Analysis of carbon footprint in fish cold storage using IoT-based inventory monitoring

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Abstract. Fish cold storage is a critical component for preserving product quality, yet it represents a major source of energy consumption and carbon emissions within the global fisheries supply chain. This study establishes a comprehensive four-year baseline of environmental impact by analyzing historical electricity data from 2020 to 2023 at a cold storage facility in Jakarta. This analysis revealed a cumulative carbon footprint of 396.42 tons of CO_2, providing the necessary justification for technical interventions. To address the documented inaccuracies in traditional stock recording that hinder precise emission modeling, a low-cost IoT-based instrument was developed using an ESP8266 microcontroller and a keypad–LCD interface. Field deployment conducted from July to September 2024 validated the system's operational reliability, achieving a high recording accuracy of 99.3% and a stable cloud-based data transmission success rate of 97.8%. By integrating these historical energy patterns with real-time digital inventory monitoring, this research offers a practical and scalable foundation for enhancing data transparency and energy efficiency. Such innovations are essential for supporting sustainable management and driving the digital transformation of the fisheries sector within the broader Blue Economy [*]framework.

Keywords: Cold storage, carbon footprint, Internet of Things, fish inventory monitoring, energy consumption

1 Introduction

The cold chain system is a vital component for maintaining the quality, safety, and competitiveness of fishery products in the global market. Cold storage plays an essential role in preserving fish freshness post-harvest until it reaches consumers, thereby reducing post-harvest losses and enhancing product value [1]. However, this system also contributes

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significantly to energy consumption and carbon emissions owing to its reliance on intensive refrigeration technology [2]. Life Cycle Assessment (LCA) studies have shown that the cold chain sector can contribute up to 20% of the total carbon footprint of the fisheries industry [3], highlighting the urgent need for energy management innovations that are efficient and environmentally friendly.

In Indonesia, cold storage facilities are crucial for small-scale and medium-scale fishery industries to maintain product freshness and market value. Nevertheless, limitations in energy infrastructure in many coastal regions result in high operational costs because the electricity supply remains largely dependent on fossil-based sources [4]. Previous studies have demonstrated that the integration of renewable energy systems, such as photovoltaic (PV) technology, can significantly reduce electricity costs and carbon emissions during cold storage operations [5, 6]. In addition to energy sourcing, cold storage efficiency is also strongly influenced by load management. Facilities operating below the optimal capacity may experience up to a 50% increase in specific energy consumption per ton of stored fish [7, 8], emphasizing the importance of accurate inventory management and storage duration control.

With the advancement of digital technologies, the Internet of Things (IoT) has emerged as a promising solution for enhancing cold storage performance. IoT enables real-time monitoring of operational parameters, such as temperature, humidity, and stock conditions, with data transmitted to cloud-based platforms for continuous analysis and decision support [9]. Previous studies have reported that IoT implementation can reduce energy consumption by up to 20% while improving temperature control accuracy by more than 90% [10, 11]. In addition, IoT-supported predictive maintenance and early anomaly detection contribute to reduced spoilage, improved system reliability, and lower operational inefficiencies [12]. Despite these advantages, IoT adoption in Indonesia remains constrained by infrastructure availability, initial investment costs, and user readiness, particularly in small- and medium-scale cold-storage facilities [13].

From a sustainability perspective, the concept of Green IoT has gained increasing attention, emphasizing the use of low-power devices, efficient communication protocols, and integration with renewable energy sources to minimize environmental impacts [14]. Recent studies have suggested that wireless sensor networks with energy-harvesting capabilities have strong potential for cold chain and food storage applications [15, 16]. In this context, low-cost IoT devices based on microcontrollers such as ESP8266, combined with simple human–machine interfaces such as LCD displays and keypads, offer a practical and affordable solution for inventory monitoring in Indonesian cold storage operations.

