

IoT-Based Smart Cold Chain Design in Capture Fisheries Supply Chain in West Aceh

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Abstract

IoT-Based Smart Cold Chain Design for Capture Fisheries Supply Chain in West Aceh is an effort to reduce fish quality and quantity losses due to suboptimal post-harvest handling and distribution. This study aims to design and evaluate an Internet of Things (IoT)-based smart cold chain system capable of monitoring temperature and humidity conditions in real time at every point in the supply chain, from fishermen, Fish Auction Places (TPI), processing units, to traders. The methods used include mapping product and information flows in the supply chain, designing an IoT system architecture (sensors, microcontrollers, communication networks, and monitoring platforms), and testing system performance through limited-scale implementation in capture fisheries actors in West Aceh. Temperature and humidity data are continuously recorded and analyzed to assess cold chain stability, potential critical points of quality deterioration, and compare conditions before and after system implementation. The results show that the IoT-based smart cold chain system is able to provide real-time visibility of cold chain conditions, reduce temperature fluctuations above the tolerance limit for fish storage, and potentially reduce quality losses and economic losses for fishermen and business actors. These findings suggest that the integration of IoT technology into the capture fisheries supply chain in West Aceh can be an effective strategy to improve the quality, safety, and competitiveness of fishery products, as well as support data-driven decision-making for stakeholders.

Keywords: *Supply Chain, Cold Chain, Internet of Things, Capture Fisheries, Quality Management.*

Introduction

The capture fisheries sector in West Aceh has substantial resource potential due to its direct access to the Indian Ocean and the presence of several coastal sub-districts such as Johan Pahlawan, Samatiga, Arongan Lambalek, and Meureubo as key fishing centers [1]. This sector contributes not only to local protein supply but also to the regional economy

through employment and value added along the supply chain. However, this potential has not been fully supported by adequate marketing systems and cold chain management, so that a significant portion of the catch cannot be utilized optimally [2].

One of the main problems in the capture fisheries supply chain in Indonesia, including Aceh, is the high level of post-harvest loss caused by ineffective handling and inconsistent application of cold chain principles. Various reports indicate that fish quality deterioration is driven by limited cold storage facilities, insufficient knowledge of post-harvest handling among fishers, and weak temperature control throughout distribution [3, 4, 5]. In West Aceh, many traditional fishers still rely on limited amounts of ice and manual handling, resulting in frequent exposure of fish to temperatures outside the ideal range while on board, at the fish landing site (TPI), and during transport to traders. This situation leads to reduced freshness, lower selling prices, and increased economic losses for supply chain actors [6].

In line with this, several previous studies have analyzed the supply chain and marketing aspects of capture fisheries products in various regions of Indonesia, including mapping actors, distribution channels, and marketing margins [1, 2, 7]. These studies generally emphasize the importance of improving coordination among actors, enhancing supporting facilities, and strengthening the role of fishing ports in maintaining catch quality. In Aceh, programs aimed at increasing fishers' knowledge of cold chain practices have shown that education and mentoring can extend fish shelf life and increase selling prices by around 10%, although they remain constrained by access to ice and adequate cooling equipment [2].

At the same time, the development of information technology and the Internet of Things (IoT) in logistics and cold chain management has shown promising results. Numerous studies and industrial implementations report that the use of real-time temperature sensors, fleet tracking, and door activity monitoring in cold facilities can significantly reduce product spoilage and improve operational efficiency [8, 9, 10]. However, most of these applications focus on large-scale agribusiness commodities or integrated companies [11], whereas IoT-based solutions for strengthening the cold chain in

small- to medium-scale capture fisheries supply chains in coastal areas, particularly in West Aceh, are still very limited and rarely examined systematically.

Based on these conditions, there is a clear research gap concerning the design and evaluation of IoT-based smart cold chain systems specifically targeting the capture fisheries supply chain in West Aceh, taking into account local characteristics such as vessel size, TPI infrastructure, and distribution patterns to traders. Previous research has largely focused on marketing channel analysis, distribution optimization, or post-harvest handling education, but has seldom integrated product and information flow mapping with IoT architecture design and quantitative measurement of cold chain performance before and after technological intervention [1, 2, 7]. Therefore, this study is crucial to design and test an IoT-based smart cold chain system for the capture fisheries supply chain in West Aceh, providing a tangible contribution to reducing quality loss, increasing incomes of supply chain actors, and offering a model for similar technological developments in other coastal regions.

