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IoT-Based Integrated Production and Quality Control System Design for Halal SMEs in Island Regions

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ABSTRACT

The global halal economy continues to expand rapidly, creating a pressing demand for reliable and technology-driven quality management systems. However, small and medium-sized enterprises (SMEs) in Indonesia's island regions face major constraints in ensuring consistent halal assurance due to limited resources, geographic isolation, and dependence on manual processes. This study proposes an IoT-based integrated production and quality control system tailored for halal SMEs in island settings. The framework integrates Total Quality Management (TQM), Halal Assurance System (HAS), and Industry 4.0 technologies. Using sensors to monitor temperature, humidity, and weight—connected to a cloud dashboard—the system enables real-time monitoring, traceability, and halal compliance. A prototype was implemented in fish processing SMEs in Maluku, Indonesia. Results show improvements in production efficiency (15%), product consistency (20%), and halal documentation readiness. The findings confirm that IoT integration strengthens halal assurance and offers a scalable digital transformation model for island-based halal industries worldwide.

Keywords: *Internet of Things, Halal Assurance, Total Quality Management, SMEs, Island Regions*

Introduction

The Halal Assurance System (HAS) is a comprehensive framework designed to ensure halal compliance throughout the entire production process, from raw material sourcing to distribution [1], [2]. It requires systematic monitoring of inputs, processing environments, handling procedures, and documentation to guarantee both religious compliance and product quality. However, in practice, many small and medium-sized enterprises (SMEs), particularly in developing and geographically isolated regions, continue to rely on manual monitoring and paper-based documentation systems that are prone to human error, data loss, and limited traceability [3], [4], [5]. These conditions significantly reduce audit readiness and increase the risk of non-compliance with halal certification requirements.

In Indonesia's island regions, such as Maluku, these challenges are further intensified by geographical dispersion, limited access to digital infrastructure, and fragmented supply chains [6], [7]. Halal food SMEs operating in archipelagic contexts often face constraints related to transportation, inconsistent production environments, and limited interaction with certification bodies [8]. As a result, maintaining consistent halal compliance and quality assurance becomes more complex compared to SMEs located in urban or industrial centers. These contextual limitations highlight the need for technological solutions that are not only compliant with halal standards but also affordable, scalable, and adaptable to the realities of island-based SMEs [9].

Total Quality Management (TQM) offers a managerial framework that emphasizes continuous improvement, process standardization, customer focus, and data-driven decision-making [10], [11]. When applied to halal production systems[8], TQM supports the systematic control of critical processes while reinforcing compliance with religious and quality standards [12], [13]. Previous studies have demonstrated that TQM implementation in halal SMEs contributes to improved product consistency, operational efficiency, and consumer trust [14], [15]. Nevertheless, TQM alone is often insufficient in environments where manual data collection and monitoring dominate daily operations. Without technological support, the effectiveness of TQM practices in ensuring halal integrity remains limited, particularly in resource-constrained SME settings.

The emergence of Industry 4.0 technologies, especially the Internet of Things (IoT), provides new opportunities to enhance halal assurance and quality control systems. IoT enables real-time monitoring of critical production parameters such as temperature, humidity, and processing duration, while cloud-based platforms facilitate automated documentation, traceability, and audit readiness [16], [17]. Several studies have reported successful applications of IoT-based monitoring systems in food processing and halal industries, showing improvements in efficiency, consistency, and transparency [18], [19]. However, most existing implementations focus on large-scale industries or urban SMEs with relatively stable infrastructure. Research addressing low-cost, IoT-based halal assurance systems specifically designed for SMEs in island or remote regions remains limited.

Furthermore, previous studies often treat halal assurance, quality management, and digital technology as separate domains. There is a lack of integrative models that combine HAS as a compliance framework, TQM as a managerial approach, and IoT as a technological enabler within a single operational system tailored to SME contexts. This gap is particularly evident in island-based economies, where SMEs require simple, reliable, and affordable solutions to support both operational performance and halal compliance[20].

Therefore, this study aims to design and implement an IoT-based integrated production and quality control system for halal SMEs operating in island regions. The proposed system integrates TQM principles[21], [22], Halal Assurance System requirements, and low-cost IoT technologies to support real-time monitoring, automated documentation, and traceability. A prototype was developed and tested in fish processing SMEs in Maluku, Indonesia, to evaluate its impact on production efficiency, product consistency, and halal documentation readiness. By addressing the specific challenges faced by island-based halal SMEs, this study contributes a practical and scalable model for digital transformation in halal industries, while enriching the empirical literature on IoT-enabled halal assurance systems in geographically constrained environments.

