nets afforded by formal insurance or credit mechanisms. From a policy perspective, Indonesia's National Medium-Term Development Plan (RPJMN) 2020–2024 explicitly identifies aquaculture technology adoption as a strategic priority for increasing fish farmer welfare and national food security, yet implementation in sub-national coastal contexts has lagged significantly behind federal ambitions (Arifin et al., 2023). The development of a context-appropriate, low-cost IoT system specifically designed for Cirebon's smallholder tambak environment therefore responds to a convergence of urgent field needs, unfulfilled policy mandates, and the broader global imperative toward smart, sustainable aquaculture. Failure to act on this gap risks perpetuating cycles of preventable loss, environmental degradation, and missed economic opportunity that disproportionately affect Indonesia's most vulnerable aquaculture communities.

A growing body of literature from the past five years has explored the application of IoT, sensor networks, and data analytics in aquaculture water quality monitoring, revealing both considerable promise and persistent limitations in the transferability of these systems to smallholder contexts. Putri et al. (2022) developed a wireless multi-sensor monitoring platform for vanamei shrimp ponds in East Java, demonstrating real-time data transmission capabilities for DO, pH, and temperature with mean accuracy rates exceeding 95%, yet their system required a stable 4G network infrastructure and dedicated power supply that limited its deployment in remote or off-grid coastal settings. Rahman et al. (2021) conducted a comparative analysis of LoRa-based and WiFi-based sensor networks for aquaculture environments in coastal Sulawesi, concluding that LoRa protocols offered superior communication range and energy efficiency but required greater technical expertise for configuration and maintenance, creating barriers for farmer adoption without sustained technical support. In a systematic review of IoT applications in Southeast Asian aquaculture, Wibowo et al. (2023) identified 47 relevant studies and found that while sensor accuracy and data transmission reliability had improved substantially since 2018, fewer than 12% of reviewed systems had undergone real-world validation with actual farming populations, and none had been specifically tailored to the ecological conditions of West Java's northern coastal zone. Supriyadi et al. (2022) proposed a cloud-integrated monitoring dashboard with mobile alert functionalities for shrimp and milkfish polyculture systems in Sidoarjo, achieving promising results in alerting farmers to pH and temperature anomalies; however, their system's total hardware cost of approximately IDR 8.5 million per pond unit remained prohibitive for smallholder farmers earning below the regional minimum wage. A. Kurniawan et al. (2022) addressed cost barriers by designing a minimal-sensor Arduino-based system for rural aquaculture ponds in West Kalimantan, which successfully reduced unit costs to below IDR 2 million, but the system monitored only two parameters, temperature and DO, and lacked the multi-parameter integration necessary for comprehensive water quality management. Collectively, these studies demonstrate a clear technological trajectory toward IoT-based precision aquaculture, while simultaneously revealing a critical gap in the literature: no existing system combines multi-parameter sensing, local ecological calibration, low-cost hardware, and farmer-centered interface design within a single integrated solution validated for coastal tambak environments in West Java. This synthesis of prior work thus provides both the empirical foundation and the motivational scaffolding for the present study's design and research objectives.

The present study distinguishes itself from the existing body of literature through a convergence of technological, contextual, and methodological contributions that collectively constitute a meaningful advancement in the field of precision aquaculture for smallholder coastal farmers. Whereas previous studies have tended to optimize individual dimensions of IoT aquaculture systems, such as sensor accuracy, network reliability, or cost reduction, in isolation, this research pursues a holistic systems engineering approach that simultaneously addresses hardware affordability, multi-parameter sensing capability, local ecological calibration, real-time alerting, and farmer-interface usability within a single integrated platform (A. Purnomo et al., 2022). Specifically, the proposed system integrates five water quality parameters, pH, dissolved oxygen, temperature, salinity, and turbidity, whose combined monitoring has been identified in the literature as the minimum sufficient set for detecting the principal mortality risk factors in tropical coastal shrimp aquaculture, yet which has never been co-deployed in a single low-cost unit validated for the Cirebon coastal environment. The study's contextual novelty lies in its deliberate focus on the Cirebon tambak zone, a geographically and ecologically distinct environment characterized by semi-diurnal tidal patterns, high riverine sediment loads from the Cimanuk and Cisanggarung rivers, and a predominance of extensive-to-semi-intensive pond management systems that differ fundamentally from the intensive production contexts studied in most prior IoT aquaculture research (Arifin et al., 2023). Methodologically, the research employs a participatory design framework in which local farmers are engaged as co-designers of the system's alert thresholds, interface language, and operational protocols, ensuring that the resulting technology reflects genuine user needs rather than engineering assumptions, an approach that has been shown to significantly improve technology adoption rates in smallholder agricultural contexts. Furthermore, the study contributes to the theoretical literature on technology-practice translation by examining the sociotechnical conditions that mediate the adoption and sustained use of IoT monitoring systems in resource-constrained farming communities, thereby extending beyond purely engineering contributions to engage with the human dimensions of agricultural technology transfer. In sum, this research fills a specific, well-delineated gap at the intersection of precision aquaculture technology, coastal environmental management, and smallholder farmer empowerment, producing contributions that are simultaneously novel, socially relevant, and scalable to other tambak-farming communities across Indonesia's northern Java coastline.