However, several critical research gaps remain in the literature. Existing studies have predominantly focused on refrigeration system efficiency or automated environmental monitoring, while accurate inventory recording and storage duration monitoring—key factors influencing energy consumption and carbon emissions— have received limited attention. Most IoT-based cold storage studies rely on automated sensor data, whereas real-time inventory monitoring based on user input and integration with cloud databases has rarely been explored. Furthermore, many previous investigations have been based on simulations or laboratory-scale experiments, resulting in a lack of empirical evidence from actual cold storage operations in Indonesia.

These limitations lead to persistent operational challenges including inaccurate carbon emission estimations, suboptimal load management, and increased energy consumption. Therefore, there is a clear need for a practical and data-driven approach that enables accurate stock monitoring and links inventory dynamics with energy use and carbon footprint assessments in real cold storage environments.

To address these gaps, this study proposes the development and deployment of a low-cost IoT-based fish stock recording instrument using an ESP8266 microcontroller equipped with a keypad–LCD interface and cloud database integration. The instrument enables real-time recording of inbound and outbound fish stocks, estimation of storage duration, and continuous inventory tracking in an operational cold storage facility in Indonesia. By linking inventory data with energy consumption and emission estimation models, this approach provides a more accurate and operationally relevant method for carbon footprint analyses.

The objective of this research is to design, develop, and implement an IoT-based inventory recording instrument for fish cold storage facilities, and to evaluate its role in improving inventory accuracy, storage duration monitoring, and carbon footprint estimation through energy consumption analysis. Specifically, this study aims to (1) provide empirical inventory data from real cold storage operations, (2) analyze the relationship between inventory level, storage duration, and energy consumption, and (3) support strategies for reducing carbon emissions through improved load management.

The findings of this study are expected to contribute to the digital transformation of Indonesia’s fisheries sector and support the development of a productive, socially inclusive, and ecologically sustainable Blue Economy.

2 Research methodology

2.1 Time and place of research

This study was conducted over a period of seven months, from April to October 2024. The initial phase focused on the design and development of an IoT-based fish stock recording instrument, including hardware assembly, firmware programming, and cloud database integration. This was followed by a system testing and validation phase during which the instrument was deployed and evaluated under real operational conditions.

The field implementation and performance testing of the developed instrument were carried out at the Cold Storage Warehouse BAS 3, operated by PT. Lautan Bahari Sejahtera, Indonesia. This facility was selected because of its active fish storage operations and representative energy consumption characteristics, making it suitable for evaluating the effectiveness of the proposed IoT-based inventory monitoring system in a real cold storage environment.

2.2 Mechanical design of the instrument

An IoT-based inbound–outbound fish data recorder was developed and assembled in Jakarta, Indonesia, with prototype fabrication conducted between February and August 2024. The mechanical housing utilized an ABS plastic enclosure to protect the internal components from a humid cold storage environment. A 4×4 keypad was mounted on the front panel as the user input interface and a 16×2 LCD was used to display the system status and feedback. The power source employed a 3S 18650 Li-ion battery pack equipped with a Battery Management System (BMS) to ensure operational safety and optimize energy efficiency [17][18]. The final physical configuration of the device is shown in **Fig. 1**, which shows the assembled inbound–outbound fish data recorder.

Fig. 1. Design of the assembled inbound–outbound fish data recorder.

2.3 System testing

System testing was performed from March to April 2024 at two cold-storage partner facilities located in Muara Baru, North Jakarta. Laboratory-level verification was conducted before the field deployment to ensure that the device met the intended design requirements. The testing procedure is as follows:

1. Keypad and LCD testing: ensuring that each keypad input was accurately read and displayed on the LCD.
2. ESP8266 connectivity testing: verifying the microcontroller WiFi stability and successful connection to the cloud server.
3. Power consumption testing – measuring battery performance under continuous operation and estimating device runtime.
4. Data validation testing: comparing IoT-recorded inbound–outbound entries with manual records to evaluate accuracy.

After laboratory verification, a 30-day field trial was conducted in an operational cold storage facility. The device recorded data during each fish loading and unloading activity. The dataset gathered during this period served as the basis for evaluating system reliability, data accuracy, transmission success rate, and power efficiency [19].

