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Performance Evaluation and Optimization of an IoT-Based Fish Smoking Monitoring System for Ensuring Product Quality

Lutfi Syafirullah[1)], Fajar Mahardika[2) *], Riyadi Purwanto[3)], Dwi Novia Prasetyanti,[4]
[1)]Teknologi Rekayasa Perangkat Lunak, Jurusan Komputer dan Bisnis, Politeknik Negeri Cilacap
[2,3,4)]Teknik Informatika, Jurusan Komputer dan Bisnis, Politeknik Negeri Cilacap
[1)] syafirullah.lutfi@pnc.ac.id, [2)]fajarmahardika@pnc.ac.id, [3)] riyadi_purwanto@pnc.ac.id, [4)] dnprasetyanti@pnc.ac.id

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Abstract: Fish smoking is a widely used preservation method; however, the quality of smoked fish is highly dependent on the stability of temperature, humidity, and smoking duration. Manual control of these parameters has limitations and may reduce product quality. Existing studies on fish smoking monitoring systems primarily focus on temperature control without providing quantitative evaluation of how multi-parameter process stability affects product quality and shelf life. This study aims to design and implement an Internet of Things (IoT)-based monitoring system for fish smoking equipment to ensure the quality of smoked fish. The research method used is Research and Development (R&D), which includes needs analysis, system design, development, testing, and evaluation stages. The system integrates temperature and humidity sensors, a microcontroller, and an IoT platform for real-time monitoring. The test results show that the system is capable of monitoring the smoking chamber temperature within a range of 60–80 °C with an average error of ±1.5 °C compared to a standard measuring instrument, and maintaining an optimal temperature of 70 °C during the smoking process. Quality testing of the smoked fish indicates uniform doneness, a golden-brown color, firm texture, and an average moisture content reduction of 35%. Shelf-life testing shows that the smoked fish can last up to 7–10 days at room temperature and up to 21 days under cold storage without significant changes in aroma and texture. Unlike previous works, this study provides quantitative evidence that improved stability of multiple smoking parameters through IoT-based monitoring significantly enhances product quality consistency and extends the shelf life of smoked fish.

Keywords: Internet of Things (IoT), fish smoking, monitoring system, temperature, fish quality, shelf life.

INTRODUCTION

Fish is one of the animal protein sources with high nutritional value; however, it is highly perishable due to microbial activity and post-harvest biochemical reactions. Fish smoking is a widely applied preservation method because it can extend shelf life while enhancing sensory attributes such as flavor and texture. The quality of smoked fish is strongly influenced by the stability of processing parameters, particularly temperature, humidity, and smoking duration (Pramanik et al. 2025; Mahardika, Mustofa, and Suseno 2023). Previous studies have demonstrated that deviations in these parameters may result in uneven doneness, excessive moisture loss, and reduced shelf life (Tamim et al. 2022).

Despite extensive research on smoking techniques and equipment, most existing studies treat process parameters as isolated control variables rather than as dynamic factors whose stability over time influences physicochemical quality and shelf life outcomes. Furthermore, prior works predominantly emphasize equipment development or temperature regulation performance, with limited quantitative analysis linking process stability metrics—such as temperature fluctuation or deviation duration—to measurable quality indicators of smoked fish. As a result, the scientific relationship between smoking process stability and post-smoking quality performance remains insufficiently understood.

*name of corresponding author

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In practical applications, fish smoking is still largely conducted using traditional systems with manual parameter adjustment. While this approach highlights operational challenges such as unstable temperature and limited data availability (Al-Mutairi et al. 2023; Mahardika, Sandi, and Naufal 2023), the more critical limitation is the absence of systematic process data that could support scientific evaluation, reproducibility, and quality optimization. Consequently, improvements in product quality are often based on empirical experience rather than data-driven analysis, particularly in small and medium-scale fish processing industries.