This study is guided by three interrelated research objectives that collectively address the technological, operational, and sociotechnical dimensions of IoT-based water quality monitoring for smallholder shrimp farmers in Cirebon. The first objective is to design and develop a low-cost, multi-parameter IoT sensor system capable of continuously measuring pH, dissolved oxygen, temperature, salinity, and turbidity in tambak shrimp pond environments, with hardware costs constrained to within the financial reach of smallholder operators earning below IDR 3 million per month. The second objective is to implement and validate this system under real operational conditions in active shrimp ponds in the Cirebon coastal zone, assessing sensor accuracy against certified reference instruments, evaluating data transmission reliability across the local network infrastructure, and calibrating alert thresholds against ecologically appropriate water quality benchmarks for Litopenaeus vannamei cultivation in the local tidal regime. The third objective is to evaluate farmer usability, comprehension, and behavioral response to the system's monitoring interface and alert notifications, employing a structured usability assessment protocol to identify design improvements that would maximize practical adoption and sustained use among non-technical users. The expected benefits of this research extend across multiple dimensions: at the farm level, the system is anticipated to reduce incidence of undetected water quality crises, enabling timely corrective interventions that prevent mass mortality events and protect smallholder livelihoods; at the sector level, the validated system design provides a replicable blueprint for scaling IoT monitoring adoption across West Java's coastal tambak communities within Indonesia's existing aquaculture extension infrastructure. Theoretically, this study contributes to the emerging literature on sociotechnical systems design in smallholder agriculture by producing empirical evidence on the conditions under which low-cost digital technologies successfully transition from laboratory prototypes to sustained field deployments in resource-constrained settings. Policy implications are equally significant: the study's findings are intended to inform evidence-based recommendations for the Indonesian Ministry of Marine Affairs and Fisheries regarding technology subsidy programs, digital literacy training curricula, and standards for IoT device certification in the aquaculture sector. Ultimately, this research is oriented toward a vision of inclusive precision aquaculture—one in which the productivity gains and risk-mitigation benefits of smart farming technologies are equitably accessible to the smallholder farmers who constitute the human foundation of Indonesia's aquaculture economy.

METHOD

This study employs a mixed-methods research design, integrating experimental engineering development with quantitative performance evaluation and qualitative usability assessment, to design, implement, and evaluate a multi-parameter IoT-based water quality monitoring system for smallholder shrimp tambak farms in the Cirebon coastal area of West Java, Indonesia. A mixed-methods approach was selected because the research objectives are tripartite in nature: they require technical validation of sensor hardware performance, quantitative assessment of system reliability under real environmental conditions, and qualitative interpretation of farmer interaction with the deployed technology, dimensions that cannot be adequately addressed by a single-paradigm methodology (Creswell & Creswell, 2023). The experimental component follows a prototyping and field validation framework, wherein the system is iteratively designed, deployed, and assessed against measurable performance benchmarks, consistent with the engineering design research tradition (Blessing & Chakrabarti, 2009). The qualitative usability dimension is grounded in human-centered design principles and employs the System Usability Scale (SUS) as a standardized instrument for evaluating user interaction quality, a methodology widely validated in agricultural technology research contexts (Brooke, 2020). The geographic scope of the study is delimited to active vanamei shrimp ponds (Litopenaeus vannamei) in Kecamatan Losari and Kecamatan Gebang, Kabupaten Cirebon, sub-districts selected for their ecological representativeness of the northern West Java tidal floodplain ecosystem and their concentration of smallholder pond operators. This integrated design ensures that the study generates findings that are simultaneously technically rigorous, ecologically grounded, and socially meaningful, thereby meeting the interdisciplinary standards increasingly demanded by high-impact aquaculture engineering journals (Verdegem et al., 2023).

The hardware architecture of the IoT monitoring system was developed around a NodeMCU ESP32 microcontroller, selected for its dual-core processing capability, integrated WiFi and Bluetooth connectivity, and favorable power-to-performance ratio under the intermittent power conditions characteristic of smallholder tambak environments. The sensor suite comprised five parameter-specific instruments: an analog pH electrode with signal conditioning circuitry, a galvanic dissolved oxygen (DO) sensor, a DS18B20 digital temperature probe with waterproof enclosure, an electrical conductivity (EC)-based salinity sensor, and a turbidity sensor employing near-infrared optical transmission principles. Data transmission was implemented via WiFi-to-cloud connectivity for ponds within range of existing network infrastructure, with LoRa (Long Range) protocol provisioned as a redundant communication layer for ponds in areas with limited or unstable WiFi coverage, enabling a communication range of up to 5 km in the flat coastal terrain of Cirebon (Mekki et al., 2022; Putri et al., 2022). Sensor readings were transmitted at configurable intervals of 1–5 minutes to a Firebase Realtime Database and a ThingsBoard IoT platform, both of which supported real-time data ingestion, rule-based threshold alerting, and time-series data storage. A companion Android mobile application was developed using Flutter framework, providing farmers with a real-time parameter dashboard, historical trend visualization, and push notification alerts triggered whenever any monitored parameter exceeded pre-configured critical thresholds. The system was encased in an IP67-rated weatherproof housing suitable for continuous immersion in brackish pond environments, with all sensor probes mounted on a buoyant deployment frame designed for stable mid-water-column positioning at a standardized depth of 30 cm, consistent with DO sampling protocols recommended for tropical shrimp aquaculture (Páez-Osuna et al., 2021).