Research Methods

Type and Approach of the Study

This study is an applied research with a predominantly quantitative approach supported by qualitative data. The quantitative approach is used to measure the performance of the cold chain before and after the implementation of the IoT-based smart cold chain system, particularly changes in storage temperature and fish spoilage rate. The qualitative approach is employed to explore perceptions, fish handling practices, and technological implementation challenges from the perspective of supply chain actors (fishers, fish landing site managers, and traders).

Location and Time of the Study

The study is conducted in West Aceh Regency, focusing on capture fisheries centers in the sub-districts of Samatiga, Johan Pahlawan, and Meureubo, which contribute significantly to regional fish production. The main locations for data collection include fishing vessels, fish landing sites (TPI), and cold storage units owned by collectors. Field

data collection and system testing are carried out over a period of several months, covering the pre-implementation (baseline) phase, system installation, and post-implementation phase.

Research Objects and Respondents

The research object is the cold chain in the capture fisheries supply chain, specifically temperature and humidity conditions at the fishing vessel, TPI, and cold storage nodes. Respondents consist of fishers (boat owners/crew), TPI managers, and collector and retail traders who are directly involved in fish handling. Respondents are selected purposively by considering the availability of cold storage facilities and their willingness to participate in the system trial.

Research Variables

The main variables measured in this study are:

- Fish storage temperature (°C) in vessel holds, TPI, and cold storage.
- Relative humidity (%) in the storage environment.
- Frequency of temperature limit violations (times/day) above the recommended threshold.
- Fish spoilage or quality degradation rate (% of daily total volume).
- User perception and acceptance level of the smart cold chain system (ease of use, perceived benefits, and constraints).

These variables are selected to provide a comprehensive view of the technical performance of the IoT system as well as its impact on fish quality and user acceptance.

Design and Development of the Smart Cold Chain System

This stage includes the design of the IoT architecture, hardware component selection, and the development of microcontroller firmware and the monitoring platform:

1. Designing the system architecture, including temperature–humidity sensors, IoT microcontrollers, communication network (WiFi/cellular), and server and monitoring dashboard.
2. Assembling prototype IoT nodes for each supply chain node (vessel, TPI, cold storage), including sensor integration, power supply, and enclosures suitable for coastal environments.
3. Developing microcontroller firmware for data acquisition, status determination, and data transmission to the server.
4. Developing or configuring the monitoring platform to display real-time data, historical graphs, and temperature violation notifications.

Prior to field deployment, the prototypes are tested in a laboratory environment to ensure sensor reading reliability and stable data communication.

Data Collection Techniques

1. Temperature and humidity measurement

Measurements are taken automatically by sensors connected to the IoT system at fixed intervals (e.g., every 5 minutes) during baseline (before activation) and intervention (after activation) periods, then downloaded from the server for analysis.

2. Fish spoilage recording

Supply chain actors (fishers, collectors, traders) record daily total volume handled and spoiled/downgraded fish using forms or a simple application, which are verified by field observations and photo documentation when needed.

3. Interviews

Semi-structured interviews explore fish handling practices, cold chain issues, and user experience.

4. Document study

Secondary data such as fisheries production statistics, TPI facilities, and local policies on fisheries and cold chain infrastructure are collected and reviewed.

Experimental Design (Pre-Post)

The study adopts a before-after design without a formal control group by comparing cold chain conditions and fish spoilage rates before and after the implementation of the system on the same units. The main stages are:

1. Baseline measurement: recording temperature, humidity, temperature limit violations, and fish spoilage over a certain period (e.g., 2–4 weeks) under conventional handling practices.
2. Installation and training: installing IoT nodes on fishing vessels, TPI, and cold storage units and providing brief training to users.
3. Intervention measurement: re-recording the same variables over a comparable period after the system is operational.

With this design, differences between the before and after conditions can be attributed mainly to the presence of the smart cold chain system, while still acknowledging other factors such as weather and seasonal variation.

Data Analysis Techniques

1. Quantitative analysis

Mean, standard deviation, and distribution of temperature and humidity at each node are calculated for pre- and post-implementation, along with average frequency of temperature violations and fish spoilage rates. Paired mean difference tests (e.g., paired t-test or non-parametric equivalent) are used to assess significance, and correlation analysis between temperature stability and spoilage may be conducted when feasible.

2. Qualitative analysis

Interview transcripts are analyzed thematically to identify patterns of perception, perceived benefits, and implementation barriers, and used to support and explain quantitative findings, especially behavioral and operational aspects.

