

Strengthening local aquaculture management in a group of Vannamei shrimp farmers through an MQTT-based early warning system for water quality monitoring

¹Nirwana Haidar Hari, ²Ahmad Khairul Umam, ³Ibnu Cipta Ramadhan, ³Taufiqurrahman, ¹Bagus Edi Fathorrasi, ²Richa Latifatin Nisa', ²Satria Utama Disawa, ¹Ainur Taufikur Rahman, ¹Moh. Khairil Anwar, ¹Faiq Muntashir, ¹Dorik Prayogik F.

¹Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Surabaya, Indonesia

²Department of Creative Multimedia Technology, Politeknik Elektronika Negeri Surabaya (PENS), Surabaya, Indonesia

³Department of Electrical Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Surabaya, Indonesia

*Corresponding author's email: nhh@pens.ac.id

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Abstract

Vannamei shrimp farming is an important source of livelihood and local food production for coastal communities, yet its productivity is highly sensitive to rapid fluctuations in pond water quality. In many small-scale and group-based ponds, monitoring is still conducted manually and intermittently, leading to delayed corrective actions and avoidable production losses. This community engagement program aimed to strengthen local aquaculture management in the Jaring Emas Vannamei shrimp farmer group in Sumenep Regency, Indonesia, through the implementation of an Internet of Things (IoT)-based Early Warning System (EWS) for real-time water quality monitoring. The program was carried out using a participatory and practice-based approach that actively involved the partner group throughout the process, from problem identification and solution design to system installation, practical training, and ongoing assistance. The intervention introduced three ESP32-based IoT nodes equipped with pH, temperature, and dissolved oxygen (DO) sensors, supported by an MQTT communication server and integrated web and mobile applications that provided real-time dashboards, early warning alerts, and more systematic records for feeding and harvesting activities. The evaluation examined system operability, continuity of monitoring, and changes in partners' operational practices. The findings showed that the system operated continuously and enabled real-time monitoring through both web and mobile access. The partners were increasingly able to interpret data trends, understand alerts, and use this information to take corrective actions, such as adjusting aeration when DO levels declined. Operational record-keeping also became more systematic, while harvest data indicated improved outcomes after system adoption: yields increased from approximately 830–880 kg per pond with grade B quality to approximately 1,190–1,220 kg per pond with grade A quality. Overall, the program strengthened not only technical monitoring capacity but also more preventive, responsive, and data-informed pond management practices at the community level. Future programs should strengthen post-deployment mentoring and develop simple recommendations based on historical data to support sustained adoption and broader impact.

Keywords

Early Warning System; Internet of Things; MQTT; Vannamei Shrimp Farming; water quality monitoring

Abstrak

Budidaya udang Vaname merupakan sumber penghidupan yang penting sekaligus penopang produksi pangan lokal bagi masyarakat pesisir. Namun,



produktivitas budidaya ini sangat dipengaruhi oleh perubahan kualitas air tambak yang dapat terjadi secara cepat. Pada banyak tambak skala kecil dan berbasis kelompok, pemantauan kualitas air masih dilakukan secara manual dan tidak berkesinambungan, sehingga tindakan korektif sering terlambat dilakukan dan kerugian produksi yang sebenarnya dapat dicegah tetap terjadi. Program pengabdian kepada masyarakat ini bertujuan memperkuat pengelolaan akuakultur lokal pada Kelompok Pembudidaya Udang Vaname *Jaring Emas* di Kabupaten Sumenep, Indonesia, melalui penerapan Early Warning System (EWS) berbasis Internet of Things (IoT) untuk pemantauan kualitas air secara real-time. Kegiatan ini dilaksanakan dengan pendekatan partisipatif dan berbasis praktik, yang melibatkan mitra sejak tahap identifikasi permasalahan, perancangan solusi, pemasangan sistem, pelatihan langsung, hingga pendampingan lanjutan. Sistem yang diterapkan terdiri atas tiga node IoT berbasis ESP32 yang dilengkapi sensor pH, suhu, dan dissolved oxygen (DO), didukung oleh server komunikasi berbasis MQTT serta aplikasi web dan mobile yang menyediakan dashboard real-time, notifikasi peringatan dini, dan pencatatan kegiatan pakan serta panen yang lebih sistematis. Evaluasi dilakukan untuk menilai kinerja sistem di lapangan, keberlanjutan proses pemantauan, serta perubahan praktik operasional mitra setelah sistem diterapkan. Hasil menunjukkan bahwa sistem dapat beroperasi secara berkelanjutan dan memungkinkan pemantauan kondisi tambak secara real-time melalui akses web maupun mobile. Mitra juga semakin mampu membaca tren data, memahami peringatan yang muncul, dan memanfaatkan informasi tersebut untuk mengambil tindakan korektif secara lebih cepat, misalnya dengan menyesuaikan aerasi saat kadar DO menurun. Selain itu, pencatatan operasional menjadi lebih tertata, dan data panen menunjukkan adanya perbaikan setelah sistem diadopsi, yaitu dari sekitar 830–880 kg per tambak dengan kualitas grade B menjadi sekitar 1.190–1.220 kg per tambak dengan kualitas grade A. Secara keseluruhan, program ini tidak hanya memperkuat kapasitas teknis dalam pemantauan kualitas air, tetapi juga mendorong praktik pengelolaan tambak yang lebih preventif, responsif, dan berbasis data di tingkat komunitas. Ke depan, program serupa perlu didukung dengan pendampingan pascaimplementasi yang lebih kuat serta pengembangan rekomendasi sederhana berbasis data historis agar pemanfaatannya dapat berkelanjutan dan memberi dampak yang lebih luas.