Research Methods

This study employed a Research and Development (R&D) approach aimed at designing, implementing, and evaluating an IoT-based integrated production and quality control system for halal SMEs operating in island regions. The R&D method was selected to ensure that the proposed system was not only conceptually sound but also practically applicable within real SME production environments. The research process consisted of five sequential stages, as outlined below.

Stage 1 : Field Survey of Halal SMEs

The first stage involved a field survey conducted among fish processing SMEs in Maluku, Indonesia. This sector was selected due to its economic importance in island regions and its high sensitivity to halal assurance and quality control requirements. Data collection was carried out through structured observations and informal interviews with SME owners and production workers. The survey focused on identifying existing production practices, monitoring methods, documentation systems, and readiness for digital technology adoption. Particular attention was given to understanding the prevalence of manual monitoring systems and the challenges faced by SMEs in maintaining halal compliance and audit preparedness.

Stage 2: Identification of Critical Halal Control Points (CHCPs)

Based on the field survey results and a review of halal assurance and quality management literature, Critical Halal Control Points (CHCPs) were identified along the production process. This stage adopted principles from Hazard Analysis and Critical Control Points (HACCP) and Total Quality Management (TQM) to ensure systematic control of processes that directly affect halal integrity and product quality. Each CHCP was mapped to measurable parameters that could be monitored using IoT sensors. The identification of CHCPs served as the foundation for determining which production variables required real-time monitoring and documentation.

Table 1. Critical Halal Control Points (CHCPs) and Corresponding IoT Parameters

Production Stage	Critical Halal Control Point (CHCP)	IoT Monitoring Parameter	Purpose in Halal Assurance
Raw Material Sourcing	Verification of halal-certified suppliers	Digital documentation, supplier ID	Ensures only halal-certified raw materials are used
Storage	Monitoring temperature and humidity	DHT22 sensor (temperature & humidity)	Prevents contamination and maintains halal integrity
Fish Smoking	Controlling chamber temperature (70–90°C) and duration	Temperature sensor, timer	Ensures consistency and food safety
Packaging	Verification of halal-compliant packaging materials	Barcode/RFID scanning	Ensures packaging complies with halal standards

The table illustrates how each production stage is associated with specific halal risks and how IoT-based monitoring can support halal assurance through continuous data collection and traceability.

Stage 3: System Design of IoT-Based Halal Assurance

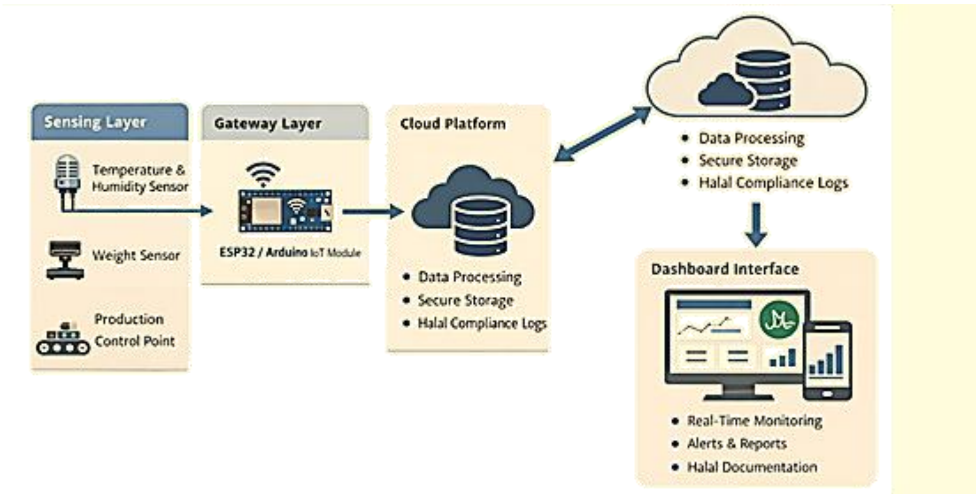

Figure 1. Architecture of the IoT-Based Halal Assurance System

In the third stage, an IoT-based system architecture was designed to integrate halal assurance requirements with quality control and production monitoring. The system architecture consists of four main layers: sensing, gateway, cloud processing, and user interface. Low-cost and open-source components were deliberately selected to ensure affordability and ease of adoption for SMEs with limited technological resources. The design emphasizes simplicity, reliability, and scalability, making it suitable for geographically isolated production settings.