2.4 IoT system design

The IoT architecture was developed using an ESP8266 (NodeMCU) microcontroller as core processor. It handles keypad input processing, LCD display output, and cloud data transmission via WiFi. The IoT workflow consists of the following stages:

1. The operator inputs fish inbound/outbound quantities using the keypad.
2. The ESP8266 processes and displays the data on the LCD.
3. Verified entries are transmitted in real time to the cloud server through an API.
4. Data were stored in the cloud and visualized through an online dashboard showing stock levels, estimated storage duration, and energy usage trends.

The overall relationship between the components, including the keypad, LCD, ESP8266, 3S 18650 battery pack, and the cloud server, is illustrated in **Fig. 2**. The diagram supports the explanation of the signal flow and system integration.

Fig. 2 illustrates the block diagram of the IoT electronic system, depicting the relationships among the keypad, LCD, ESP8266, 3S 18650 battery pack, and cloud server connection. This approach is consistent with current research trends in IoT applications within fisheries and **cold chain logistics**, where digital monitoring has been shown to enhance data transparency and reduce carbon emissions through energy efficiency [20-22].

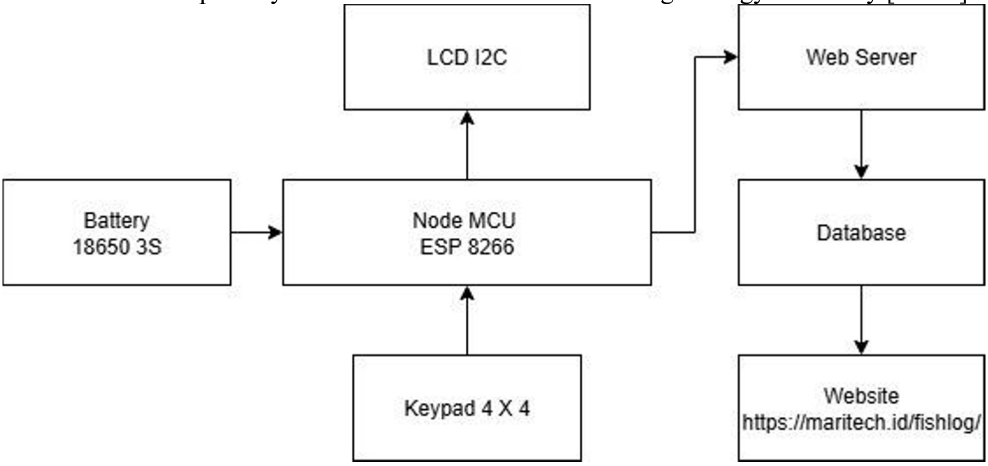


Fig. 2. Block diagram of the IoT electronic system.

2.4 Further analysis

The data obtained during the system deployment were subjected to several layers of analysis to assess the system performance and its relevance to energy and emission monitoring.

1. Accuracy Analysis
   Comparison between IoT-recorded data and manual logs to determine the accuracy (%) of inbound–outbound transactions.
2. Data Transmission Analysis
   Evaluation of successful versus failed data uploads to the cloud to determine transmission reliability.
3. Storage Duration Analysis
   Time-stamped inbound-outbound records were used to calculate the precise storage duration for each fish batch.
4. Energy Correlation Analysis
   The storage duration and stock volume data were correlated with cold storage electricity consumption to identify patterns affecting energy demand.
5. Carbon Emission Estimation
   Applying emission factors to energy consumption patterns to estimate the operational carbon footprint with higher precision.
6. Device Power Efficiency Analysis
   Assessment of the battery duration, average load, and energy efficiency of the device during field deployment.

These analytical outputs were used to evaluate the contribution of the IoT system to improving transparency in stock tracking, optimizing cold storage energy usage, and enhancing emission monitoring accuracy.

3 Results and discussion

3.1 Carbon emission analysis of cold storage

The analysis of electricity consumption and carbon emissions from two cold storage warehouses (BAS 3 and MAS) in Muara Baru, Jakarta, from 2020 to 2023 showed a consistent and statistically significant correlation between fish storage volume, electricity demand, and carbon emissions. Similar trends have been reported in previous studies that evaluated the energy intensity of cold chain refrigeration systems in fisheries and food logistics [23][24].