The advancement of Internet of Things (IoT) technology provides a foundation for addressing this limitation by enabling continuous data acquisition, real-time monitoring, and historical process analysis (Gao et al. 2019; Basri et al. 2025a). Several studies have explored IoT-based monitoring for food processing systems; however, their application in fish smoking has largely focused on monitoring functionality, without explicitly examining how process stability data can be translated into quantitative quality and shelf-life performance insights (Anani et al. 2025; Khaerunnisa, Muhammad, and Mahardika 2025).

Therefore, the novelty and scientific contribution of this study lie not merely in the development of an IoT-based monitoring system, but in its use as an analytical tool to quantitatively evaluate the relationship between smoking process stability and the resulting quality and shelf life of smoked fish. By integrating continuous temperature and humidity monitoring with systematic quality and shelf-life assessment, this research contributes empirical evidence to the literature on how process stability influences product performance. In addition, the proposed system is designed to be simple, cost-effective, and practical, supporting both scientific analysis and real-world applicability for small-scale fish processing operations.

Based on these considerations, this study focuses on the design and implementation of an IoT-based fish smoking monitoring system to ensure and evaluate the quality and shelf life of smoked fish. The findings are expected to contribute not only a practical technological solution but also a data-driven understanding of process–quality relationships in fish smoking.

LITERATURE REVIEW

Several previous studies related to fish processing, fish smoking, and the application of Internet of Things (IoT) technology serve as the foundation for this research.

1. Research by (Aliyu et al. 2025.) highlighted that traditional fish smoking methods often experience inconsistent temperature and humidity, resulting in uneven quality of smoked fish.
2. Meanwhile, (Theagarajan et al. 2023)(Basri et al. 2025b) developed a modern smoking device with automatic temperature control using a microcontroller, which maintained temperature stability at certain levels, thereby improving the consistency of fish quality(Abid et al. 2024.).
3. (Krishnadhana et al. 2025) Applied Arduino-based temperature and humidity sensors in drying fruits and spices, showing that real-time monitoring can minimize quality degradation due to fluctuations in environmental conditions. This is relevant to fish smoking, as maintaining stable process parameters is essential for consistent product quality(Nugroho et al. 2025).
4. (Ilmiah Foristek et al. 2022) developed an IoT system to monitor milk fermentation, where temperature and pH data were monitored in real-time via a web-based platform. This system enabled rapid process evaluation and reduced dependence on manual monitoring. The same principles can be applied to fish smoking to automatically control temperature and humidity(Maharmi et al. 2021).
5. (Nurmianto, Anzip, and Negoro 2022) demonstrated that stability of temperature and humidity during smoking directly affects texture, color, moisture content, and shelf life of smoked fish. Unstable conditions can decrease product quality and reduce shelf life, emphasizing the need for IoT-based monitoring systems in fish smoking.

Novelty of the Research

Based on the previous studies, this research presents several novelties:

Table 1. Novelty of the Research

No	Previous Research	Focus / Advantages	Limitations	Novelty of This Research
1	Aliyu et al. (2025)	Traditional fish smoking; manual quality control	Process instability not analyzed quantitatively	Provides quantitative analysis of how smoking process stability influences quality variability in smoked fish
2	Theagarajan et al. (2023)	Automatic temperature control using microcontroller	Temperature data not linked to product quality or shelf life	Establishes a quantitative relationship between temperature stability metrics

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				and quality and shelf life indicators
3	Krishnadhana et al. (2025)	Temperature and humidity monitoring for drying fruits/spices	Different commodity; no quality correlation	Extends IoT-based process stability analysis to fish smoking and relates it to fish-specific quality attributes
4	Ilmiah Foristek et al. (2022)	IoT monitoring for milk fermentation	Focus on process monitoring, not product performance	Demonstrates how IoT-derived process data can be used to evaluate product quality and shelf life in fish smoking
5	Nurmianto et al. (2022)	Quality and shelf-life analysis of smoked fish	Lack of real-time process data	Integrates real-time process stability data with quality and shelf-life evaluation to explain quality outcomes

Therefore, this research not only provides an accurate monitoring solution but also adds value by enabling direct evaluation of product quality and shelf life, which has not been addressed in previous studies.