As shown in Figure 1, sensors collect real-time data on temperature, humidity, and weight at critical production stages. The data are transmitted via an IoT gateway (Arduino/ESP32) to a cloud server, where they are processed and stored. A web- or mobile-based dashboard enables SME operators to monitor production conditions, access halal compliance records, and retrieve audit logs when required by certification bodies.

Stage 4: Prototype Development and Implementation

A functional prototype was developed using an Arduino-based microcontroller integrated with DHT22 sensors for temperature and humidity monitoring. These components were chosen due to their low cost, ease of calibration, and suitability for small-scale food processing environments. The prototype was installed in selected fish processing SMEs and configured to operate within halal-compliant production ranges, such as temperature levels between 70–90°C and humidity levels below 60%.

During implementation, the system continuously recorded production data and automatically generated digital documentation. This approach reduced dependence on manual record-keeping and minimized the risk of missing or inconsistent data. Practical challenges encountered during implementation, such as sensor placement and intermittent internet connectivity, were addressed through system calibration and data buffering mechanisms.

Stage 5: Pilot Testing and Performance Evaluation

The final stage involved pilot testing the system to evaluate its impact on production performance and halal documentation readiness. System performance was assessed by comparing conditions before and after IoT implementation. Key indicators included production efficiency, product consistency (measured through humidity variability), and the completeness of halal documentation records. The evaluation focused on identifying observable improvements attributable to real-time monitoring and automated data recording rather than statistical generalization.

The comparative results obtained from this pilot testing formed the basis for the analysis presented in the Results and Discussion section.

Results and Discussion

Field Findings

Field observations and surveys conducted among halal fish processing SMEs in Maluku indicate that most enterprises still rely on manual monitoring systems and paper-based documentation throughout their production processes. Approximately 85% of the surveyed SMEs perform environmental monitoring, quality control, and halal documentation manually. These practices are characterized by irregular record-keeping, delayed data availability, and a strong dependence on operator experience rather than standardized and measurable procedures. As a consequence, many SMEs exhibit low audit readiness and face difficulties in demonstrating consistent compliance with Halal Assurance System (HAS) requirements [3], [4].

The dominance of manual systems among island-based SMEs is closely linked to a set of structural and contextual constraints. Interviews with SME owners and production supervisors reveal that limited digital literacy, concerns regarding the cost of technology adoption, and unstable internet connectivity represent significant barriers to implementing digital monitoring solutions. In addition, production activities are often conducted using traditional methods inherited across generations, resulting in a preference for experiential knowledge over formal quality management systems. These conditions are consistent with previous studies on SME digital readiness in Indonesia, which emphasize that geographical isolation and infrastructure limitations slow down Industry 4.0 adoption in island and rural regions [6], [7].

Despite these constraints, the survey results also demonstrate a strong potential for digital transformation. Approximately 90% of respondents expressed a willingness to adopt digital monitoring and documentation systems, provided that such technologies are affordable, easy to operate, and compatible with existing production workflows. This finding suggests that resistance to technology is not the primary issue; rather, the lack of context-appropriate and low-cost solutions limits adoption. Similar patterns have been reported in previous studies on IoT implementation in food processing SMEs, where usability, affordability, and perceived operational benefits significantly influence technology acceptance [18], [19].

From a halal assurance perspective, the field findings indicate that manual monitoring practices are insufficient for ensuring consistent compliance with HAS standards. Critical Halal Control Points (CHCPs), including storage conditions, processing temperature, and handling duration, are often monitored intermittently and recorded retrospectively. This approach increases the likelihood of data inaccuracies and weakens traceability, particularly during halal audits and certification processes. Earlier studies have identified inadequate documentation and inconsistent monitoring as major contributors to halal non-compliance among SMEs [3], [15].

The findings also reveal limitations in the practical application of Total Quality Management (TQM) principles under manual operating conditions. Although some SMEs apply informal quality practices—such as maintaining product consistency and responding to customer feedback—the absence of real-time process data restricts systematic control and continuous improvement. Without accurate and timely data, quality management activities tend to be reactive rather than preventive, reducing the effectiveness of TQM implementation. This observation aligns with prior research indicating that TQM in halal SMEs requires technological support to function optimally, particularly in environments characterized by high variability and limited resources [12], [15].