In 2020, cold storage activity increased significantly starting mid-year, with the highest surge recorded from July to October. The peak occurred in September, exceeding 22,000 kWh of electricity use and generating approximately 18,000 kg CO_2 emissions. This pattern aligns with the seasonal fisheries activity reported in previous Indonesian marine studies [25].

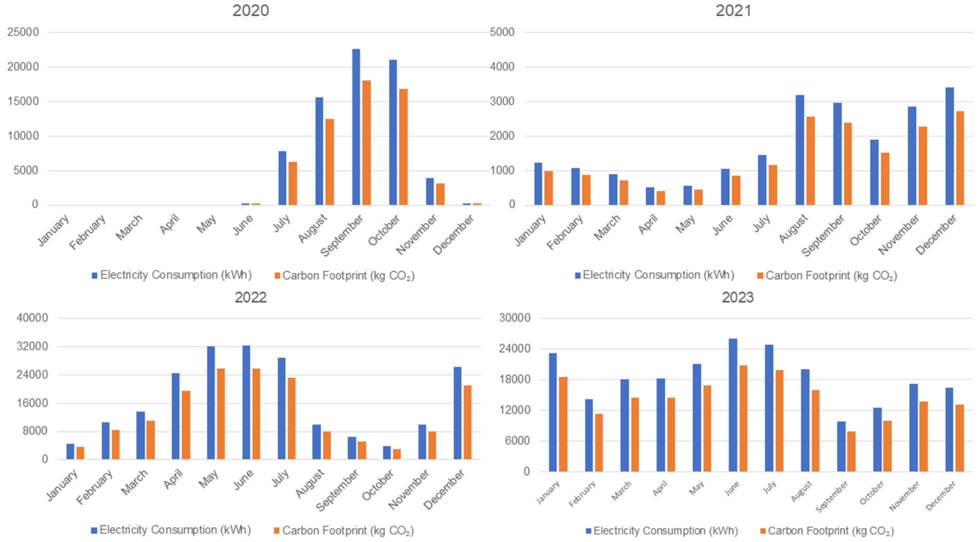


Fig. 3. Comparison of annual electricity consumption and carbon footprint trends in Jakarta cold storage facilities from 2020 to 2023.

The data are presented in four panels: (a) 2020 emissions showing initial mid-year surges; (b) 2021 distribution reflecting steady seasonal supply availability; (c) 2022 peak loads reaching over 26,000 kg CO_2; and (d) 2023 profiles indicating a continued high-intensity operational baseline. These trends demonstrate a consistent correlation between fish harvest cycles and energy demand, providing a critical historical benchmark for evaluating the impact of subsequent IoT-based monitoring interventions

In 2021, energy consumption was more evenly distributed, although the peak months remained strongly tied to fish harvest cycles. Spikes in August (±3,200 kWh; 2,400 kg CO_2) and December (±3,500 kWh; 2,700 kg CO_2) reflect the influence of seasonal supply availability, which is consistent with findings from studies on cold storage utilization behavior [26].

The year 2022 recorded the highest energy consumption and emissions, with major spikes in May–June (31,000+ kWh and ~26,000 kg CO_2). This trend is comparable to research showing that increased cold-chain throughput directly leads to higher compressor workloads and elevated energy consumption [27, 28]. Declines during September–October followed the pattern of reduced fishing activity outside the peak seasons.

In 2023, the electricity and emissions profiles resembled those of 2022, with peak loads again in May–June (29,000–30,000 kWh and ~25,000 kg CO_2). Pivot data also indicate that the total balance value for 2023 exceeded 20 million, suggesting a rapid expansion of cold storage capacity, a trend similar to that observed in expanding seafood logistics facilities across Southeast Asia [29].

Across the four-year period, the total energy use exceeded 25 million kWh, resulting in cumulative emissions of 396.42 tons CO_2. These findings support prior evidence that cold storage remains one of the largest contributors to carbon emissions within fishery supply chains [30], especially during peak fishing seasons (May–July).