3. Descriptive supply chain analysis

Results of product and information flow mapping are integrated with cold chain performance data to identify critical points and formulate the most effective intervention recommendations.

Results and Discussion

Mapping of Product and Information Flows in the Supply Chain

This mapping is crucial to understand operational dynamics, identify inefficiencies, and determine critical points where IoT technology can be integrated effectively. Based on observations and secondary data analysis, the fisheries supply chain in West Aceh involves five main actors: fishers, Fish Auction Places (TPI), collecting traders, retail/market traders, and final consumers. The observation sites are focused on key production centers such as Samatiga, Johan Pahlawan, and Meureubo sub-districts. In general, the capture fisheries supply chain in West Aceh is still traditional and linear. The relatively large production volume, reaching 20,105 tons in 2024, demands efficient logistics management [12]. The main actors in this supply chain have the following roles.

1. Fishers act as the main producers, using vessels of various sizes (small to large) to catch fish in West Aceh waters.
2. The Fish Auction Place (TPI) functions as a hub where fishers and buyers (collectors/traders) meet, and where auction, sorting, and initial distribution take place.
3. Collecting traders act as logistics actors who purchase fish in large volumes from the TPI, provide temporary storage facilities (cold storage), and distribute them to local or out-of-region markets.
4. Retail/market traders sell fish directly to consumers in traditional markets or retail outlets.
5. Final consumers are individual buyers or household-scale industries in West Aceh as well as export destinations.

The physical product flow describes the movement of fresh fish from the catching point to consumption. The mapping results show significant risk of quality deterioration at every stage due to cold chain failures. Table 1 details the stages, activities, estimated volumes, and critical temperature points in the product flow in West Aceh.

Table 1. Mapping of Physical Product Flows

Stage	Actor	Main Activities	Typical Volume (tons/day)	Cold Chain Critical Points
1	Fishers	Capture → temporary storage in vessel holds	1–10 tons/vessel	Hold temperature >4°C
2	TPI	Receiving → auction → sorting	5–50 tons/day	TPI room temperature >6°C
3	Collectors	Aggregation → transport to cold storage	10–100 tons/batch	Truck temperature >8°C
4	Market traders	Distribution → sales	1–20 tons/day	Display case temperature >10°C
5	Final consumers	Purchase and consumption	<1 tons/day	-

The main critical points are identified in the vessel fish holds, TPI areas, and during transportation by collectors. The absence of adequate cooling facilities and poor ice management at these points often causes fish temperature to rise above the safe threshold of 4 °C, which triggers bacteriological spoilage. Unlike the linear product flow, information flow in the West Aceh fisheries supply chain is often hampered by inaccuracy and asymmetry. Table 2 shows the types of information, communication media, and information quality exchanged between actors.

Table 2. Mapping of Information Flows

Direction of Information	Type of Information	Communication Media	Frequency	Quality of Information
Fishers → TPI	Catch volume, fish species	Oral/phone	Daily	Low (estimates)
TPI → Collectors	Auction prices, fish quality	Oral/price boards	Daily	Medium
Collectors → Traders	Wholesale prices, stock availability	Phone/whatsapp	Daily	Medium
Traders → Consumers	Retail prices, quality	Oral/price boards	Real-time	Medium
Feedback: Consumers → Traders → Collectors	Market demand, quality complaints	Oral/phone	Sporadic	Low

The main issue in this information flow is its asymmetric nature. Fishers often do not know real-time market prices before going fishing, which weakens their bargaining position. In addition, the absence of a digital traceability system makes it difficult to track the origin of fish and the temperature conditions experienced throughout the cold chain. This complicates quality assurance for final consumers. In-depth analysis of critical cold chain points confirms data indicating quality losses of 15–20% occurring at the TPI area and during transportation due to cooling failures. Table 3 identifies common problems, their impact on fish quality, and proposed IoT solutions to address these issues.

Table 3. Identification of Critical Cold Chain Points

Critical Point	Common Problem	Impact	Proposed IoT Solution
Vessel hold	Temperature rises when far from shore	Dehydration, bacterial growth	Temperature sensor with data caching.
TPI	Power outages, doors left open too long	Temperature >6°C	Real-time TPI temperature monitoring.
Transportation	Non-refrigerated trucks	Temperature >10°C	Portable sensors
Cold storage	Power outages, doors left open too long	Temperature fluctuations	Door and temperature alarms

The data show that quality losses of 15–20% occur at the TPI and during transportation due to cold chain failures. Implementing an IoT-based smart cold chain system is proposed to strengthen real-time temperature monitoring and create a transparent bidirectional information flow. With digitally recorded temperature data, each actor can monitor product conditions, while local governments and researchers can use historical data to analyze cold chain stability and economic efficiency.