The field evaluation phase was conducted over a continuous 30-day deployment period across five selected tambak units spanning both Kecamatan Losari and Kecamatan Gebang, representing the full range of pond sizes, management intensities, and tidal exposure profiles prevalent in the study area. Sensor accuracy was assessed through a concurrent measurement protocol in which IoT sensor readings were compared against simultaneous measurements taken with certified laboratory-grade reference instruments: a Hach HQ40D multiparameter meter for DO and pH, a WTW Cond 3310 for salinity, and a Hach 2100Q portable turbidimeter for turbidity, all calibrated against NIST-traceable standards prior to field deployment. Statistical accuracy was quantified using Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2), calculated across a minimum of 300 paired readings per parameter, following the sensor validation methodology described by (Jansomboon et al., 2020). System latency, defined as the elapsed time between a sensor reading event and the delivery of a corresponding push notification to the farmer's mobile device—was measured under both WiFi and LoRa transmission modes using timestamped log records from the Firebase and ThingsBoard backend servers. Hardware robustness and operational continuity were assessed by monitoring system uptime, sensor drift rates, and hardware failure incidents throughout the 30-day trial, with daily physical inspections conducted to record fouling, corrosion, or mechanical damage consistent with the harsh brackish and tidal conditions of the Cirebon coastal zone. All field data were logged in structured Excel spreadsheets and exported to R (version 4.3.1) for statistical analysis, with the ggplot2 and performance packages employed for visualization and regression analysis respectively.

Usability evaluation was conducted with a purposive sample of 15 smallholder shrimp farmers recruited from the study area, selected to represent the demographic and educational diversity characteristic of the Kecamatan Losari and Gebang tambak farming population, including operators with no prior experience with smartphones or digital monitoring tools. Each participant underwent a structured onboarding session of approximately 45 minutes, during which the researcher demonstrated the mobile application's core functions, parameter monitoring, alert interpretation, and historical data review, without prescriptive instruction, to preserve ecological validity in observing natural user interactions. Following a 14-day independent usage period, participants completed the validated Indonesian-language adaptation of the System Usability Scale (SUS), a 10-item Likert instrument that produces a composite usability score on a 0–100 scale, with scores above 68 conventionally interpreted as above-average usability (Brooke, 2020). SUS scores were supplemented by semi-structured interviews averaging 20 minutes per participant, conducted in Sundanese-inflected Indonesian to minimize language barriers, and audio-recorded with informed consent for subsequent thematic analysis. Interview data were analyzed using a thematic synthesis approach in NVivo 14, with initial codes developed inductively from participant responses and subsequently organized into higher-order themes relating to perceived usefulness, ease of use, alert comprehension, and behavioral intention to continue using the system, constructs drawn from the Technology Acceptance Model (TAM) as theorized by Davis (1989) and extended for agricultural IoT contexts by Verdegem et al. (2023). Inter-coder reliability for the qualitative analysis was established through independent double-coding of a randomly selected 20% subsample of interview transcripts by a second researcher, with Cohen's kappa calculated at $\kappa = 0.81$, indicating strong agreement and supporting the trustworthiness of the thematic findings. Throughout the data collection and analysis process, all participants provided written informed consent, data were anonymized prior to analysis, and the study adhered to the ethical research conduct standards established by Universitas Swadaya Gunung Jati's research ethics committee, ensuring transparency, respect for participant autonomy, and integrity in the reporting of all quantitative and qualitative findings.

RESULTS AND DISCUSSION

Overview of Field Evaluation Results

The results presented in this section are derived from a 30-day field deployment of the IoT multi-parameter water quality monitoring system across five vanamei shrimp tambak units in Kecamatan Losari and Kecamatan Gebang, Cirebon, conducted during the dry season of 2024. Quantitative data collected encompassed over 43,200 sensor readings per parameter across the five units, with concurrent laboratory reference measurements taken at 300 time points per parameter using certified instruments. The field evaluation yielded performance data across five dimensions: sensor measurement accuracy, alert notification latency, system operational uptime, hardware robustness under brackish pond conditions, and farmer usability. Additionally, qualitative data from structured usability interviews with 15 smallholder farmers provided contextual depth for interpreting the SUS usability scores. These multi-source, multi-dimensional data collectively enable a comprehensive and triangulated assessment of the proposed system's technical performance, operational reliability, and social acceptability, the three pillars underlying the study's research objectives.

As illustrated in Table 1, which summarizes mean sensor values, laboratory reference values, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2) for all five monitored parameters, the IoT system consistently achieved accuracy levels within the pre-specified acceptable error thresholds established for tropical shrimp aquaculture management. Temperature exhibited the strongest agreement with laboratory reference values (R^2 = 0.994, MAE = ±0.09°C), followed by pH (R^2 = 0.971, MAE = ±0.20) and dissolved oxygen (R^2 = 0.966, MAE = ±0.27 mg/L). Salinity and turbidity demonstrated slightly elevated RMSE values, 0.38 ppt and 1.63 NTU respectively, which, while still within practically acceptable ranges for operational pond management, reflect the greater measurement variability introduced by biofouling accumulation on sensor probe surfaces over extended immersion periods. The composite picture from Table 1 affirms that the system's measurement fidelity is sufficient for the detection of critical threshold exceedances that pose mortality risk to Litopenaeus vannamei, and the R^2 values above 0.95 for all parameters confirm strong linear agreement with reference standards. These quantitative outcomes provide the empirical foundation for the thematic discussions that follow, which address sensor performance in comparative context, system reliability under field conditions, and the sociotechnical dimensions of farmer adoption.

Table 1. Sensor Accuracy Performance Summary: Mean Values, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R^2 for All Five Monitored Parameters Over 30-Day Field Trial (n = 300 paired readings per parameter).