Kata Kunci

Sistem Deteksi Dini; Internet of Things; MQTT; budidaya udang Vannamei; pemantauan kualitas air

1. Introduction

Vannamei shrimp farming (*Litopenaeus Vannamei*) is one of Indonesia's leading aquaculture commodities and contributes to food security and coastal livelihoods. Its high economic value, relatively short production cycle, and stable market demand make it attractive for small-scale and community-based producers. However, productivity is highly dependent on pond water quality, particularly pH, temperature, and dissolved oxygen (DO), which fluctuate rapidly and are sensitive to environmental changes (Albab et al., 2025).

In practice, many smallholder farmers and community groups still rely on manual measurements and experiential judgment to monitor water quality. This approach is limited because it does not provide continuous, real-time data, requires physical presence at the pond site, and increases the risk of delayed corrective action when sudden changes occur. Evidence from prior work indicates that late responses to water quality deterioration can elevate shrimp stress, increase mortality, and reduce harvest yields (Ahmed et al., 2024; Shete et al., 2024).

Digital technologies, especially the Internet of Things (IoT), offer a practical pathway to address these constraints. IoT enables the integration of environmental sensors, microcontrollers, and data communication to support automated and continuous monitoring. In aquaculture contexts, IoT adoption has been reported to improve operational efficiency, enhance environmental monitoring accuracy, and support data-driven decision-making (Hari & Darmawan, 2023; Rachmatullah et al., 2023). A key application is an Early Warning System (EWS), which generates alerts when monitored parameters move beyond safe thresholds, enabling preventive interventions rather than reactive responses.

Despite this potential, technology adoption in community-based aquaculture often faces barriers beyond hardware availability. Common constraints include limited digital literacy,

insufficient operational skills, and weak sustainability after external assistance ends. Prior community programs emphasize that failures in adoption are frequently associated with technology-centered approaches that do not adequately incorporate empowerment processes, capacity building, and ongoing mentoring (Ningsih, 2024; Rachmatsyah, 2025). From a community engagement perspective, this aligns with the principle that sustainable innovation diffusion requires meaningful participation, co-ownership, and iterative learning, rather than one-time technology transfer (Supriyono & Bahrudin, 2024; Yulian et al., 2022).

Previous studies have shown the relevance of digital monitoring and web-based management tools in aquaculture. For example, (Rachmatullah et al., 2023) developed a web-based feed management and water-quality monitoring system for Vannamei Shrimp farming, demonstrating the usefulness of digital records and online monitoring for farm operations. Other recent studies, such as (Mohd Jais et al., 2024) and (Shete et al., 2024), highlighted the effectiveness of IoT-based real-time monitoring for improving responsiveness to water-quality changes in aquaculture settings. However, most of these works primarily emphasize technical system performance, while less attention is given to community engagement aspects such as participatory adoption, hands-on training, and continuous mentoring in small-scale farmer groups. Therefore, the present program is positioned not only as a technology implementation initiative but as a participatory community engagement effort to strengthen local aquaculture management through real-time monitoring, early warning, and improved operational practices in a farmer-group setting.

These challenges were also identified in the partner community, *Kelompok Usaha Tambak Udang Vaname "Jaring Emas"* in Sumenep Regency, a coastal small-scale aquaculture group whose daily production activities contribute to local food supply and household livelihoods. As a farmer group operating in a coastal setting with limited access to continuous digital monitoring and structured farm-management tools, the partners still relied on manual and intermittent water-quality checks. Preliminary observations and group discussions showed that water quality management had not yet been integrated into a unified monitoring system, and the group did not have accessible real-time dashboards or systematic feed and harvest records. As a result, decisions related to aeration, water exchange, and feeding were often taken reactively after problems became visible, rather than preventively based on timely data. At the same time, the group demonstrated strong collective motivation, practical farming experience, and openness to adopting appropriate technology, making them a relevant partner community for a participatory community engagement program aimed at strengthening local aquaculture management.

Accordingly, this program adopted a participatory approach that combined an IoT-based EWS with hands-on training and continuous mentoring to strengthen adoption and sustainability. Previous community engagement initiatives suggest that integrating digital tools with direct training can improve partners' understanding of production processes and promote more adaptive work practices (Pinandhita & Susanto, 2025). To clarify the relationship between partner problems, the proposed technological solution, and the expected community-level impact, a conceptual framework is presented in Figure 1.