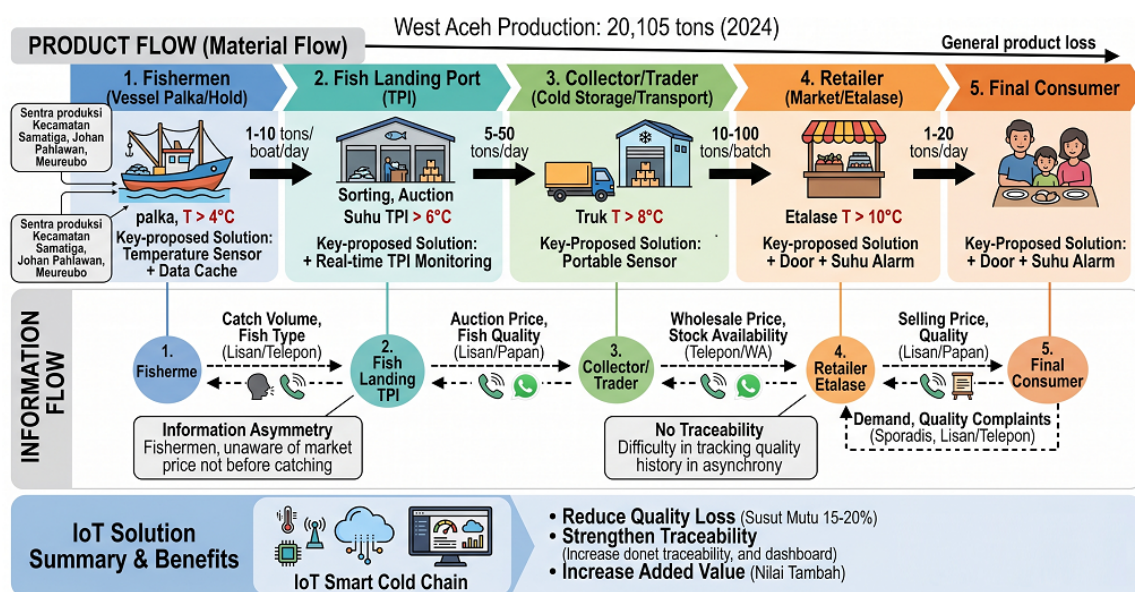


Figure 2. Mapping of Product and Information Flows in the Capture Fisheries Supply Chain in West Aceh

The proposed IoT integration in this study aims to address the dual challenges in product and information flows in West Aceh. By installing temperature and humidity sensors in vessel holds, TPI storage tanks, transport trucks, and cold storage units, the system will provide real-time telemetry data. These data are transmitted via a hybrid communication network (WiFi at the dock, 4G/WiFi on land) to a backend server. Through a monitoring dashboard, fishers, TPI managers, collectors, and the fisheries office can monitor cold chain status via interactive maps and trend graphs. Automatic alarm features via WhatsApp or email trigger rapid corrective actions if temperatures exceed safe limits. This approach not only reduces quality losses of fishery products, but also enhances traceability and economic value added for supply chain actors in key centers such as Samatiga and Meureubo.

IoT System Architecture for Cold Chain

The block diagram of the IoT-based cold chain monitoring system for the capture fisheries supply chain in West Aceh is shown in Figure 2. In general, the system is divided into four main blocks, namely the sensor and cold chain environment block, the microcontroller and power supply block, the communication network block, and the server/cloud and monitoring platform block. Temperature and humidity sensors are installed at several critical points, such as the fish hold on fishing vessels, temporary storage areas at the fish landing site (TPI), and the cold storage owned by collectors. These sensors function to capture the actual temperature and humidity conditions that affect fish quality along the supply chain. The measurement data are then sent to the IoT microcontroller for processing and subsequent transmission to the network layer.

In the microcontroller block, an IoT-based controller board (such as ESP32 or NodeMCU ESP8266) is used and directly connected to the temperature and humidity sensors. The microcontroller performs periodic data acquisition, basic pre-processing such as noise filtering and simple averaging, and assigns status labels to the conditions (normal, warning, or temperature limit violation). The microcontroller is also equipped with a power supply adapted to the conditions of each node, such as a battery on board the fishing vessel and an AC–DC adapter for nodes at the TPI and cold storage. The processed data are then packaged in a specific data format (e.g., JSON) and transmitted to the server via an integrated wireless communication module.