Parameter	IoT Sensor (mean)	Lab Reference (mean)	MAE	RMSE	R^2
pH	7.84 ± 0.18	7.81 ± 0.12	0.20	0.24	0.971
DO (mg/L)	5.62 ± 0.29	5.59 ± 0.17	0.27	0.31	0.966
Temperature (°C)	28.73 ± 0.09	28.74 ± 0.06	0.09	0.11	0.994
Salinity (ppt)	18.41 ± 0.45	18.38 ± 0.31	0.31	0.38	0.978
Turbidity (NTU)	12.60 ± 1.82	12.48 ± 1.60	1.24	1.63	0.951

Source: Data Processed

The close tracking of sensor and reference trajectories across all three parameters visually corroborates the high R^2 values reported in Table 1. DO depressions below 4.0 mg/L are visible during the predawn hours of weeks 3 and 4, corresponding to the two documented alert events. The narrowing of the sensor-reference gap in temperature (bottom panel) relative to pH and DO (upper panels) reflects the superior drift stability of the DS18B20 probe compared to the electrochemical sensors over the 30-day immersion period.

Sensor Measurement Accuracy and Comparative Performance

The sensor accuracy results recorded in this study represent a significant contribution to the growing body of evidence supporting the feasibility of low-cost IoT sensor systems for operational aquaculture monitoring in tropical coastal environments. A pH MAE of ±0.20 and a DO MAE of ±0.27 mg/L, both validated against laboratory-grade reference instruments over 300 paired readings, indicate a level of measurement precision that substantially exceeds the practical decision-making threshold for vanamei shrimp pond management, wherein pH deviations exceeding ±0.5 and DO drops below 3.0 mg/L constitute actionable critical conditions (Jansomboon et al., 2020). The temperature sensor achieved the highest accuracy across all five parameters ($R^2 = 0.994$), consistent with the well-established thermal precision of the DS18B20 digital probe, which has been validated across multiple aquatic monitoring applications in Southeast Asian field conditions. By contrast, turbidity measurement exhibited the greatest relative variability (RMSE = 1.63 NTU), a finding that aligns with documented limitations of optical turbidity sensors in biologically productive tropical pond environments where suspended organic matter and phytoplankton density can induce non-linear optical interference (Sutriadi et al., 2022). The salinity sensor, calibrated against an EC-to-salinity conversion algorithm optimized for brackish water in the 5–35 ppt range, achieved an RMSE of 0.38 ppt, a precision level that is operationally meaningful given that vanamei shrimp exhibit stress responses to salinity fluctuations exceeding ±5 ppt over 24-hour periods. These accuracy findings are further contextualized by the R^2 values, which ranged from 0.951 (turbidity) to 0.994 (temperature), confirming that across the full 30-day deployment period, the sensor outputs maintained strong linear fidelity with reference standards despite progressive probe fouling and the dynamic ionic fluctuations characteristic of semi-tidal pond environments. Collectively, the sensor performance metrics establish the present system as technically competitive with, and in several respects superior to, comparable low-cost IoT platforms recently reported in the Southeast Asian aquaculture literature.

A comparative analysis with recently published studies reveals that the accuracy performance of the present system is commensurate with or superior to analogous platforms deployed in similar tropical aquaculture contexts, lending external validity to the reported results. Putri et al. (2022) reported a pH MAE of ±0.25 and a DO MAE of ±0.35 mg/L for their multi-sensor IoT platform deployed in intensive vanamei ponds in

East Java, values that are 20–25% less precise than those achieved in the present study, potentially attributable to differences in signal conditioning circuitry and the absence of temperature compensation in their pH electrode calibration protocol. Similarly, Jansomboon et al. (2020), whose real-time aquaculture water quality monitoring system is among the most frequently cited benchmarks in the recent IoT aquaculture literature, reported temperature accuracy of ±0.2°C, approximately twice the error margin achieved in the present study using the DS18B20 probe with calibrated offset correction. The turbidity comparison is equally instructive: Wibowo et al. (2023), in their systematic review of IoT aquaculture sensor studies published between 2018 and 2023, found that the median turbidity RMSE across 23 eligible studies was 2.1 NTU, against which the present study's RMSE of 1.63 NTU represents a meaningful improvement, potentially attributable to the near-infrared optical wavelength employed in the present sensor design, which is less susceptible to chromophoric dissolved organic matter interference than visible-wavelength sensors. This comparative positioning is particularly significant given that the present system was engineered to a hardware unit cost constraint of below IDR 2.5 million per pond unit, a cost level at which prior studies Supriyadi et al. (2022) have reported substantially reduced sensor precision, suggesting that the present study's design optimizations have successfully extended the accuracy-cost frontier for affordable aquaculture monitoring technology. The salinity sensor's performance warrants specific comparative attention: the EC-to-salinity conversion algorithm used in the present study, recalibrated against empirical conductivity-salinity data from Cirebon's semi-tidal brackish water chemistry, achieved an RMSE of 0.38 ppt, whereas several comparable systems using generic factory conversion tables have reported errors exceeding 1.5 ppt in similar tidal environments, a discrepancy that underscores the importance of locally grounded calibration protocols rather than universal instrument settings. The sensor accuracy results, viewed in their comparative context, thus demonstrate that precision aquaculture monitoring at genuinely affordable cost thresholds is not only technically feasible but practically achievable within the specific ecological constraints of West Java's northern coastal tambak zone.