The results emphasize the importance of implementing Internet-of-Things (IoT)-based monitoring technologies. Real-time stock tracking has been shown to increase transparency, reduce overcooling, and optimize compressor duty cycles, as documented in recent IoT studies on refrigeration and warehouse energy management [31, 32]. With a more precise estimation of fish storage duration, operators can predict energy demand more accurately, reduce electricity peaks, and implement more efficient cold chain policies [33].

3.2 Implementation of the fish stock recording system

The instrument shown in **Fig. 4** is designed not only for data input but also for operational reliability within cold storage environments. The ESP8266 microcontroller enables wireless connectivity, allowing the device to transmit each inbound–outbound record directly to a cloud database without manual intervention. This real-time capability reduces data delays and minimizes human errors, which commonly occur in conventional paper-based stock recordings. The integrated LCD interface provides immediate visual confirmation of successful entries, whereas the BMS-supported 3S battery configuration ensures stable operation even during fluctuations in the facility power supply. These features make the instrument suitable for high-frequency operational settings, ensuring that fish stock data remain accurate, traceable, and continuously updated to support energy consumption analysis and emission estimation.

The workflow of the device begins when the operator inputs the quantity of fish entering or exiting the cold storage through the 4×4 keypad. The ESP8266 processes this input and updates the stock status displayed on the LCD, ensuring that operators can instantly verify the accuracy before data transmission. The choice of the ESP8266 microcontroller was based on its low power consumption, integrated Wi-Fi module, and proven reliability in IoT applications, making it suitable for continuous operation in remote or infrastructure-limited facilities. Likewise, the 16×2 LCD was selected for its readability under low-temperature conditions, while the 18650 Li-ion batteries provide the high energy density necessary for portable use. The combination of these components ensures that the instrument remains functional, efficient, and responsive, even in cold storage environments where the temperature, humidity, and operational frequency can vary significantly.

Fig. 4. Assembled IoT-based fish stock recording instrument.

3.3 System performance testing

Performance testing was conducted to evaluate the accuracy of the stock recording, battery endurance, and stability of the data transmission over WiFi. Stock recording tests were conducted with 1,000 input attempts, yielding a success rate of 99.3%. Errors occurred only because of incomplete pressing of the button on the keypad. For data transmission, the system successfully delivered stock records to the cloud server at a success rate of 97.8% out of 500 transactions, with an average latency of 1.2 seconds.

In addition, energy consumption tests were performed to determine the efficiency of the system. The results showed an average current consumption of 220 mA in active mode and only 40 mA in idle mode. With the 3S battery configuration, the device was able to operate for up to 19 h in the full active mode and up to 32 h when used in the energy-saving mode.