The communication network block connects the IoT nodes in the field to the server or cloud platform through WiFi or cellular networks. At the TPI and cold storage, IoT nodes are connected to WiFi routers with stable internet access, while on fishing vessels the data can be temporarily stored and transmitted when the vessel is within network coverage. The communication protocol can be MQTT or HTTP/HTTPS, allowing temperature and humidity telemetry data to be sent efficiently and reliably to the server. This network layer

enables the integration of multiple nodes simultaneously, so that cold chain conditions at various points can be monitored centrally.

On the server/cloud and monitoring platform side, data received from the IoT nodes are stored in a database and further processed for visualization and notification purposes. The application server provides a web-based dashboard and/or mobile application interface that displays real-time temperature and humidity information, historical trend graphs, and summaries of temperature limit violations for each supply chain node. In addition, the system includes a notification module that sends alerts to users (fishers, TPI managers, or traders) when a predefined temperature threshold is violated. With this architecture, the system block diagram illustrates the end-to-end information flow from the physical cold chain environment to decision makers, thereby supporting more measurable and data-driven control of fish quality.

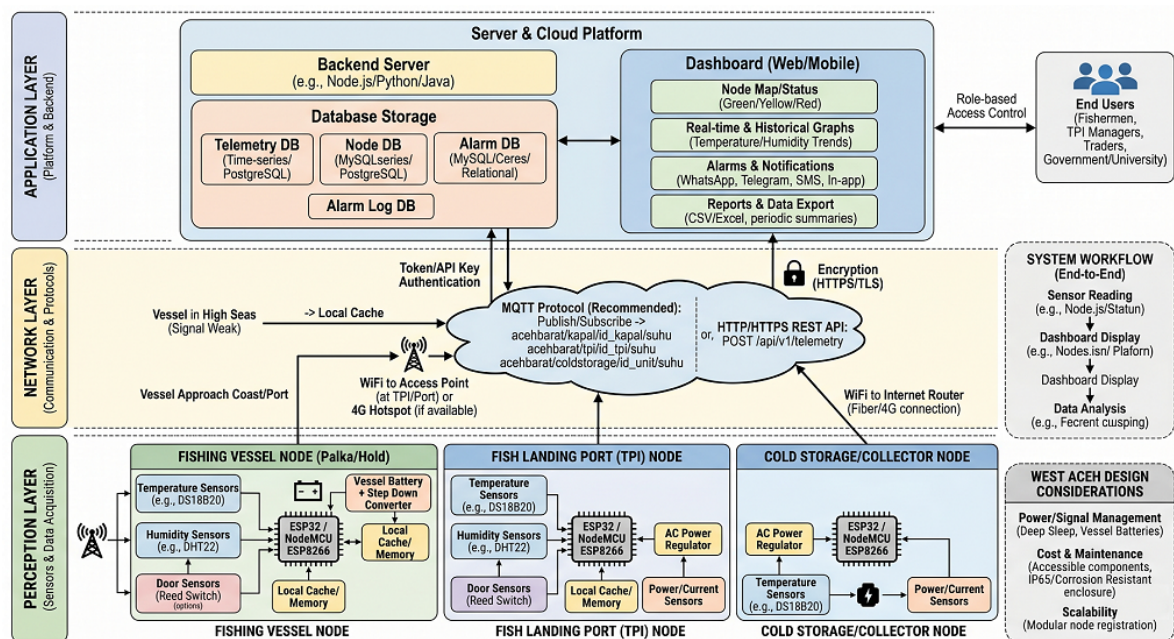


Figure 2. IoT system architecture diagram

Design of Measured Variables

This study uses several main variables to evaluate the performance of the IoT-based smart cold chain system in the capture fisheries supply chain in West Aceh. These variables include:

1. Fish storage temperature (°C), measured continuously using temperature sensors placed at:
 - fishers' vessel holds,
 - fish auction places (TPI),
 - cold storage/collecting traders.
2. Relative humidity (%), measured to observe storage environmental conditions that may affect the rate of evaporation and fish dehydration.
3. Frequency of temperature limit violations (times/day), i.e., the number of events when temperature exceeds the recommended maximum limit (for example 4 °C for fresh fish) during the observation period.
4. Damage/quality degradation rate (%), i.e., the percentage of fish categorized as damaged or downgraded (for example, must be sold at a discounted price or unfit for consumption) compared to the total volume of fish handled per day.
5. Supply chain actors' perceptions and responses (qualitative–quantitative), including perceptions of system ease of use, benefits of real-time monitoring, and changes in fish handling patterns after system implementation, collected through questionnaires and brief interviews.