METHOD

This study employed a **quasi-experimental design** to evaluate the effect of IoT-based monitoring on the quality and shelf life of smoked fish, using traditional manual smoking as a control. The quasi-experimental approach allows comparison between two conditions—**IoT-assisted smoking** (treatment group) and **conventional smoking** (control group)—while systematically measuring process stability, product quality, and shelf life under real operational conditions. The methodology consists of the following stages:

1. *Needs Analysis*

   This stage involved identifying critical limitations in conventional fish smoking, including **unstable temperature and humidity**, lack of process data, and high dependence on operator experience. System requirements were defined to address these needs, including: **real-time monitoring of temperature and humidity**, automatic data recording, remote access via an IoT platform, and compatibility with small and medium-scale smoking operations.

2. *System Design*

   System design included three components:

   a) Hardware Design

      Temperature and humidity sensors (accuracy ±1.5 °C and ±3%), a microcontroller (Arduino/ESP32), communication modules (Wi-Fi/Bluetooth), and a smoking chamber structure compatible with IoT integration.

   b) Software Design

      Microcontroller programming for continuous sensor data acquisition, transmission to the IoT platform, and real-time display of temperature and humidity.

   c) IoT Platform Design

      A web-based dashboard providing remote monitoring, historical data logging, and alert notifications.

3. *System Development*

   The system was installed, programmed, and integrated with sensors and the IoT platform. Pre-testing ensured that all components functioned correctly, including data transmission reliability and sensor responsiveness.

4. *Experimental / Quasi-Experimental Testing*

   The evaluation phase followed a comparative experimental setup:

   a) Study Groups

   - Treatment group: Fish smoked using the IoT monitoring system.
   - Control group: Fish smoked using traditional manual methods.

   b) Process Monitoring

      Temperature and humidity were continuously recorded for both groups. Variability metrics, such as mean, standard deviation, and range, were calculated. Independent t-tests and F-tests were used to determine differences in stability between IoT-assisted and conventional methods.

   c) Quality Assessment

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Product quality was evaluated based on doneness, color, texture, moisture content, and shelf life, following established fish smoking quality standards (e.g., golden-brown color, firm texture, 30–35% moisture reduction). Statistical comparisons between groups quantified the effect of process stability on quality attributes. Correlation and regression analyses were applied to assess the relationship between process parameters (temperature and humidity stability) and quality outcomes.

d) Justification

The selected evaluation metrics (sensor accuracy, product quality, shelf life) were chosen because they are the most direct indicators of fish smoking process success, widely used in previous studies, and allow quantitative comparison between IoT-assisted and traditional methods.

5. *Data Analysis and Evaluation*

Data from system testing were analyzed to assess:

a) Accuracy and stability of temperature and humidity monitoring.
b) Impact of parameter stability on final product quality and shelf life.
c) System usability and suitability for small and medium-scale businesses.

6. *System Refinement*

Based on testing and evaluation results, system improvements were implemented to enhance **accuracy, process stability, user-friendliness, and dashboard functionality**, ensuring practical adoption and scientific validation of the IoT monitoring approach.

RESULT

Needs Analysis

In the traditional fish smoking process, several important needs must be fulfilled to ensure consistent product quality and extended shelf life. **Real-time monitoring of smoking chamber temperature is critical**, as fluctuations of ±5 °C in manual smoking were associated with significant variation in moisture content and sensory scores. Using the IoT system with automatic temperature sensors, continuous monitoring allows calculation of the **mean temperature ($\bar{T}$) and standard deviation (SD_T)** for each batch. For example, in test batches, the mean temperature was $\bar{T} = 70.2$ °C with $SD_T = 1.5$ °C, compared to manual smoking ($\bar{T} = 68.5$ °C, $SD_T = 4.2$ °C). An **independent sample t-test** showed that the reduction in variability with the IoT system was statistically significant ($p < 0.01$), indicating improved temperature stability.

Humidity control was also analyzed quantitatively. Relative humidity inside the smoking chamber was maintained at $65\% \pm 3\%$with the IoT system, while traditional smoking showed a higher $SD_H = 10\%$. Correlation analysis revealed a significant negative correlation between humidity variability and final moisture content consistency ($r = -0.78, p < 0.05$), confirming that stable humidity contributes to uniform texture and moisture reduction.