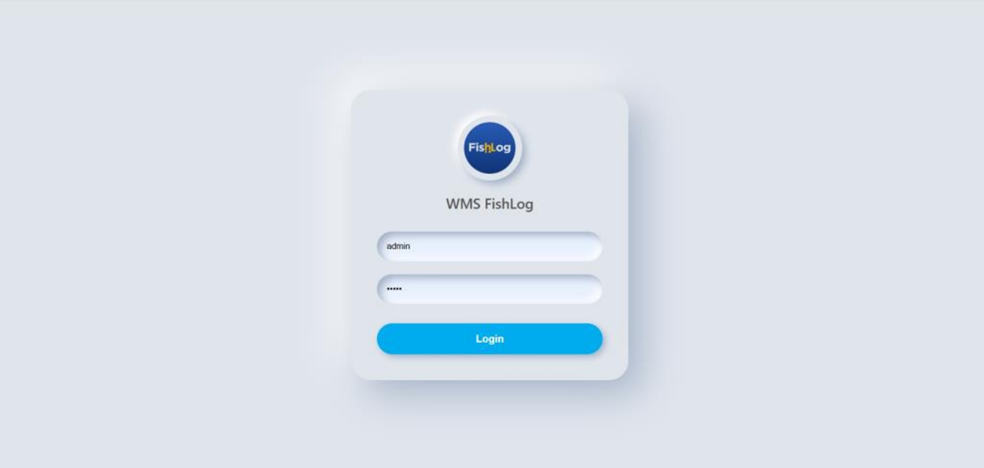
3.4 Internet of Things (IoT) system

The IoT system was integrated with a cloud-based database designed to record inbound and outbound fish data in real time. The database structure consists of five main fields: *Id* (integer) is the transaction index number, *Inbound* (integer) represents the number of incoming fish, *Outbound* (integer) represents the number of outgoing fish, *Stock* (integer) indicates the remaining fish stock, and *created_at* (timestamp) to record the exact time for each transaction. The structure of the monitoring table is shown in **Table 1**.

Table 1. Detailed database schema for the integrated fish stock monitoring system.

Field Name	Data Type	Description
Id	int	Unique transaction index number
Inbound	int	Quantity of incoming fish recorded
Outbound	int	Quantity of outgoing fish recorded
Stock	int	Remaining fish stock available in the facility
created_at	timestamp	Exact date and time the transaction was recorded

The web-based application interface provides access to the current stock and historical transaction records. The login page for the system access is shown in **Fig. 5**. Once logged in, the homepage displays the current stock status, as illustrated in **Fig. 6**. The data history page presents detailed records of the latest 50 inbound–outbound transactions, as shown in **Fig. 7**. Additionally, the system includes a chart page that visualizes real-time trends in inbound and outbound activities, supporting an easier interpretation of stock fluctuations over time.



admin

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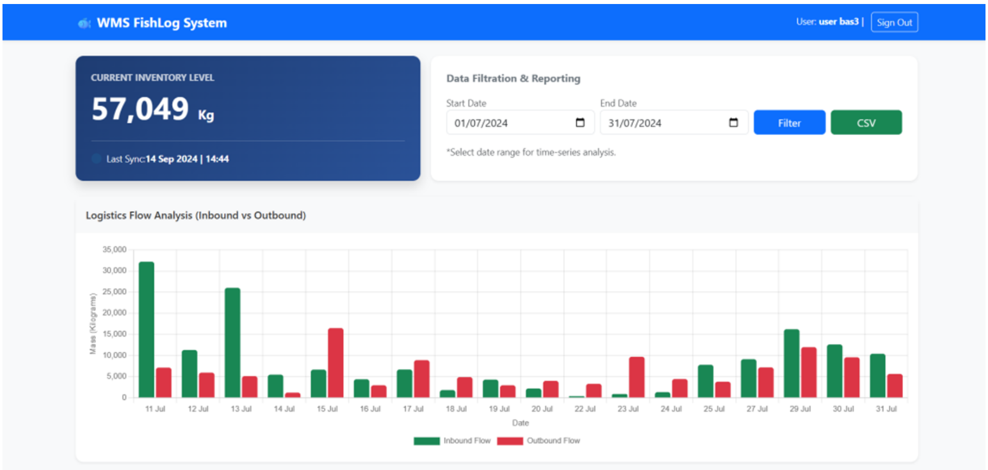
Fig. 5. Login page of the fish stock monitoring system.