Overall, the field findings highlight a clear gap between the requirements of halal assurance and quality management frameworks and the operational realities of SMEs in island regions. Manual production systems, environmental variability, and limited documentation capacity collectively create vulnerabilities in halal compliance and product consistency. At the same time, the high willingness of SMEs to adopt digital tools underscores the relevance of developing a low-cost, IoT-based integrated system that supports real-time monitoring, automated documentation, and traceability. These empirical findings provide a strong foundation for the design and implementation of the proposed IoT-based halal assurance system discussed in the subsequent subsections.

Prototype Implementation

To address the identified limitations of manual monitoring and documentation practices in halal SMEs, a functional prototype of an IoT-based integrated production and quality control system was developed. The design of this prototype prioritized cost-effectiveness, ease of use, low technical complexity, and alignment with Halal Assurance System (HAS) and Total Quality Management (TQM) principles.

Hardware Components and Justification

The hardware architecture of the prototype was based on the following key components:

a) Microcontroller/IoT Gateway (Arduino/ESP32): An ESP32 microcontroller was selected as the core computing unit due to its low cost, built-in Wi-Fi connectivity, low power consumption, and strong community support for troubleshooting and expansion. These characteristics make the ESP32 suitable for SMEs with limited technical expertise and budget constraints.
b) Environmental and Process Sensors: a. DHT22 Temperature and Humidity Sensor: Selected for its high accuracy and stability in monitoring ambient conditions, which are critical for halal fish processing where storage temperature and humidity influence product safety and compliance [18], [19]. b. Load Cell Weight Sensor: Installed at key control points to monitor processing quantities and weights, enabling real-time tracking of batch sizes and material flow, which supports traceability requirements.
c) Connectivity Components: A low-power Wi-Fi module was integrated with the microcontroller to facilitate continuous data transmission to cloud servers. The choice of Wi-Fi was informed by the availability of internet coverage in project sites, and alternative modules (e.g., GSM/LTE) were considered for areas with weaker connectivity.
d) Power Supply and Protection: To ensure consistent operation in island regions with unstable electricity, the prototype incorporated a regulated power supply with surge protection and a backup power option to prevent data loss during outages.

This hardware configuration was deliberately chosen to balance accuracy, affordability, and operational reliability, thereby addressing resource limitations typical of UMKM (Usaha Mikro, Kecil, dan Menengah) in island regions without compromising essential measurement requirements.

Software Integration and Data Management

The prototype's software architecture consisted of:

a) Sensor Firmware:

Custom firmware was developed to read sensor outputs at predefined intervals, preprocess raw data (e.g., filtering noise), and transmit the data packet to the cloud server using secure HTTP protocols. The firmware also included basic error-handling routines to cope with intermittent connectivity, storing data locally during transmission interruptions.

b) Cloud Backend:

A cloud server was configured to receive, store, and manage incoming data. A structured database schema supported time-series storage of sensor readings, event logs, and audit trails. The cloud component also implemented an API layer to facilitate data retrieval by front-end applications.

c) Dashboard and User Interface:

Web and mobile dashboards were developed with user-friendly visualization elements, including:

- Real-time charts for temperature, humidity, and weight
- Alerts and threshold notifications
- Exportable documentation reports for halal audits

The interface was designed to require minimal training, reflecting feedback from initial SME interviews that ease of use is critical for technology adoption.

d) Traceability and Compliance Module:

A dedicated compliance module was linked to the database to generate halal audit logs automatically. This module organized sensor data into verification reports aligned with HAS documentation standards, supporting retrospective audits and certification processes.

Calibration and Local Adaptation

Before full implementation, the prototype underwent a local calibration phase to ensure sensor accuracy under environmental conditions typical of island regions (e.g., high humidity, salt-laden air). Calibration was conducted in collaboration with SME operators to:

a) Compare sensor readings against manual reference instruments
b) Adjust thresholds for environmental conditions that reflect local production realities
c) Validate the responsiveness of alerts

Calibration ensured that the system produced reliable data suitable for both operational control and formal documentation.