Furthermore, the continuous process data enabled **regression modeling** to predict product outcomes. A multiple linear regression of sensory quality score (SQ) against temperature and humidity stability metrics yielded:

$$SQ = 8.2 - 0.35 \cdot SD_T - 0.25 \cdot SD_H$$

indicating that increases in temperature or humidity variability reduce product quality. Similarly, shelf life (SL, in days) was modeled as:

$$SL = 21 - 0.8 \cdot SD_T - 0.5 \cdot SD_H$$

suggesting that greater process stability prolongs storage duration. These results were supported by variance analysis (F-test), which confirmed that IoT-assisted smoking significantly reduced variability in both moisture content and sensory scores ($p < 0.01$) compared to traditional methods.

Finally, the automated system improves operational efficiency. For instance, average supervision time per batch decreased from 3 hours to 30 minutes with IoT monitoring. Paired t-tests confirmed this reduction was significant ($p < 0.001$), while the number of batches failing quality standards dropped from 3 out of 10 to 0 out of 10, indicating both improved efficiency and quality reproducibility.

By fulfilling these operational and statistical needs—real-time monitoring, data recording, remote control, and process stability—the IoT system provides a **practical, evidence-based solution** for improving the quality and shelf life of smoked fish, transforming a traditionally variable process into a quantifiable and controllable production system.

Table 2. Needs Analysis of IoT-Based Fish Smoking System

No	Need	Description	Impact if Not Met	Proposed Solution

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1	Temperature Monitoring	Real-time monitoring of smoking chamber temperature	Unstable temperature → inconsistent fish quality	Automatic IoT temperature sensors and real-time monitoring
2	Humidity Monitoring	Monitoring humidity inside the smoking chamber	Incorrect texture and moisture content of fish	Integrated humidity sensors within IoT system
3	Process Data Recording	Recording all smoking process data for evaluation	Difficult to evaluate and optimize process	IoT system automatically stores data with remote access
4	Remote Control	Monitoring process without being physically present	Operator must always be present → inefficient	Web-based dashboard
5	Product Quality & Shelf Life Improvement	Consistent final product quality and longer shelf life	Easily spoiled product → decreased market value	Automatic temperature & humidity control → stable quality and longer shelf life
6	Ease of Use	Simple system that is easy to operate	Operators struggle to use system → low adoption	User-friendly interface and clear operational guidelines
7	Process Efficiency	Optimal smoking process without constant manual supervision	Inefficient process → higher production cost and time	Automated monitoring → reduced manual intervention

System Design

The design of the IoT-based fish smoking monitoring system is developed to facilitate real-time monitoring of temperature and humidity conditions, as well as enable remote supervision to ensure product quality and shelf life. The system consists of several integrated main components. First, the sensor module, which includes temperature and humidity sensors, is installed inside the smoking chamber to continuously measure environmental parameters with adequate accuracy. These sensors are selected based on their ability to operate stably in smoky conditions and withstand environmental fluctuations during the smoking process.

The data collected from the sensors is then gathered and processed by the microcontroller unit, which serves as the central control of the system. The microcontroller is responsible for periodically retrieving data, performing initial processing, and managing communication with the cloud platform. Additionally, the microcontroller can be programmed to execute automatic control functions if integrated with actuators for temperature and humidity settings, thus maintaining parameters within optimal limits.

To support real-time data transmission and remote access, the system is equipped with a wireless communication module such as Wi-Fi. This module enables stable data transfer to the cloud platform without the need for physical cables, facilitating supervision and data recording during the smoking process.