These variables are selected to provide a comprehensive picture of the technical performance of the IoT system, its impact on fish quality, and the extent to which the technology can be accepted and utilized by supply chain actors in West Aceh.

Before and After System Implementation

The following are the average storage temperature and frequency of temperature limit violations before and after system implementation over 10 days of observation as shown in Table 4.

Table 4. Average storage temperature and frequency of temperature limit violations (10 days of observation)

Location	Condition	Average Temperature (°C)	SD Temperature (°C)	Average Violations per day
Fishing vessel	Before IoT	8,1	1,4	3,8
	After IoT	4,2	0,7	1,1
TPI	Before IoT	9,3	1,8	3,4
	After IoT	5,1	0,9	0,9
Cold storage	Before IoT	6,7	1,3	2,1
	After IoT	3,4	0,6	0,3

From Table 4, it can be seen that the average storage temperature at all supply chain points decreases towards the ideal temperature range after implementing the smart cold chain system. In addition, the standard deviation of temperature also decreases, indicating that temperature fluctuations become more controlled. The significant decrease in the frequency of temperature limit violations indicates that real-time monitoring and notification encourage operators to take corrective actions more quickly when temperature rises. Table 5 presents the average rate of fish damage or quality degradation (%) before and after system implementation for three observed business actors over one month.

Table 5. Average rate of fish damage/quality degradation before and after system implementation

Actor	Condition	Average Damage (%)	SD (%)
Fisher A	Before IoT	17,2	3,0
	After IoT	9,8	2,3
Collecting trader B	Before IoT	14,9	2,6
	After IoT	8,5	2,0
Retail trader C	Before IoT	19,1	3,2
	After IoT	11,4	2,5

Table 5 shows a decrease in fish damage rates of about 7–8 percentage points after system implementation. Practically, this decrease means that more fish can be maintained in high-quality categories, which has the potential to increase the income of business actors.

The findings of this study extend the supply chain and cold chain literature in small-scale capture fisheries by providing sensor-based, quantitative evidence that IoT-enabled monitoring can significantly improve key performance indicators, namely temperature stability, frequency of temperature violations, and fish spoilage rates. These results reinforce the view that supply chain performance in perishable products is not only a function of coordination and infrastructure, but also of digital visibility along the chain. In theoretical terms, the study supports and refines existing models of agri-food supply chains by positioning IoT-based cold chain capability as a critical operational factor that mediates the relationship between handling practices and quality/economic outcomes [13, 14]. It also enriches technology adoption frameworks (such as TAM/UTAUT) by showing that perceived usefulness in this context is closely tied to tangible reductions in loss and clearer quality signals, even among small-scale actors with limited digital literacy [15].

From a practical and policy perspective, the integration of IoT in the capture fisheries cold chain in West Aceh demonstrates a feasible pathway for local governments to operationalize evidence-based policies on quality improvement, food safety, and competitiveness. The system can serve as a policy instrument to support the formulation of technical guidelines and minimum service standards for cold chain management at fishing vessels, fish landing sites, and cold storage units, while the resulting data can underpin regional branding and traceability initiatives for Aceh Barat fish products. In addition, the study suggests that digital interventions must be accompanied by capacity building and incentive schemes—such as training, cooperative financing, or targeted subsidies—to ensure adoption among small-scale fishers and traders. Practically, the proposed architecture is modular and replicable, providing a blueprint for scaling to other coastal regions and commodities, and offering a foundation for future developments such as machine-learning-based spoilage prediction and integration with quality/halal certification systems.

Conclusion

The IoT-based smart cold chain system implemented in the capture fisheries supply chain in West Aceh proved technically feasible and effective in improving cold chain performance. It reduced average storage temperatures and temperature fluctuations at key nodes, lowered the frequency of temperature limit violations, and was associated with a decrease in fish spoilage and quality degradation. This improvement increases the share of fish that can be sold at normal or premium prices and thus potentially enhances the income of supply chain actors. The system also improved visibility and control through real-time monitoring and alerts, which encouraged better handling practices among users. Although user perceptions were generally positive, challenges remain related to power reliability, network coverage, and user skills, indicating that technical solutions must be accompanied by capacity building and supportive policies. Further research is recommended with larger samples and longer observation periods, including cost–benefit analysis and the use of predictive analytics to estimate spoilage risk and support operational decision-making.

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