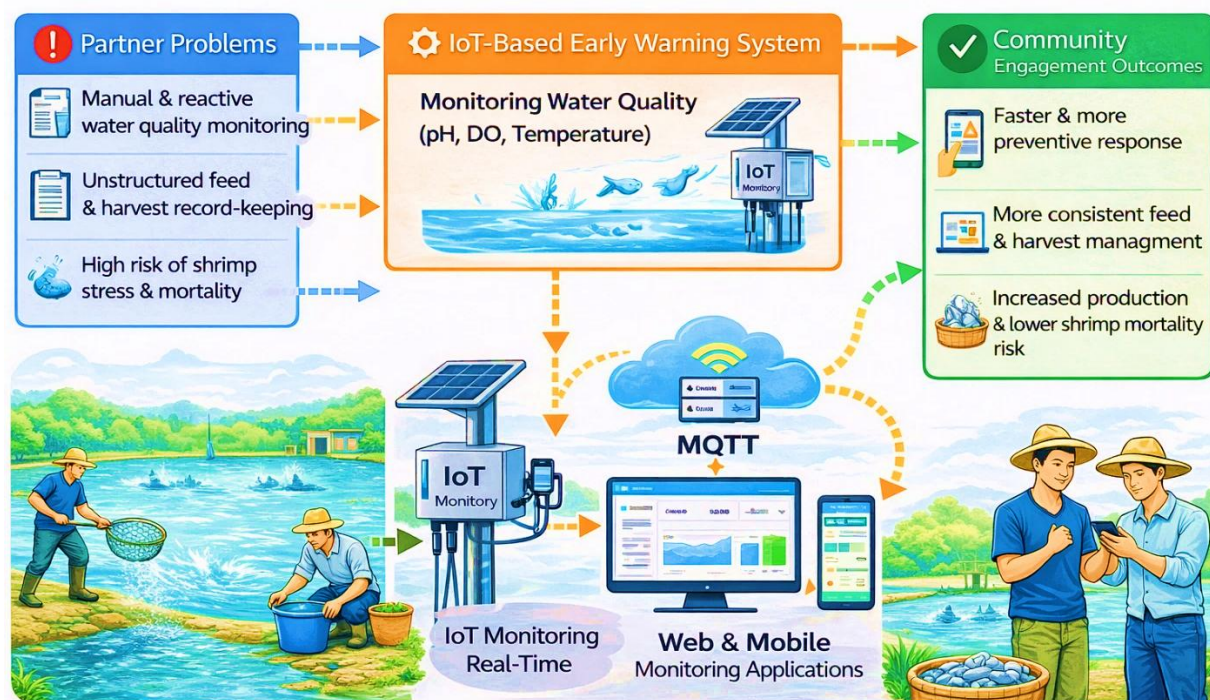


Figure 1. Conceptual Framework of Partner Problems, IoT-Based Early Warning System Solution, and Community Engagement Outcomes

The conceptual framework illustrates that the primary challenges faced by the partner group, namely limited water quality monitoring and delayed operational decision-making, are addressed through the implementation of an IoT-based Early Warning System integrated with real-time monitoring dashboards. The technological intervention is embedded within a structured program of training and continuous mentoring, enabling partners to progressively develop the capacity to operate, interpret, and utilize the system independently.

From a community engagement perspective, the framework highlights that the expected outcomes go beyond the technical installation of the system. By combining technology adoption with participatory capacity building, the program is intended to encourage changes in pond management practices, helping partners move from reactive responses toward more preventive, timely, and data-informed decision-making. Over time, these changes are expected to support shrimp farming practices that are more responsive, efficient, and sustainable at the community level.

Based on this framework, the community engagement program was developed with two main objectives: implementing the technology and strengthening human capacity. In general, the program sought to introduce an Internet of Things (IoT) based Early Warning System in Vannamei Shrimp ponds while improving the partners' ability to use digital technology in their daily operational management. More specifically, the program aimed to: (1) develop and deploy a water-quality monitoring system capable of providing real-time data on key parameters; (2) provide hands-on training and mentoring to support partners in using web and mobile-based monitoring applications; and (3) promote faster, more preventive, and data-informed decision making in aquaculture management to support the sustainability of community-based shrimp farming operations.

2. Methods

This community engagement program employed a participatory and practice-oriented approach, positioning the partner group as active co-actors throughout the program cycle. The approach was selected to increase the likelihood of technology adoption and post-program sustainability at the community level, particularly for productive-sector interventions using appropriate technology (Adila Novianti et al., 2024; Habil Cahaya Gusti et al., 2025).

2.1 Time and Site of Implementation

The program was conducted from June to November 2025 at the Vannamei Shrimp ponds operated by the *Jaring Emas* community group in Sumenep Regency, East Java Province, Indonesia. The site was selected based on (1) partners' need for more accurate and real-time water quality monitoring and (2) the group's readiness to adopt and operate a digital innovation within daily pond management.