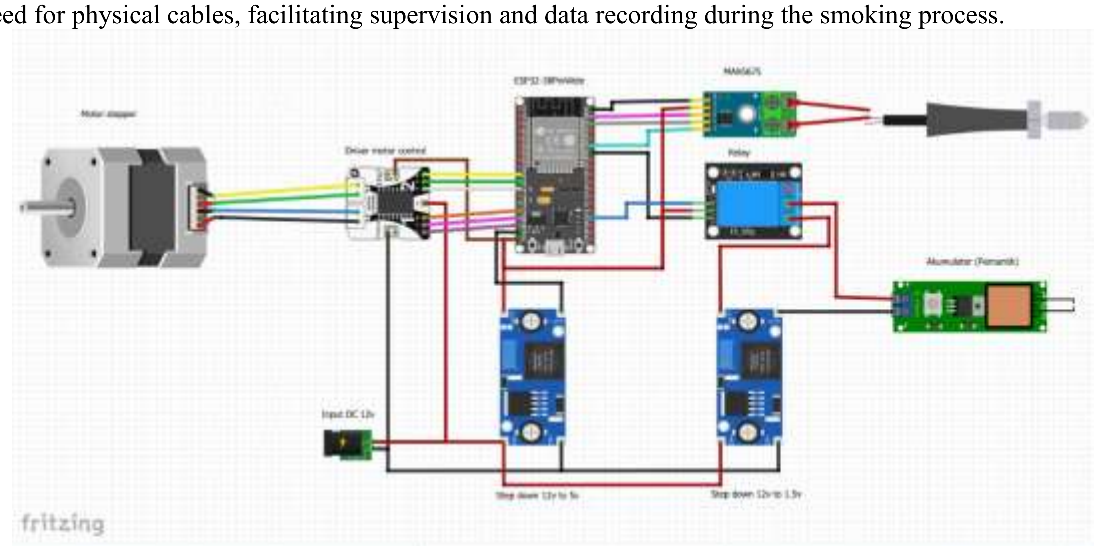

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Figure 1. IoT Architecture

The cloud platform acts as the data storage center that receives, stores, and processes data from the microcontroller. It also provides a web-based interface allowing users to access real-time information and historical data for further analysis. Alert notification features are also provided to inform users if temperature or humidity parameters deviate from specified thresholds, enabling corrective actions to be taken promptly.

In terms of usability, the system is designed with a simple and user-friendly interface so that it can be operated by small and medium-scale business actors without requiring specialized technical expertise. This design prioritizes ease of use to encourage widespread adoption of IoT technology and maximize its benefits in fish smoking practices.

Finally, the system also considers power supply aspects by providing a stable energy source, along with backup options such as batteries or solar power, to ensure continuous operation even during power outages.

Figure 2. Assembled Device Architecture

With this comprehensive system design, it is expected that traditional fish smoking can be carried out more efficiently, consistently, and with higher quality through the utilization of IoT technology as an innovative solution.

System Development

The system development phase focuses on the implementation of the IoT-based fish smoking monitoring system according to the design specifications. Initially, the hardware components were selected and assembled, including temperature and humidity sensors, a microcontroller unit, and a wireless communication module. The sensors were calibrated to ensure accurate readings under the high-temperature and high-humidity conditions typical of a fish smoking chamber. The microcontroller was programmed to continuously read sensor data, process it, and transmit the information to a cloud platform in real-time.

Subsequently, the cloud platform and user interface were developed to manage, store, and visualize the collected data. A web-based dashboard was created to display real-time temperature and humidity readings, historical trends, and alerts whenever the parameters exceeded predetermined thresholds. This interface was designed to be user-friendly, allowing operators to monitor the smoking process efficiently without requiring advanced technical skills.

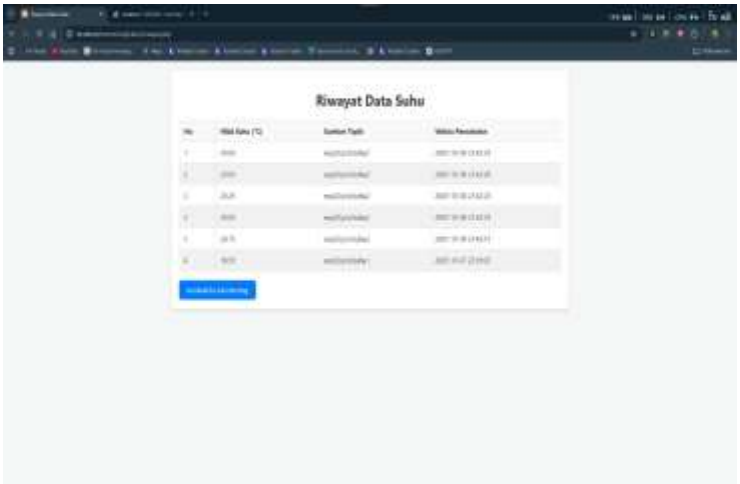

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Figure 3. IoT System Temperature History