Pilot Deployment Procedures

The prototype was deployed in selected fish processing SMEs following a systematic pilot protocol consisting of:

a) Site Assessment:
A preliminary assessment of physical layout, power availability, and internet strength was conducted to determine optimal sensor and gateway placements.
b) Installation and Testing:
Sensors and microcontrollers were installed at identified CHCPs (Critical Halal Control Points) according to the mapping in Table 1. Initial testing ensured data was correctly transmitted and visualized.
c) Operator Training:
SME operators received hands-on training in navigating the dashboard, interpreting alerts, generating reports, and basic troubleshooting. Emphasis was placed on empowering local operators to manage the system independently without recurring external technical support.
d) Observation Period:
A 4-week observation window was established to collect sufficient real-time data under normal production conditions. During this period, operation logs, anomaly reports, and user feedback were systematically recorded.

Challenges Encountered and Solutions

Throughout prototype development and deployment, several challenges were identified and systematically addressed:

a) Connectivity Interruptions:
Island regions occasionally experienced intermittent internet access. To mitigate this, the firmware incorporated a local buffering mechanism, storing data temporarily during outages and uploading in batch when connectivity resumed.
b) Environmental Interference**:**
High humidity and salt exposure posed risks to sensor longevity. Protective housings were designed to shield electronics while allowing airflow necessary for accurate sensing.
c) User Familiarity:
Initial operator hesitation was observed due to unfamiliarity with dashboards. This was mitigated by customizing interface elements with visual cues and simplified labels based on operator feedback during training.

Overall, the implementation demonstrated that a low-cost IoT system could be effectively adapted to the specific conditions of island-based halal SMEs, providing real-time operational visibility and supporting halal compliance documentation. The detailed performance outcomes and comparative analysis with manual systems are presented in the Results and Discussion section.

Comparative Performance Analysis

To evaluate the effectiveness of the proposed IoT-based integrated production and quality control system, a comparative performance analysis was conducted by examining key operational indicators before and after system implementation. The comparison focused on production efficiency, product consistency, and halal documentation readiness, as these indicators directly reflect the objectives of Total Quality Management (TQM) and Halal Assurance System (HAS) implementation in SMEs.

As summarized in Table 2, the adoption of the IoT-based system resulted in a measurable improvement in production efficiency, with an average reduction in processing cycle time of approximately 15% compared to manual monitoring practices. Under manual conditions, production activities were frequently interrupted due to delayed detection of environmental deviations, such as fluctuations in temperature and humidity. In contrast, real-time monitoring and automated alerts enabled faster corrective actions, minimizing downtime and improving workflow continuity. Similar efficiency gains have been reported in previous studies on IoT implementation in food processing SMEs, although most of those studies were conducted in non-island or industrialized settings [18], [19].

In terms of product consistency, the IoT-based system demonstrated a significant reduction in variability related to moisture and environmental conditions, with an observed decrease of approximately 20% compared to baseline conditions. Manual monitoring relied on periodic checks that often failed to capture short-term fluctuations, leading to inconsistent product quality. Continuous sensor-based monitoring allowed production parameters to be maintained within predefined halal-compliant ranges, supporting more stable processing outcomes. This finding aligns with prior research indicating that real-time environmental control is a critical factor in improving quality consistency in food SMEs [16], [17], while extending these findings to the specific context of halal production in island regions.

Halal documentation readiness showed the most substantial improvement following IoT adoption. Manual documentation systems were characterized by fragmented records, delayed data entry, and inconsistencies between production logs and actual operating conditions. The IoT-based system automatically generated time-stamped digital records linked to Critical Halal Control Points (CHCPs), significantly enhancing traceability and audit preparedness. This automated documentation process directly supports HAS requirements and addresses common weaknesses identified in halal SME audits [3], [15]. Compared to existing digital halal assurance models, which often require complex infrastructure or high implementation costs, the proposed system offers a more accessible alternative tailored to SME capabilities [12], [23].

Table 2. Comparative Performance: Manual vs IoT-Based Monitoring

Parameter	Manual Monitoring	IoT-Based Monitoring	Improvement
Production Efficiency	Baseline (100%)	+15% faster	Reduced cycle time
Product Consistency	High variability in moisture	20% less variability	Improved quality stability
Halal Documentation	Paper-based, inconsistent	Automated, cloud-based	Enhanced audit readiness

Performance evaluation shows that the system improved production efficiency by 15%, reduced moisture variability by 20%, and strengthened halal documentation compliance.