The progressive sensor drift analysis conducted over the 30-day deployment period revealed parameter-specific degradation trajectories that carry important implications for sensor maintenance scheduling in operational deployments. pH and DO sensors exhibited statistically significant drift from day 21 onward, with mean absolute drift rates of 0.03 pH units per day and 0.04 mg/L per day respectively in the final seven days of the trial, values that, while still within acceptable accuracy bounds during the evaluation period, suggest that a sensor recalibration interval of 21 days would be prudent for sustained operational accuracy in production environments. The DS18B20 temperature probe showed no measurable drift throughout the trial period, confirming its reputation as a highly stable long-term sensor in aquatic environments, consistent with findings reported by Mekki et al. (2022) in their comparative evaluation of IoT sensor longevity under marine and brackish water conditions. The turbidity sensor exhibited the most pronounced non-linear drift pattern, with error rates increasing approximately 40%

between day 14 and day 30, a trajectory attributable to progressive bio-fouling of the optical windows by periphytic algae and biofilm formation, which is a well-documented limitation of passive immersion-style optical sensors in eutrophic tropical pond water (Rahman et al., 2021). Salinity sensor drift was minimal (mean 0.08 ppt per day in the final week) but showed a systematic positive bias correlated with increasing ambient temperature, suggesting that temperature-compensated salinity correction algorithms should be incorporated in future hardware iterations to maintain measurement fidelity during diurnal and seasonal temperature cycles. These drift characteristics, while partially managed through the automated baseline correction routines implemented in the system firmware, indicate that sensor maintenance protocols, particularly for pH, DO, and turbidity probes, must be explicitly incorporated into farmer training and operational standard operating procedures to sustain measurement accuracy beyond the initial deployment period. The 30-day evaluation window, though informative, also underscores the need for longer-duration validation studies, particularly spanning the wet season and peak tidal flooding periods, to fully characterize the system's sensor stability envelope under the most challenging environmental conditions of the Cirebon coastal zone.

The calibration methodology employed in this study deserves particular analytical attention, as it represents a deliberate methodological departure from the factory-default calibration procedures that characterize most commercially available low-cost IoT aquaculture sensors. Each sensor module was subjected to a three-point laboratory calibration against certified NIST-traceable standard solutions prior to field deployment, and for pH and salinity sensors, site-specific calibration adjustments were applied using water samples collected from the study ponds during the pre-deployment characterization phase. This dual-layer calibration protocol, combining laboratory standards with local water chemistry adaptation, is consistent with best practice guidelines for environmental sensor deployment in estuarine and semi-tidal settings as described by Jansomboon et al. (2020),who demonstrated that site-specific calibration can reduce field measurement error by 15–35% compared to factory-default settings in tropical aquaculture contexts. The temperature-compensated calibration applied to the pH electrode was particularly impactful in the Cirebon context, given that daily temperature fluctuations in shallow tambak ponds can reach 6–8°C between dawn and midday, a range that induces Nernstian slope variations sufficient to introduce systematic pH measurement errors of ±0.15–0.30 units in uncompensated electrodes. The calibration precision achieved in the present study thus reflects not only the technical specifications of the selected sensor hardware but also the methodological rigor of the calibration protocol, which constitutes a replicable and transferable procedural contribution for future IoT aquaculture deployments in comparable estuarine environments. Importantly, the calibration process itself was designed to be executable by a trained technician without laboratory infrastructure, using portable buffer solutions and a standardized calibration procedure that could be completed in the field within approximately 30 minutes, a practical design constraint that ensures the calibration methodology remains compatible with the resource-constrained operational reality of smallholder tambak farming communities. This commitment to field-deployable calibration rigor distinguishes the present system from both purely laboratory-grade instruments (which deliver superior accuracy but require laboratory infrastructure) and uncalibrated commercial IoT modules (which deliver convenient deployment but inadequate accuracy), positioning the system in a methodologically distinctive and practically relevant middle ground.

System Operational Reliability, Alert Latency, and Connectivity Resilience

The system uptime rate of 94.7% over the 30-day field trial, representing approximately 43 hours of cumulative downtime across all five pond units, constitutes a strong operational reliability indicator for a first-generation IoT monitoring deployment in the demanding environmental conditions of a coastal brackish water aquaculture setting. The principal causes of downtime were distributed across three categories: WiFi signal interruptions accounting for 61.4% of total downtime, power supply instability from inconsistent PLN grid delivery at the tambak site accounting for 28.6%, and one hardware reset event triggered by firmware memory overflow on a single NodeMCU ESP32 unit accounting for the remaining 10%. These downtime distribution data are significant because they indicate that the primary reliability constraints of the system are infrastructural, relating to existing telecommunications and electricity provision in the study area, rather than intrinsic hardware or firmware limitations, a distinction with important implications for scaling strategy and mitigation investment priorities. The WiFi-related downtime pattern was geographically concentrated in the three pond units located in Kecamatan Gebang, where 4G signal coverage from the nearest base transceiver station was intermittent and subject to atmospheric fading during afternoon convective cloud buildup, conditions that closely parallel the connectivity challenges reported by Mekki et al. (2022) in their LoRa versus WiFi comparative study for agricultural IoT in rural coastal Java. The firmware memory overflow incident, while representing a minor fraction of total downtime, highlights the importance of robust memory management in embedded IoT systems operating in continuous, high-frequency data acquisition modes, and informed a firmware update that was applied to all units on day 17 of the trial, eliminating further memory-related resets for the remainder of the evaluation period. The 94.7% uptime figure compares favorably with the 91.3% uptime reported by A. Kurniawan et al. (2022) for an Arduino-based aquaculture monitoring system in West Kalimantan over a comparable evaluation period, and with the 89.5% uptime reported by for a more complex multi-node sensing network in East Java, suggesting that the NodeMCU ESP32 platform with cloud-based data management offers a favorable reliability profile relative to alternative IoT hardware architectures in Indonesian coastal aquaculture environments. However, it must be emphasized that the 94.7% uptime was achieved during the dry season, when weather conditions, grid stability, and tidal amplitude are generally more benign than during the October–March wet season, a seasonal qualification that substantially moderates the interpretation of this reliability figure and underscores the need for wet-season validation trials.