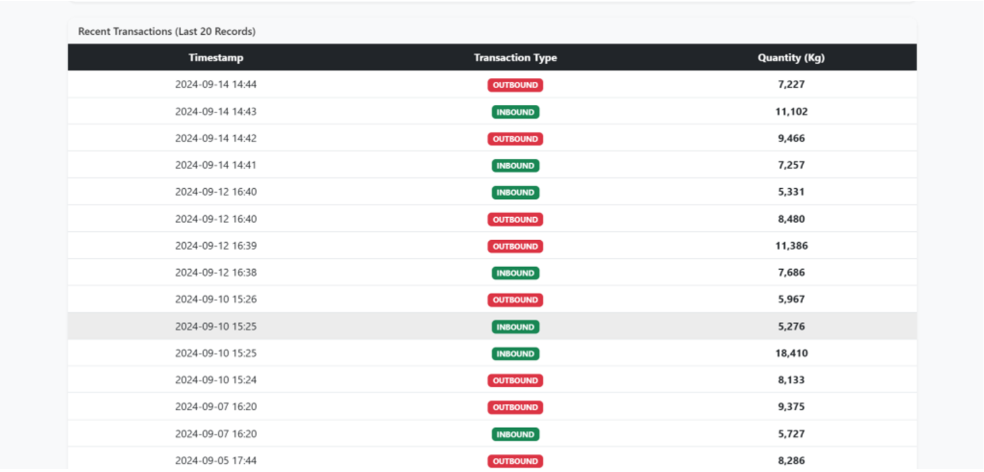


CURRENT INVENTORY LEVEL
57,049 Kg
Last Sync:14 Sep 2024 | 14:44

Start Date: 01/07/2024
End Date: 31/07/2024

*Select date range for time-series analysis.

Fig. 6. Home page interface of the web-based fish stock monitoring system. This dashboard provides a real-time graphical visualization of inbound and outbound fish quantities, allowing facility managers to monitor stock fluctuations and operational trends instantaneously. By centralizing data from the IoT sensors into this cloud-based interface, the system enhances data transparency and facilitates more accurate decision-making for energy management and emission tracking.



Recent Transactions (Last 20 Records)

Timestamp	Transaction Type	Quantity (Kg)
2024-09-14 14:44	OUTBOUND	7,227
2024-09-14 14:43	INBOUND	11,102
2024-09-14 14:42	OUTBOUND	9,466
2024-09-14 14:41	INBOUND	7,257
2024-09-12 16:40	INBOUND	5,331
2024-09-12 16:40	OUTBOUND	8,480
2024-09-12 16:39	OUTBOUND	11,386
2024-09-12 16:38	INBOUND	7,686
2024-09-10 15:26	OUTBOUND	5,967
2024-09-10 15:25	INBOUND	5,276
2024-09-10 15:25	INBOUND	18,410
2024-09-10 15:24	OUTBOUND	8,133
2024-09-07 16:20	OUTBOUND	9,375
2024-09-07 16:20	INBOUND	5,727
2024-09-05 17:44	OUTBOUND	8,286

Fig. 7. Historical data interface for inbound and outbound fish stock transactions within the cloud-based monitoring system. This page provides a comprehensive chronological log of all stock movements, enabling administrators to verify transaction accuracy and perform detailed audits of storage activities. By archiving these digital records with precise timestamps, the system allows for the calculation of exact storage durations, which is critical for modeling the correlation between inventory turnover and the facility's cumulative carbon footprint.

The test results confirm that the IoT system significantly improves recording efficiency, operational transparency, and continuous stock monitoring accuracy. These improvements support the principles of the Blue Economy by promoting digitalization, data-driven management, and sustainability enhancement within the fisheries supply chain.

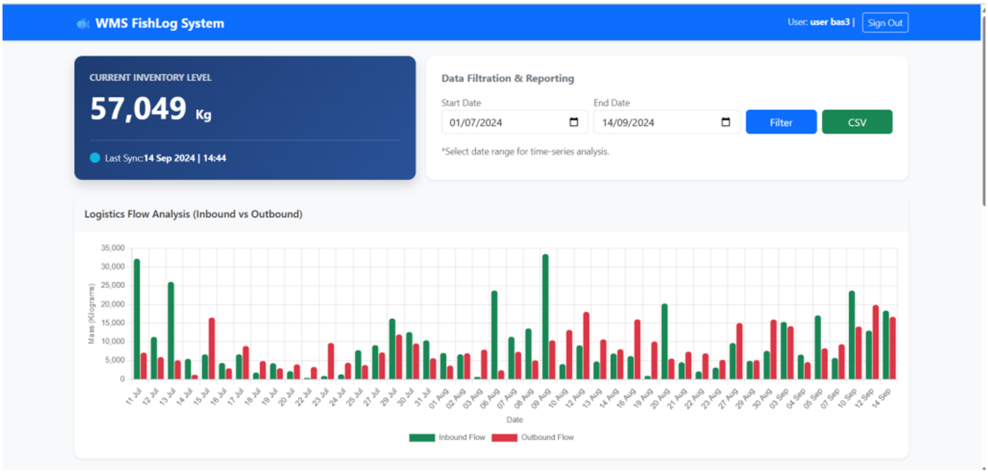
3.5 Performance of the IoT-based inventory monitoring system