2.2 Partner Group and Participants

The partner in this program was the *Jaring Emas* Vannamei shrimp farmer group, which consists of 15 active members. The participants involved in the program included group leaders, pond operators, and other members who are directly engaged in daily aquaculture activities. Their involvement was directed toward key operational aspects, including decision-making, water-quality monitoring, and routine pond management practices such as aeration and feeding adjustments. This arrangement was intended to ensure that the intervention remained closely aligned with the partners' actual work patterns and existing responsibilities.

2.3 Program Stages and Community Participation

Implementation followed a structured sequence to ensure alignment between the developed solution and partners' practical needs. The main stages are summarized in Table 1.

Table 1. Stages of the Community Engagement Program

Stage	Description of Activities
Problem identification	Field observation and joint discussions with partners regarding existing pond conditions and management practices
Solution design	Co-design of an IoT-based Early Warning System (EWS) tailored to partners' requirements
Technology deployment	Device assembly, system configuration, and on-site installation
Partner training	Hands-on training on web-mobile monitoring dashboards and early warning notifications
Mentoring and evaluation	Ongoing operational mentoring and evaluation of system use and practice change

These stages were intentionally arranged to ensure that the program did not focus solely on technology installation but also on strengthening partners' capacity to operate and sustain the system independently over time.

2.4 System Design and Technology Deployment

The technical solution was an Internet of Things (IoT)-based Early Warning System (EWS) for monitoring key pond water quality parameters: pH, temperature, and dissolved oxygen (DO). The system used ESP32 microcontrollers as sensor nodes, environmental sensors, and Message Queuing Telemetry Transport (MQTT) for periodic data transmission to a server. MQTT was selected due to its lightweight protocol design, bandwidth efficiency, and suitability for environments with limited or unstable connectivity, such as coastal pond areas (D'ortona et al., 2022; Putri & Tjenreng, 2025).

Data transmitted by IoT nodes was stored and visualized in real-time through integrated web- and mobile-based dashboards. In addition to monitoring, the web application included record-keeping features for feeding and harvesting to support more structured daily operations. The overall workflow of the IoT-based EWS is illustrated in Figure 2.

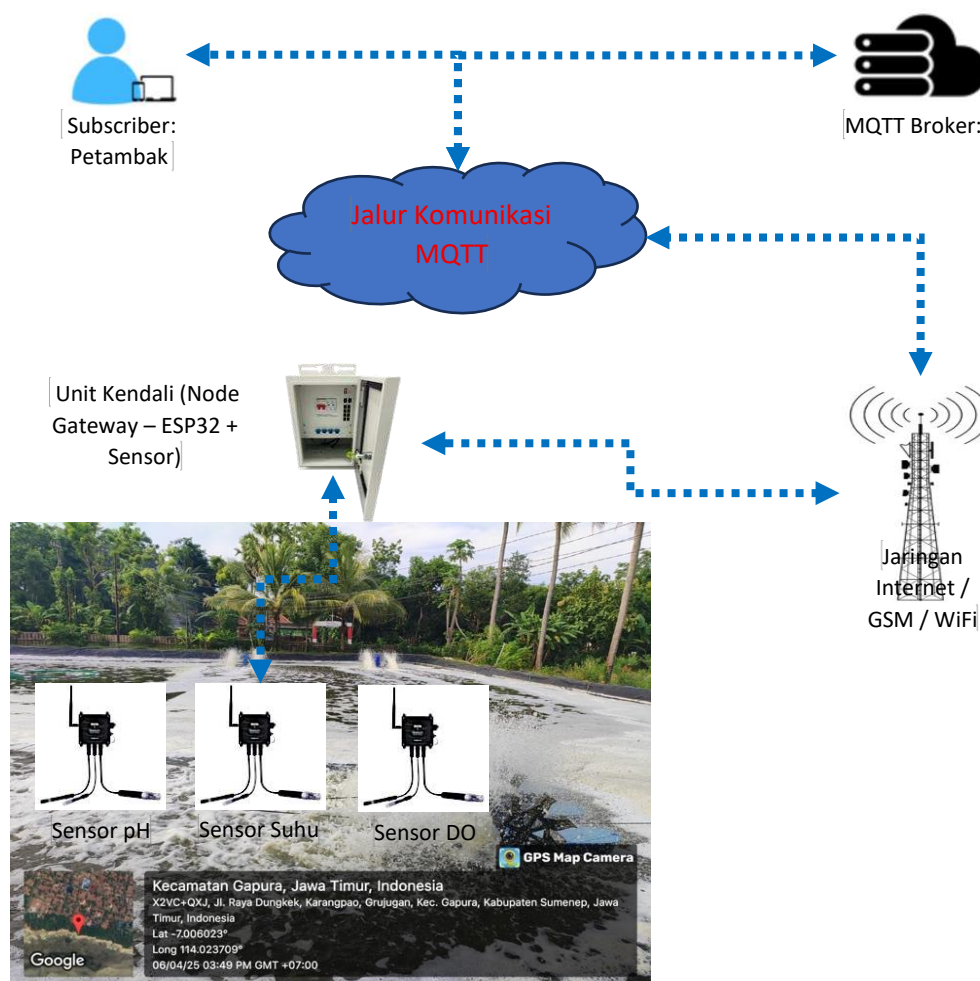


Figure 2. Architecture of the IoT-Based Early Warning System for Pond Water Quality Monitoring
Source: Program Documentation (2025)

The system architecture depicts end-to-end data flow from sensors to IoT nodes, the MQTT server, and web-mobile dashboards. Through this configuration, partners can monitor pond conditions in real time and receive early warnings when parameter values exceed predefined thresholds aligned with Vannamei shrimp farming standards (Ahmed et al., 2024; Herrera et al., 2025).