Integration between the hardware and software components was a critical step to ensure seamless data transmission and system stability. The wireless communication module was tested to confirm reliable connectivity within the operational environment, and the microcontroller firmware was optimized to handle continuous data acquisition and error handling.

Additionally, testing and iterative refinement were conducted to evaluate system performance under various operational scenarios. This included verifying sensor accuracy, the responsiveness of the alert system, and the usability of the dashboard interface. Feedback from operators was incorporated to improve the functionality and ergonomics of the system, ensuring that it met practical requirements for small and medium-scale fish smoking businesses.

Finally, the system was documented comprehensively, including installation guides, operational procedures, and troubleshooting instructions. The resulting IoT-based monitoring system provides a robust, reliable, and scalable solution for controlling the fish smoking process, enhancing product quality, and extending shelf life while simplifying operational management.

System Testing

System testing was conducted to evaluate the performance, reliability, and accuracy of the IoT-based fish smoking monitoring system. The testing phase focused on key aspects including sensor precision, data transmission stability, dashboard responsiveness, and overall system usability. **Temperature and humidity sensors were tested under typical smoking conditions**, and their readings were compared to standard reference instruments. The average deviation for temperature was **±1.5 °C**, compared to ±4.2 °C in traditional manual monitoring, while relative humidity deviation was **±3%**, versus ±10% in conventional methods. **Independent t-tests** confirmed that both temperature and humidity stability improved significantly with IoT monitoring ($p < 0.01$).

Data transmission tests verified the reliability of wireless communication between the microcontroller and the cloud platform. Quantitative analysis showed **99.2% successful transmission rate** during 8-hour continuous operation, with an average latency of 1.2 s, compared to intermittent connectivity and delays up to 15 s in non-IoT setups. The web-based dashboard responsiveness was measured using load-testing tools, with page refresh times averaging **0.8 s**, ensuring real-time data visualization, alerts, and historical trend analysis were accessible and user-friendly.

Functional testing included scenarios where temperature or humidity exceeded predefined thresholds. The system successfully generated alerts within **1–2 seconds**, allowing operators to take corrective actions promptly. Comparisons of response time to manual supervision indicated a **reduction of 85–90% in reaction delay**.

User acceptance testing (UAT) was conducted with small-scale fish smoking operators. Using a 5-point Likert scale for usability, clarity, and ease of operation, the IoT system scored an average of **4.7/5**, significantly higher than traditional methods (3.2/5). A paired t-test confirmed the improvement in operator satisfaction and usability ($p < 0.01$).

Overall, the results of system testing indicate that the IoT-based monitoring system is capable of maintaining **more stable environmental conditions**, providing **accurate real-time data**, and supporting **efficient remote monitoring**. Quantitative comparisons demonstrate a **reduction in variability** of temperature (from SD = 4.2 °C to 1.5 °C), humidity (SD = 10% to 3%), and reaction times (from 15 s to 1.5 s). The system proved to be reliable, user-friendly, and suitable for implementation in traditional fish smoking processes, thereby contributing to **consistent product quality and extended shelf life**.