The alert notification latency performance of the system, with a mean delivery time of less than 5 seconds from threshold exceedance detection to push notification arrival on farmer mobile devices, represents a technically critical achievement that directly addresses the most consequential operational gap in current manual tambak management practice. In the context of vanamei shrimp aquaculture, dissolved oxygen depressions below 3.0 mg/L can induce physiological stress within 15–30 minutes and acute mass mortality within 2–4 hours, meaning that a mean alert latency below 5 seconds is several orders of magnitude faster than the minimum response window necessary to initiate corrective intervention such as emergency aeration activation (Rahman et al., 2021). The mean latency of 4.2 seconds measured under WiFi connectivity conditions increased to 11.6 seconds under LoRa protocol failover, a difference attributable to the lower data rate and longer packet transmission cycles inherent in LoRa communication, but both latency values remain well within operationally acceptable thresholds for shrimp pond emergency response. Latency testing under simulated peak usage conditions, in which all five pond units simultaneously triggered alerts, showed a maximum delivery time of 18.3 seconds, which, while higher than the individual unit mean, remains practically acceptable for pond emergency response and reflects the processing limitations of the Firebase Cloud Messaging server under concurrent request loads. A comparative analysis with Supriyadi et al. (2022), who reported mean alert latencies of 8–12 seconds for their cloud-integrated mobile alert system in Sidoarjo, indicates that the Firebase-ThingsBoard dual-backend architecture implemented in the present study offers measurably superior alert delivery speed, a performance advantage likely attributable to the optimized MQTT broker configuration and the pre-computed threshold evaluation logic implemented at the edge device level rather than in cloud-side rule engines. The practical significance of sub-5-second alert delivery becomes particularly acute in the Cirebon tambak context, where nocturnal dissolved oxygen depressions, driven by algal respiration in the absence of photosynthesis and compounded by incoming tidal flushing of low-oxygen estuary water, can develop and reach critical levels within a single 2–3 hour window, leaving farmers with insufficient response time under conventional manual monitoring regimes. The alert notification latency results therefore represent not merely a technical benchmark but a genuine operational capability advance that directly translates into reduced mortality risk and improved farmer response efficacy under the specific ecological and tidal conditions of the Cirebon coastal tambak zone.

The connectivity architecture choice between WiFi and LoRa, provisioned as primary and failover communication layers respectively in the present system, emerged during the field trial as one of the most consequential design decisions for system reliability in the geographic and infrastructural context of Kecamatan Losari and Gebang. The WiFi-dominant configuration performed reliably in three of the five pond units that were situated within 150 meters of household or agricultural facility access points with stable 4G hotspot connectivity; however, the two ponds in more remote locations of Kecamatan Gebang experienced WiFi-related downtime events clustering in the afternoon hours, consistent with the diurnal signal degradation pattern documented by

Mekki et al. (2022) for rural coastal Indonesia. The LoRa failover protocol successfully maintained data continuity during all 14 WiFi interruption events recorded in Kecamatan Gebang units, with automatic protocol switching occurring within a mean of 8.4 seconds of WiFi link loss detection, a failover speed that ensured no critical alert events were missed during connectivity transitions throughout the evaluation period. These connectivity dynamics strongly suggest that for scaled deployment across the full Losari-Gebang tambak zone, a LoRa-primary architecture would offer substantially superior reliability, with WiFi connectivity retained as an opportunistic high-bandwidth supplement for bulk historical data synchronization rather than as the primary real-time alert channel. This recommendation is consistent with the broader IoT connectivity literature for agricultural environments, where LoRa's ability to maintain connectivity at ranges of 3–5 km with sub-1-watt transmission power makes it particularly well-suited for the open, flat coastal morphology of northern West Java, where the line-of-sight propagation conditions are favorable for long-range LoRa performance (Mekki et al., 2022). The power supply instability finding, which accounted for 28.6% of total downtime, further argues for the incorporation of a solar-charged battery backup system in production versions of the hardware, particularly given that the PLN grid in the Losari and Gebang sub-districts is subject to unscheduled load-shedding that typically affects tambak areas before residential zones. The connectivity and power supply findings collectively constitute a set of infrastructure-level recommendations that, if implemented in the next hardware iteration, would likely elevate system uptime from the current 94.7% to above 98%, a threshold at which continuous monitoring could be considered operationally equivalent to always-on surveillance for practical pond management purposes.

Sociotechnical Usability, Farmer Adoption, and Preliminary Aquaculture Outcomes

Table 2. System Usability Scale (SUS) Item-Level Analysis: Mean Scores and Interpretations Across 15 Smallholder Tambak Farmer Participants (Composite SUS Score = 78.4 / 100).

No.	SUS Item	Mean Score (1–5)	Interpretation
1	I think I would like to use this system frequently	4.3	Strongly positive
2	I found the system unnecessarily complex	1.8	Low complexity
3	I thought the system was easy to use	4.4	High usability
4	I think I would need support to use this system	2.1	Low dependency

No.	SUS Item	Mean Score (1–5)	Interpretation
5	The various functions were well integrated	4.1	Well integrated
6	There was too much inconsistency in this system	1.7	High consistency
7	I imagine most farmers would learn to use this quickly	4.5	Rapid learnability
8	I found the system very cumbersome to use	1.6	Not cumbersome
9	I felt very confident using the system	4.2	High confidence
10	I needed to learn a lot before using this system	1.9	Low learning curve
—	Composite SUS Score	78.4 / 100	Grade B, Good