2.5 Training and Continuous Mentoring

Partner training was delivered using a hands-on method to ensure participants could operationalize the system rather than only understand concepts. Training content covered EWS principles, interpretation of dashboard indicators and trend graphs, and recommended actions when early warning notifications appear. Continuous mentoring was provided throughout the implementation process to help partners address both technical and non-technical issues, including connectivity problems, adaptation to new work habits, and the consistent use of the system in daily practice. This practice-based learning process is in line with previous findings suggesting that experiential learning tends to be more effective than lecture-based instruction alone in strengthening technical skills at the community level. (Dwi et al., 2024; Selvester Thadeus et al., 2023).

2.6 Evaluation Design and Outcome Measures

Evaluation applied descriptive qualitative and quantitative approaches using field observation, semi-structured partner interviews, and analysis of system usage records. Key evaluation aspects included: (1) level of system utilization by partners, (2) perceived usability

of the web-mobile applications, and (3) changes in operational decision-making patterns for pond water quality management. This mixed descriptive approach is commonly used in technology-based community engagement programs to capture both direct implementation outcomes and practice changes experienced by the partner community (Putro et al., 2024; Sonjaya et al., 2025).

3. Results and Discussion

This section presents the results of the community engagement program involving the implementation of an Internet of Things (IoT)-based Early Warning System (EWS) in Vannamei Shrimp ponds and discusses its implications for partners' capacity building and pond management practices. The discussion focuses on the program's main outputs-IoT devices, an MQTT-based communication server, and web-mobile monitoring applications-as well as changes in partners' operational behavior and production outcomes as indicators of technology-based community engagement success (Ahmed et al., 2024; Rachmatullah et al., 2023).

3.1 Implementation of the IoT-Based EWS at the Partner Site

The implementation results indicate that the IoT-based EWS was successfully installed and operated at the partner ponds using three ESP32-based IoT nodes equipped with water quality sensors (pH, temperature, and dissolved oxygen/DO) and protective casings suitable for pond environments. The devices performed periodic data acquisition and transmitted measurements to the server using the Message Queuing Telemetry Transport (MQTT) protocol.

The use of MQTT was appropriate for pond-area network conditions, which are often unstable, because the protocol is lightweight, bandwidth-efficient, and capable of maintaining data continuity during connectivity fluctuations (Albab et al., 2025; Shete et al., 2024). This architecture enabled continuous water quality data provision, forming a reliable basis for monitoring and operational decision-making by the partner group.

To summarize the system configuration and its operational roles, the main components and functions are presented in Table 2.

Table 2. IoT-Based EWS Components and Operational Functions

System Component	Program Implementation	Main Function
IoT devices (3 nodes)	ESP32 nodes with pH, temperature, and DO sensors plus protective casing	Periodic water quality data acquisition and transmission
MQTT VPS server	MQTT broker with backend services	Receiving data from nodes, maintaining connections, and distributing data to applications
Mobile monitoring application	Application access with an admin account	Real-time monitoring via smartphone and early warning notifications
Web monitoring and management application	Web access with admin account	Real-time monitoring and structured feed and harvest records

These results demonstrate that program outputs extended beyond hardware installation to form an integrated information ecosystem encompassing data acquisition, communication, and end-user utilization. Such integration is critical because EWS effectiveness in shrimp farming depends heavily on data continuity and ease of access for farmers (Albab et al., 2025).

3.2 Data Visualization and Web-Mobile Monitoring Access

Following installation, water quality data were visualized through web and mobile based monitoring dashboards using numerical indicators and historical trend graphs. Real-time visualization enabled partners to interpret current pond conditions and observe parameter dynamics over time, reducing reliance on sporadic and reactive manual measurements.

During the mentoring period, partners actively used the dashboards particularly to monitor DO and temperature fluctuations during nighttime and early morning, which are critical periods in Vannamei Shrimp culture. Mobile access allowed remote monitoring without requiring physical presence at the pond, enabling faster responses to potential risks. Simple and intuitive visualization was also a key factor supporting community-level technology adoption, as the system could be used immediately without high cognitive burden (Amirkhanov et al., 2025; Satra et al., 2024). Dashboard views and examples of early warning notifications are presented in Figure 3.