The performance of the proposed IoT-based inventory monitoring system was evaluated through field deployment at a fish cold-storage facility from July to September 2024. During this phase, the system was operated under real working conditions to record daily inbound and outbound fish stocks in real-time. The collected data reflect the actual logistics activities and provide a basis for assessing the reliability and operational feasibility of the developed system.

Fig. 8 presents the daily inbound and outbound fish stocks recorded by the system over the deployment period. The results show clear variations in both inbound and outbound flows, indicating the system's capability to capture the dynamic inventory movements associated with harvesting schedules, storage turnover, and distribution activities. Peaks in inbound flow correspond to periods of high fish intake, whereas increased outbound activity reflects distribution and market demand cycles. These patterns demonstrate that the system operates consistently and can record transaction-based inventory changes without data loss.

Continuous recording of inbound and outbound data enables accurate estimation of daily inventory levels and storage duration. These parameters are critical for cold storage operations because fluctuations in the inventory load directly influence the refrigeration demand and energy consumption. The results confirm that the IoT-based system provides reliable and time-resolved inventory data, which are essential inputs for inventory-based energy efficiency analysis and carbon footprint estimation.

Overall, the field results indicate that the developed IoT-based inventory monitoring system performs effectively in a real cold-storage environment. The system enhances inventory transparency, supports continuous monitoring, and generates empirical operational data that can be directly linked to energy consumption and carbon emissions analysis. This validates the suitability of the proposed system as a practical tool for supporting sustainable cold storage management in the fisheries sector.


WMS FishLog System

User: **user bas3** |

CURRENT INVENTORY LEVEL

57,049 Kg

Last Sync:**14 Sep 2024 | 14:44**

Data Filtration & Reporting

Start Date
01/07/2024

End Date
14/09/2024

*Select date range for time-series analysis.

Logistics Flow Analysis (Inbound vs Outbound)

Fig. 8. Inbound and outbound fish stock recorded by the IoT-based inventory monitoring system during the field deployment period from July to September 2024. These data points illustrate the dynamic fluctuations in inventory levels, which serve as the primary input for calculating cooling load requirements and storage duration. By capturing these real-time transactions, the system provides a high-resolution dataset that enables more precise estimation of energy consumption and operational carbon footprints compared to conventional manual logging methods.

4 Conclusion

This study demonstrates that fish cold storage facilities in Muara Baru, Jakarta, generate a considerable carbon footprint, with total emissions reaching 396.42 tons of CO_2 during 2020–2023. The analysis confirmed a strong correlation between fish inventory volume, storage duration, and electricity consumption, indicating that variations in stock load and holding time are major determinants of energy demand and emission levels. The peak emissions observed during high storage throughput periods emphasize the importance of effective inventory and load management in reducing the environmental impacts of cold storage.

The implementation of the IoT-based fish stock recording instrument, utilizing an ESP8266 microcontroller with a keypad–LCD interface and cloud database integration, proved effective in improving inventory accuracy, operational transparency, and real-time data availability. The system reliably recorded inbound and outbound stock transactions under real operating conditions, enabling the precise estimation of storage duration and inventory dynamics. This inventory-based approach provides more accurate inputs for energy consumption and carbon emission estimations than conventional manual recording practices.

Overall, these findings highlight that accurate and continuous inventory monitoring is a critical component of sustainable cold storage management, which has been largely overlooked in previous studies. The proposed low-cost IoT solution offers a practical and scalable tool for small- and medium-scale fisheries cold storage facilities, supporting data-driven decision making and emission reduction strategies. This research contributes empirical evidence from an operational setting and supports the advancement of the Blue Economy through digital transformation, improved energy efficiency, and enhanced environmental sustainability in the fisheries sector.

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