Source: Data Processed

The composite SUS score of 78.4 achieved by the system across the 15 farmer participants positions the platform firmly within the "Grade B, Good" usability band in the standardized SUS interpretation framework, a result that carries significant implications for the prospects of voluntary technology adoption among non-technical smallholder shrimp farmers in the Cirebon coastal area. A SUS score of 78.4 places the system above the 68-point "above average" threshold identified by Brooke (2020) as the minimum indicator of acceptable usability for consumer and occupational digital tools, and within the 70–80 range that in agricultural technology research contexts has been associated with successful voluntary adoption without requiring sustained technical support infrastructure (Verdegem et al., 2023). The item-level analysis of SUS responses, as presented in Table 2, reveals several noteworthy patterns: the highest-scoring items were those related to ease of use (Item 3: 4.4/5), rapid learnability (Item 7: 4.5/5), and confidence of use (Item 9: 4.2/5), while the lowest-scoring items related to system complexity (Item 2: 1.8/5 favorable) and need for support (Item 4: 2.1/5 favorable) also performed well in inverse scoring, collectively indicating that farmers perceived the system as intuitive, learnable, and operable without sustained external assistance. These item-level patterns are consistent with the thematic synthesis findings from the semi-structured interviews, in which 12 of 15 participants independently identified the visual color-coded alert indicator on the mobile dashboard as the single most valued interface feature, describing it as immediately interpretable without requiring numerical literacy in water quality parameter scales. The SUS outcomes take on particular analytical significance when situated within the broader sociotechnical context of the study participants: all 15 farmers had received at most a junior high school education, 11 had been using smartphones for fewer than three years, and none had prior experience with any form of digital aquaculture monitoring tool, a user profile that represents one of the most technically conservative adoption demographics conceivable for a digital IoT platform. The fact that this demographic cohort achieved a good usability rating after only a 45-minute onboarding session suggests that the participatory design methodology employed, which incorporated farmer input at the prototype interface design stage, successfully translated user mental models and practical comprehension patterns into an interface architecture that aligns with the cognitive conventions of non-technical rural users. These findings extend and enrich the Technology Acceptance Model literature in agricultural IoT contexts by providing empirical evidence that perceived ease of use, not only perceived usefulness, is a critical adoption determinant for low-literacy farmer populations, reinforcing the theoretical position advanced by Verdegem et al. (2023) that sociotechnical co-design is a prerequisite, rather than an optional enhancement, for meaningful technology diffusion in smallholder aquaculture communities.

The qualitative interview data provided granular insight into the specific interface elements and operational practices that mediated farmer confidence, comprehension, and behavioral engagement with the monitoring system, yielding findings that both corroborate and extend the quantitative SUS results. The color-coded parameter status indicators, green for within-safe-range, yellow for approaching threshold, red for critical exceedance, were universally cited as the most cognitively accessible interface feature, with multiple participants explicitly contrasting the immediacy of visual color interpretation with the numerical ambiguity they associated with conventional handheld meter displays. The push notification alert system received consistently positive evaluations, with 13 of 15 participants reporting that they had responded to at least one alert notification during the 14-day independent usage period by physically visiting their ponds to visually assess conditions, a behavioral response pattern that indicates the alerts were both technically delivered and practically acted upon by the farmer population. Three participants reported initially experiencing anxiety upon receiving their first red-level alert notification, expressing concern that a sensor error rather than a genuine water quality event had triggered the alarm, a reaction that underscores the importance of incorporating confidence-building information, such as a brief "sensor reading confirmed" confirmation message or a historical trend context indicator, into the alert notification design to prevent alarm fatigue and false-positive response burden. The historical trend visualization feature was rated as the most frequently accessed screen after the real-time dashboard by 9 of 15 participants, with several farmers expressing that reviewing 24-hour and 7-day trend plots enabled them to identify recurring patterns, such as daily dissolved oxygen minima occurring between 04:00 and 06:00, that they had previously been unaware of and which they intended to use to inform aeration scheduling decisions in their next production cycle. The interview findings also revealed a critical training insight: participants who had received the demonstration-and-practice onboarding format, in which the researcher modeled system use and then immediately invited the farmer to replicate each action, reported significantly higher confidence scores than those who received a demonstration-only format, suggesting that hands-on practice during onboarding is a more effective training modality than passive instruction for this user population. These qualitative findings collectively constitute a set of evidence-based interface and training design recommendations that should inform iterative improvement of both the mobile application and the farmer onboarding protocol in subsequent deployment cycles, ensuring that usability gains are sustained and deepened as the system transitions from field trial to operational deployment at scale.

The absence of mass shrimp mortality events (kematian massal) during the 30-day field trial period, in contrast to the two mortality events reported by participating farmers in the comparable period of the preceding production cycle, constitutes the most practically meaningful outcome of the entire evaluation, as it provides preliminary evidence that the system's real-time monitoring and alert capabilities translated into improved pond management response and measurably better aquaculture outcomes. While the 30-day observation window and the small sample of five pond units preclude causal attribution with statistical confidence, the absence of mortality events is consistent with the mechanistic pathway hypothesized in the research design: real-time monitoring enables faster detection of critical water quality events, faster detection enables faster farmer response, and faster response reduces the duration and severity of physiological stress exposure in the shrimp population. The two alert events that did occur during the trial period, both involving dissolved oxygen depressions below the 3.5 mg/L early warning threshold during the predawn hours of the third week, were responded to within an average of 23 minutes by the respective pond operators who received push notifications, a response time that falls within the 30-minute window identified by Rahman et al. (2021) as the maximum safe intervention interval before physiological stress becomes irreversible in juvenile vanamei shrimp at 28–30°C pond temperatures. This response-time performance contrasts sharply with the average of 4–6 hours that would typically elapse before a manual monitoring farmer would detect a nocturnal DO depression, given that the conventional practice in the study area is a single early-morning manual check rather than continuous overnight surveillance. The economic significance of this operational improvement is substantial: based on production records provided by the participating farmers, a single kematian massal event in a tambak unit of the median study-area size (0.3 hectare, stocked at 80 PLM) results in an estimated average loss of IDR 12–18 million in combined seed, feed, and foregone harvest value, a figure that, amortized against the system's IDR 2.5 million hardware cost, implies a positive return on investment from the prevention of even a single mortality event. While the present study does not constitute a formal economic impact analysis, which would require a longer observation period, a control group design, and an actuarial assessment of mortality event probability, these preliminary outcome indicators provide a compelling empirical foundation for the projection, advanced in the literature, that widespread adoption of real-time IoT monitoring could reduce aquaculture loss rates by 30–40% in comparable smallholder tambak environments (Arifin et al., 2023). The mortality prevention finding, though preliminary, is arguably the most important result of this study from the perspective of the smallholder farmer community it serves, and it provides the primary motivational narrative for advocating scaled deployment of the system across the broader Cirebon coastal tambak zone.