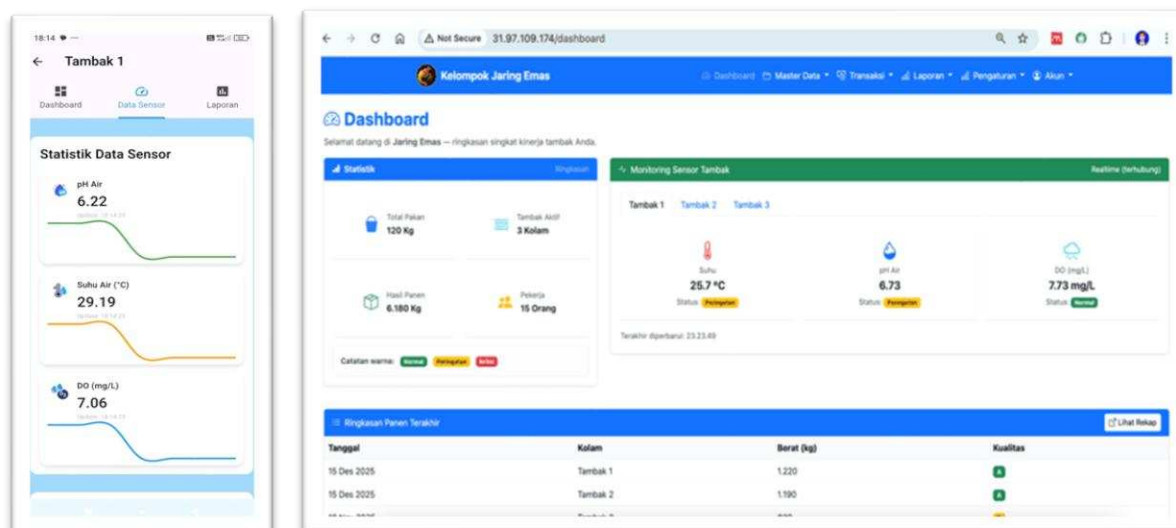


Figure 3. Web-Mobile Dashboard for Pond Water Quality Monitoring and Examples of Early Warning Notifications

Source: Program Documentation (2025)

3.3 Effectiveness of the Early Warning Mechanism in Operational Decision-Making

The EWS operated through predefined threshold values for water quality parameters that triggered early warnings when measurements deviated from optimal ranges. Based on observation and mentoring, partners began using these alerts as a basis for corrective actions, such as increasing aeration during DO declines or adjusting operational practices when pH values shifted from ideal conditions. This shift reflects a transition from intuition- and experience-based management toward data-driven pond management. Faster responses to water quality changes align with modern aquaculture management principles emphasizing preventive actions to reduce shrimp stress and mortality and to maintain productivity stability (Albab et al., 2025; Nurlaili et al., 2025). From a community engagement standpoint, increased responsiveness indicates that the technology was not merely installed but functionally understood and utilized by partners (Putri & Tjenreng, 2025).

3.4 Integration of Feed and Harvest Management through the Web Application

Beyond water quality monitoring, the program outputs included a web-based application featuring feed and harvest record-keeping. During mentoring, partners used these features to document operational activities more consistently, including planned and realized feeding schedules and harvest data by period.

Harvest records entered in the application showed clear differences before and after the adoption of the IoT-based EWS and management application. Before implementation, harvest outcomes were generally recorded as grade B, with yields ranging from approximately 830 to 880 kg per pond. After the monitoring system and management application were put into use, later harvests indicated better results, with quality improving to grade A and yields increasing to around 1,190 to 1,220 kg per pond, along with higher estimated revenue (Figure 4). These findings reinforce that integrating water quality monitoring with structured operational records supports more systematic evaluation and decision-making in shrimp farming.