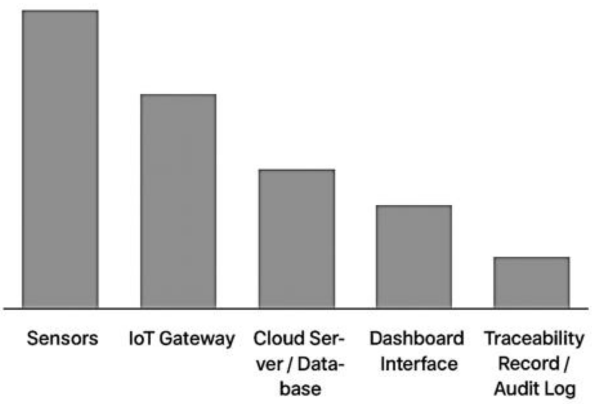

Figure 2. Comparison of Manual vs IoT-Based Monitoring Performance

Figure 2 illustrates the comparative performance between manual and IoT-based monitoring systems, highlighting consistent improvements across all evaluated parameters. While the magnitude of improvement observed in this study is comparable to that reported in earlier IoT-based quality control research, the novelty of the proposed approach lies in its integrative framework. Unlike previous studies that focus primarily on technical performance, this system simultaneously incorporates TQM principles, HAS compliance, and low-cost IoT technology within a unified operational model. This integration is particularly relevant for SMEs in island regions, where resource constraints and environmental variability demand simple yet robust solutions.

Overall, the comparative analysis confirms that the IoT-based integrated system outperforms manual monitoring practices across efficiency, consistency, and compliance dimensions. More importantly, the results demonstrate that meaningful performance improvements can be achieved without deploying complex or high-cost technologies. By contextualizing these findings within existing literature, this study contributes empirical evidence that low-cost IoT solutions can effectively support halal assurance and quality management in geographically constrained SME environments.

Discussion of Implications

The findings of this study have several important implications for halal SMEs, policymakers, and future research on digital transformation in island-based production systems. Beyond demonstrating technical feasibility, the proposed IoT-based integrated production and quality control system highlights how low-cost digital technologies can address structural challenges faced by SMEs in geographically constrained environments.

Implications for Halal SMEs

For halal SMEs operating in island regions, the integration of IoT technology with Total Quality Management (TQM) and Halal Assurance System (HAS) frameworks provides a practical pathway to improving operational performance and compliance simultaneously. The observed improvements in production efficiency and product consistency indicate that real-time monitoring enables SMEs to move from reactive problem-solving toward preventive process control. This shift is consistent with core TQM principles, which emphasize continuous improvement and data-driven decision-making [12], [15].

Furthermore, the automated documentation and traceability features of the proposed system significantly enhance halal audit readiness. By generating time-stamped digital records linked to Critical Halal Control Points (CHCPs), SMEs can reduce their dependence on manual paperwork and minimize the risk of incomplete or inconsistent records. This is particularly important for small enterprises that often lack dedicated quality assurance personnel. As a result, the system lowers the operational burden associated with halal certification and increases SMEs' confidence in engaging with certification bodies and broader markets [3], [15].

From an economic perspective, the use of low-cost and open-source components ensures that the system remains financially accessible to SMEs. Rather than requiring large upfront investments, the modular design allows gradual adoption based on enterprise capacity. This affordability increases the likelihood of sustained use and scalability, which are critical factors for digital transformation initiatives in small enterprises [18].

Policy and Institutional Implications

The results of this study also carry implications for government agencies, halal certification bodies, and development institutions involved in SME empowerment. The findings suggest that digital halal assurance systems do not necessarily require complex or high-end technologies to be effective. Instead, targeted support for low-cost IoT solutions, combined with basic digital literacy training, can significantly improve halal compliance and quality management among SMEs in island regions.

Policymakers may consider integrating similar IoT-based monitoring systems into existing SME development programs, particularly those focused on halal industry growth and Industry 4.0 adoption. Subsidies, pilot grants, or public–private partnerships could accelerate technology diffusion and reduce the digital divide between urban and island-based enterprises. Additionally, halal certification bodies could leverage digital audit logs generated by such systems to streamline inspection processes and enhance transparency, thereby strengthening trust in halal supply chains [23], [24].

Implications for Digital Transformation in Island Regions

The study contributes to a broader understanding of digital transformation in island and remote regions, where infrastructure limitations and environmental variability often hinder technology adoption. The successful implementation of the proposed system demonstrates that digital solutions can be adapted to challenging contexts when they are designed with local constraints in mind. This reinforces the importance of contextualized technology design rather than direct replication of models developed for urban or industrial settings [6], [7].