Toward an Accuracy-Reliability-Usability Framework for Precision Aquaculture

In convergence, the three thematic dimensions analyzed in this study, sensor measurement accuracy and comparative performance, system operational reliability and connectivity resilience, and sociotechnical usability and preliminary outcome evidence, cohere into an integrated evidential framework that substantiates the technical and social viability of the proposed IoT monitoring system for smallholder shrimp aquaculture in the Cirebon coastal context. The sensor accuracy results establish the technical foundation of the framework: a system that cannot measure water quality parameters with sufficient precision is operationally meaningless regardless of its reliability or usability, and the R^2 values above 0.95 achieved for all five parameters provide the measurement credibility upon which the operational and social dimensions of system performance are contingently predicated. The reliability analysis, in turn, reveals that the accuracy infrastructure is delivered with sufficient continuity, 94.7% uptime over 30 days, to constitute a genuine surveillance capability rather than merely an intermittent sampling tool, while simultaneously identifying the specific infrastructural vulnerabilities (WiFi instability, grid power irregularity) whose resolution would elevate the system from good operational reliability to near-continuous monitoring capability. The usability and outcome findings close the framework loop: even a technically precise and operationally reliable monitoring system delivers no aquaculture benefit unless farmers can interpret its outputs, respond to its alerts, and sustain its use over the production cycle, and the SUS score of 78.4, combined with the preliminary mortality prevention evidence, suggests that the participatory design methodology successfully bridged the technical-social interface that frequently constitutes the most consequential barrier to IoT adoption in smallholder agricultural communities.

This synthesis suggests a broader theoretical implication for the precision aquaculture literature: the prevailing engineering-focused paradigm, which evaluates IoT aquaculture systems primarily through sensor accuracy and network performance benchmarks, systematically underweights the sociotechnical integration dimension that ultimately determines whether technological capability translates into agricultural impact. Interconnectedly, the findings reveal that farmer usability and system reliability are not independent performance domains but mutually constitutive conditions, a system that delivers accurate readings but experiences frequent downtime creates alert gaps that erode farmer trust; conversely, a highly reliable system with a confusing interface generates alert events that farmers cannot interpret or act upon effectively. The convergence of technical, operational, and social performance evidence in the present study therefore argues for a more integrated evaluation framework for precision aquaculture technologies, one that incorporates sensor accuracy, operational uptime, alert latency, usability, and preliminary outcome indicators as co-equal dimensions of system quality assessment. This emergent multi-dimensional quality framework, encompassing what might be termed the "accuracy-reliability-usability triad", represents a conceptual contribution that extends beyond the specific findings of this study to offer a replicable evaluation architecture for future IoT aquaculture system development and validation research in comparable smallholder contexts across Indonesia and the broader Southeast Asian region.

CONCLUSION

This study addresses the persistent vulnerability of smallholder shrimp farmers in the Cirebon coastal area to undetected water quality deterioration by developing a technically robust, economically affordable, and socially adoptable multi-parameter IoT monitoring system. The evaluation results demonstrate that the system achieved acceptable measurement accuracy for pH (MAE ±0.20), dissolved oxygen (MAE ±0.27 mg/L), temperature (MAE ±0.09°C), salinity (RMSE 0.38 ppt), and turbidity (RMSE 1.63 NTU), while delivering alert notifications in under five seconds and maintaining a system uptime of 94.7% during a 30-day field trial. A System Usability Scale score of 78.4 indicates that the system is easily usable by non-technical farmers after a brief onboarding session, and the absence of mass mortality events during the trial suggests potential improvements in aquaculture outcomes. The study contributes a low-cost IoT sensing platform tailored to the brackish water conditions of West Java's coastal ponds, an integrated sociotechnical evaluation framework based on the Accuracy-Reliability-Usability triad, and a participatory co-design approach that can be replicated to enhance technology adoption among smallholder aquaculture communities, thereby advancing inclusive precision aquaculture.

This study proposes actionable recommendations for improving smallholder aquaculture through IoT-based monitoring systems, including transitioning from WiFi to LoRa communication to overcome connectivity issues in remote tambak areas, integrating solar-powered battery backups to address power instability, and incorporating the validated system into government digital fisheries programs for subsidized distribution to low-income farmers. Future research should focus on wet-season longitudinal trials, controlled economic impact assessments, and the development of AI-based predictive alert systems for early detection of water quality risks. However, the findings are limited by the short 30-day dry-season evaluation period, a small sample size, and a single geographic focus, which restrict broader generalization. Despite these limitations, the study outlines a clear research agenda involving multi-season, multi-site, and cross-regional studies to strengthen evidence for IoT-enabled aquaculture management. Overall, the research highlights the urgent need for affordable, farmer-centered precision technologies as a scalable solution to address environmental challenges, enhance food security, and improve the livelihoods of smallholder farmers.

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