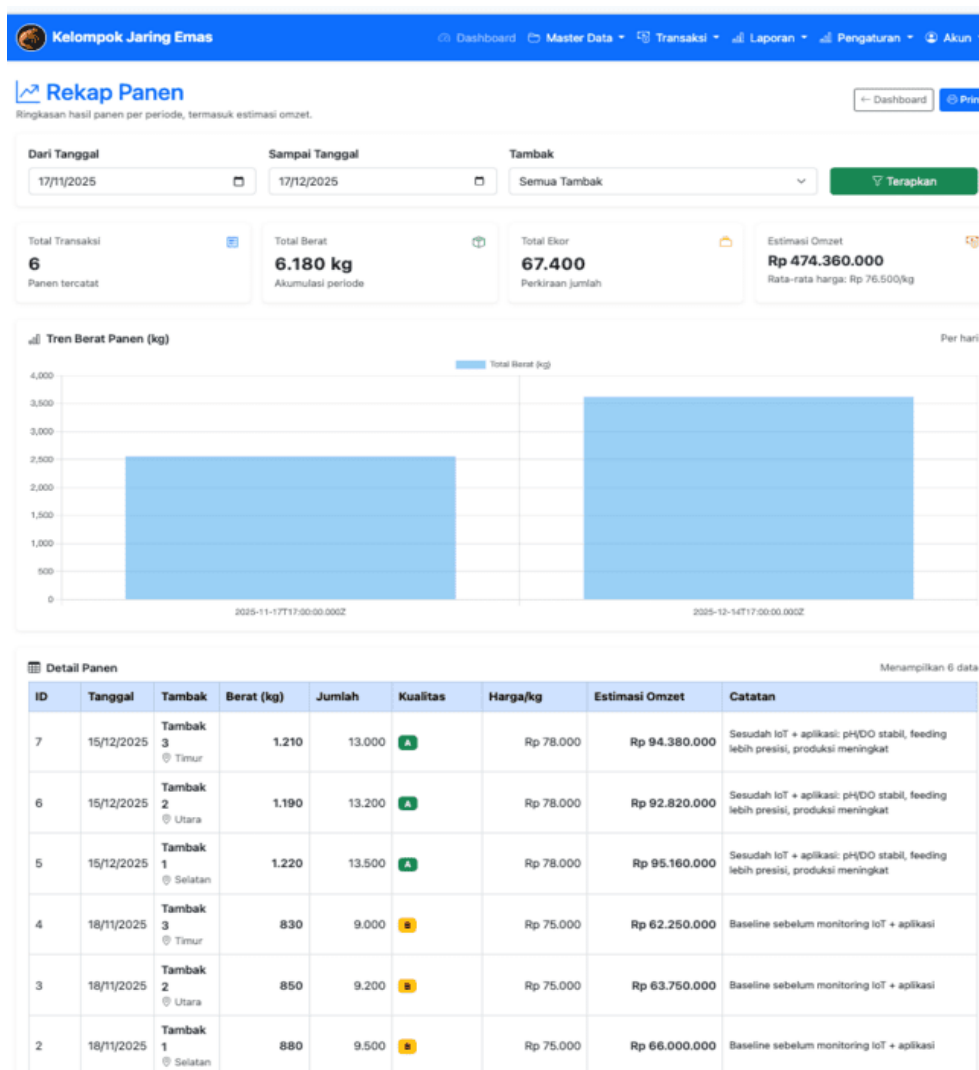


Figure 4. Harvest Records in the Pond Management Application (Baseline vs. Post-IoT-Based EWS Implementation)

The integration of monitoring and record-keeping strengthened the system's role as a pond management support tool rather than merely a measurement instrument. This approach is consistent with evidence that digital transformation in small-scale enterprises is more effective when technology directly supports core business processes and daily work routines (Ningsih, 2024; Sonjaya et al., 2025).

3.5 Capacity Building through Training and Continuous Mentoring

Training and mentoring activities produced tangible improvements in partners' digital literacy, particularly in interpreting water quality graphs, understanding early warning notifications, and determining appropriate corrective actions. Training emphasized hands-on practice using real data, trend graphs, and notifications within the monitoring application, enabling partners to apply the system directly to daily operations (Figure 5). Partners also demonstrated increased independence in accessing dashboards via web and mobile platforms without intensive assistance.



Figure 5. Partner Training and Mentoring Activities on Interpreting Water quality Data and Using the Mobile Monitoring Application

Changes in partner conditions before and after the program are summarized in Table 3.

Table 3. Partner Conditions Before and After IoT-Based EWS Implementation

Aspect	Before the Program	After the Program
Water quality monitoring	Manual and periodic	Real-time via web and mobile
Information access	Limited to pond location	Remote access available
Response pattern	Predominantly reactive	More preventive with early warnings
Feed and harvest records	Unstructured	More systematic via web application
Digital literacy	Low-moderate	Improved (independent operation)

These results indicate that program impacts extended beyond technological outputs to include changes in work practices and partner capacity. Conceptually, this reflects the effectiveness of participatory and practice-based engagement approaches that position community members as active users rather than passive recipients of technology (Supriyono & Bahrudin, 2024; Yulian et al., 2022).

3.6 Implementation Challenges and Sustainability Implications

Key challenges encountered during implementation were related to network stability in pond areas and partners' initial adaptation to digital applications. Even under less-than-ideal network conditions, the use of MQTT helped maintain stable data exchange (Amirkhanov et al., 2025; Cho & Noh, 2024). The sustainability of the program was further supported by involving partners throughout the entire process, from problem identification to evaluation, which helped

build a sense of ownership over the system. This is in line with empowerment-based community engagement approaches, which suggest that lasting adoption is more likely when solutions are developed collaboratively and tailored to local needs and conditions. (Ningsih, 2024; Rachmatsyah, 2025).

Overall, the findings demonstrate that implementing an IoT-based EWS integrated with an MQTT server, web-mobile monitoring, and feed-harvest management can enhance responsiveness, capacity, and management quality in community-based Vannamei Shrimp farming. These results strengthen the argument that technology-driven community engagement programs should integrate technical innovation with empowerment strategies to achieve tangible and sustainable impact.