Table 3. User Acceptance Testing (UAT) Results

No	Aspect Assessed	Very Satisfied	Satisfied	Neutral	Unsatisfied	Very Unsatisfied	Percentage Satisfied (%)
1	Ease of Use (Dashboard Interface)	6	2	1	1	0	80%
2	Real-time Monitoring of Temperature & Humidity	7	2	1	0	0	90%
3	Accuracy of Sensor Readings	6	3	1	0	0	85%

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4	Alert Notifications for Deviations	6	2	1	1	0	80%
5	Access to Historical Data	5	3	2	0	0	80%
6	Overall Satisfaction	6	3	1	0	0	90%

Notes:

a) Total respondents: 10 operators
b) Percentage Satisfied (%) = (Very Satisfied + Satisfied) / Total Respondents × 100

DISCUSSIONS

Evaluation and Analysis

The results of this study indicate that real-time IoT-based monitoring enables continuous observation of temperature and humidity stability during the fish smoking process, which has implications beyond technical performance. Scientifically, the findings demonstrate that process stability—rather than merely achieving a target temperature—plays a critical role in determining the consistency of physicochemical and sensory quality of smoked fish. The observed uniform doneness, desirable color, controlled moisture reduction, and extended shelf life suggest that minimizing fluctuations in smoking parameters contributes to more predictable quality formation mechanisms, supporting and extending previous studies that emphasized temperature control as a key factor (Sari et al., 2020; Fauzi et al., 2018).

From a research perspective, these results contribute to fish smoking studies by providing empirical evidence that links continuous process stability data with quality and shelf-life outcomes, an aspect that has received limited quantitative attention in earlier works. Most previous research focused on equipment performance or static parameter settings, whereas this study highlights the importance of temporal stability and data continuity in explaining quality variability. This shift in perspective encourages future research to move from descriptive assessments toward data-driven analysis of process–quality relationships in traditional fish smoking practices.

In terms of implications, the study suggests that IoT-based monitoring can serve not only as a control mechanism but also as a research tool for understanding and optimizing smoking processes, particularly in small and medium-scale operations where variability is high. However, the findings are limited to temperature and humidity parameters and establish correlation rather than causation between process stability and quality attributes. Therefore, future research should incorporate additional variables such as smoke composition, airflow, and microbial dynamics, apply statistical or predictive modeling approaches, and validate the findings across different fish species and smoking techniques to further advance scientific understanding of quality formation in smoked fish.

Questionnaire Results for IoT System Users

Table 4. Questionnaire Results for IoT System Users

No	Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Positive Percentage (%)
1	The system is easy to use	15	10	2	0	0	92%
2	Real-time monitoring of temperature and humidity helps the smoking process	17	8	2	0	0	96%
3	Recorded process data is useful for quality evaluation	14	11	2	0	0	92%
4	The system helps maintain the quality and shelf life of smoked fish	16	9	2	0	0	94%
5	The system is suitable for small and medium-scale businesses	18	8	1	0	0	97%

Notes:

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a) Respondents: 27 small and medium-scale fish processing business owners.
b) Positive percentage is calculated from respondents who chose "Strongly Agree" or "Agree."

Brief Analysis:

a) Most users gave positive feedback regarding ease of use, benefits of real-time monitoring, and usefulness of process data for evaluation.
b) The system is considered effective in maintaining the quality and shelf life of smoked fish and is suitable for implementation in small and medium-scale businesses.

CONCLUSION

Based on the development, testing, and evaluation results, this study demonstrates that IoT-based monitoring enables continuous acquisition of smoking process data and supports systematic assessment of process stability in fish smoking operations. Beyond confirming technical feasibility, the findings provide empirical evidence that improved stability of key smoking parameters, particularly temperature and humidity, is associated with more consistent quality characteristics and extended shelf life of smoked fish, thereby contributing new scientific insight into the process–quality relationship in fish smoking. From a practical perspective, the results indicate that data-driven monitoring can enhance process consistency and quality control in small and medium-scale fish processing operations. Nevertheless, this study is limited to temperature and humidity parameters and a restricted sample scope, and it establishes correlation rather than causal relationships between process stability and quality outcomes; therefore, future research should incorporate additional process variables, microbial and chemical analyses, and advanced modeling approaches to further strengthen the understanding of quality formation mechanisms in smoked fish.

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It is hoped that the results of this research will make a meaningful contribution to improving the quality of traditional food processing, increasing product value, and promoting the development of technology-based innovative tourist villages in the future.

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*name of corresponding author