4. Conclusion

This community engagement program showed that the implementation of an Internet of Things (IoT)-based Early Warning System (EWS) helped strengthen local aquaculture management in the partner group's Vannamei Shrimp ponds. The program achieved its main targets through the deployment and use of three active IoT sensor nodes, a stable MQTT-based communication server, and integrated web-mobile monitoring applications that supported daily pond management activities. The results also indicated improved partner capacity to interpret water-quality data, understand early warning notifications, and respond more quickly to changing pond conditions.

Beyond technical deployment, the program contributed to meaningful changes in operational practice. Partners gradually reduced their reliance on manual measurements and intuition and began using real-time information as a basis for decisions related to aeration, water-quality control, and routine pond management. This suggests that integrating real-time monitoring with early warning mechanisms can support more preventive, responsive, and data-driven management in community-based aquaculture settings. The impact of the program, therefore, was not limited to system functionality, but also extended to changes in how partners recognized risks and acted upon operational information.

Another important contribution of the program was the strengthening of partners' digital literacy and practical capacity. Through this participatory approach, partners were engaged not merely as end users of the technology but as active contributors throughout the adoption process through training and continuous mentoring. This suggests that the intervention was not only technically workable but also well-suited to the needs and conditions of the partner community, thereby supporting the prospect of continued use beyond the formal program period.

Overall, the program suggests that combining an IoT-based early warning system, accessible web and mobile applications, and participatory mentoring can provide an effective model for community engagement in strengthening water-quality monitoring and day-to-day management in small-scale shrimp farming groups. With appropriate adaptation to local conditions and scale, this model may also be applied to other community-based aquaculture groups facing similar challenges.

Future programs should provide more sustained post-deployment mentoring to help partners overcome early adoption challenges, particularly those related to work routines, connectivity constraints, and differing levels of digital literacy among group members. In addition, the system could be further developed by using historical data to generate simple operational suggestions, such as guidance on aeration patterns or feeding schedules, while still keeping the application easy for users to operate. Wider impact may also be achieved by involving additional farmer groups and strengthening collaboration with fisheries extension officers and local government so that technology adoption is supported by a broader ecosystem for data-driven aquaculture management.

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Authors' Information

Nirwana Haidar Hari is a lecturer and researcher at the Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His work focuses on applied Internet of Things (IoT) solutions, embedded data communication, and the development of web-mobile platforms for monitoring and decision support in community-based productive sectors, including aquaculture.

Email: nhh@pens.ac.id; ORCID  <https://orcid.org/0009-0009-3113-6916>

Ahmad Khairul Umam is a faculty member in the Department of Creative Multimedia Technology, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His interests include user-centered design, web and mobile application development, and digital learning media to support technology adoption and community capacity building.

Email: akumam@pens.ac.id; ORCID  <https://orcid.org/0000-0003-2061-4926>

Ibnu Cipta Ramadhan is affiliated with the Department of Electrical Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His expertise includes embedded systems, sensor instrumentation, and field deployment of electronic systems for environmental monitoring and IoT-based applications.

Email: ibnu.ramadhan@pens.ac.id; ORCID  <https://orcid.org/0009-0008-6147-752X>

Taufiqurrahman is a faculty member in the Department of Electrical Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His research interests include IoT device engineering, system integration, and communication reliability for remote monitoring systems in real-world settings.

Email: taufiq@pens.ac.id

Bagus Edi Fathorrasi is a laboratory staff member (laboran) at the Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His work supports applied computing and IoT laboratory activities, including system prototyping, device preparation, and technical assistance for field deployment in community-based technology programs.

Email: bagus_ef@staff.pens.ac.id

Richa Latifatin Nisa' is a Diploma-3 (D3) student in the Department of Creative Multimedia Technology, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. Her interests include UI/UX design, digital content development, and multimedia-based communication materials to support user adoption and training for applied web–mobile and IoT monitoring systems.

Email: richalatifatinnisa@mb.student.pens.ac.id

Satria Utama Disawa is a Diploma-3 (D3) student in the Department of Creative Multimedia Technology, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His interests include interface prototyping, dashboard visualization, and the development of interactive learning media to support dissemination and user training for community-oriented technology deployments.

Email: triaaz@mb.student.pens.ac.id

Ainur Taufikur Rahman is a Diploma-3 (D3) student in the Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His interests include web application development, IoT data integration, and backend services for real-time monitoring and decision-support platforms in field-oriented implementations.

Email: ainurtaufikurrahman@it.student.pens.ac.id

Moh. Khairil Anwar is a Diploma-3 (D3) student in the Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His interests include database implementation, system feature development, and data workflow

integration for operational monitoring applications and community-based deployments.
Email: khairil@it.student.pens.ac.id

Faiq Muntashir is a Diploma-3 (D3) student in the Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His interests include mobile application development, real-time data presentation, and usability-oriented implementation for monitoring dashboards and notification features in applied IoT systems.
Email: faiqmuntashir@it.student.pens.ac.id

Dorik Prayogik F. is a Diploma-3 (D3) student in the Department of Informatics and Computer Engineering, Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. His interests include system testing, deployment support, and technical documentation for field implementation of IoT-based monitoring platforms, with an emphasis on reliability and maintainability.
Email: dorikprayogii@it.student.pens.ac.id

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