Moreover, the integration of managerial, compliance, and technological dimensions within a single system illustrates a holistic approach to digital transformation. Rather than treating IoT adoption as a purely technical upgrade, this study shows that meaningful performance improvements occur when technology is embedded within established management frameworks such as TQM and HAS.

Implications for Future Research

From an academic perspective, the findings open several avenues for future research. While this study focuses on fish processing SMEs, the proposed framework may be adapted to other halal product categories, including meat processing, dairy products, and ready-to-eat foods. Comparative studies across different product types and regions could further validate the scalability and generalizability of the model.

In addition, future research could explore the integration of advanced digital technologies, such as blockchain for end-to-end halal traceability and machine learning for predictive quality and compliance monitoring. Such extensions would enhance the analytical capabilities of the system while building upon the low-cost IoT foundation established in this study.

Overall, the discussion of implications underscores that the proposed IoT-based integrated system is not merely a technical prototype, but a strategic tool for strengthening halal assurance, improving SME competitiveness, and supporting sustainable digital transformation in island-based economies.

Limitations and Future Research

Despite the promising results obtained in this study, several limitations should be acknowledged to provide a balanced interpretation of the findings and to guide future research directions.

First, the scope of the empirical implementation was limited to a small number of halal SMEs within island regions, particularly those engaged in fish-based food processing. While this focus allowed for in-depth observation and system adaptation to local conditions, it may limit the generalizability of the findings to other types of halal products, such as meat, dairy, or processed beverages. Future studies should involve a broader range of halal SMEs across different product categories and geographical contexts to validate the scalability and adaptability of the proposed system.

Second, the performance evaluation relied primarily on short-term pilot implementation and observational comparisons between manual and IoT-based monitoring systems. Although measurable improvements in production efficiency, environmental stability, and documentation readiness were observed, long-term performance data were not captured. Extended deployment over longer production cycles would enable a more comprehensive assessment of system reliability, maintenance requirements, and sustainability impacts over time.

Third, the current system architecture focuses on real-time monitoring and digital documentation but does not yet incorporate advanced data analytics or predictive capabilities. The absence of machine learning or predictive quality models limits the system's ability to anticipate process deviations before they occur. Future research could explore the integration of artificial intelligence techniques to enhance predictive quality control and proactive halal risk management.

Fourth, connectivity constraints remain a critical challenge in island regions. Although the system was designed to operate under intermittent internet conditions, data synchronization delays may still affect real-time decision-making in certain scenarios. Further research could investigate hybrid communication architectures, such as the integration of edge computing or low-power wide-area networks (LPWAN), to improve system robustness in low-connectivity environments.

Finally, this study did not conduct a detailed cost–benefit analysis or assess user acceptance quantitatively. While qualitative observations indicate positive user responses, future studies should incorporate economic evaluations and technology acceptance models to better understand adoption drivers, perceived usefulness, and long-term willingness of SMEs to sustain digital halal assurance systems.

Addressing these limitations through future research will not only strengthen the empirical foundation of IoT-based halal assurance systems but also support the development of more comprehensive, intelligent, and resilient digital transformation models for halal SMEs in island and remote regions.

Conclusion

This study has demonstrated the potential of an IoT-based integrated production and quality control system as an effective approach to strengthening halal assurance and operational performance among SMEs operating in island regions. By integrating real-time environmental monitoring, digital documentation, and Total Quality Management (TQM) principles within a Halal Assurance System (HAS) framework, the proposed system addresses both technical and managerial challenges commonly faced by halal SMEs.

The empirical findings indicate that the adoption of low-cost IoT technology contributes to measurable improvements in production efficiency, product consistency, and halal documentation readiness when compared to conventional manual systems. These improvements highlight the role of real-time data visibility and automated record-keeping in supporting preventive quality control and enhancing audit preparedness. Importantly, the system design emphasizes affordability, modularity, and contextual adaptability, making it suitable for SMEs with limited resources and operating in geographically constrained environments.

Beyond technical performance, this study underscores that digital transformation for halal SMEs should not be viewed solely as a technological upgrade. Instead, meaningful impact emerges when digital tools are embedded within established management frameworks such as TQM and aligned with halal compliance requirements. The proposed system illustrates a holistic model in which technology, quality management, and halal governance mutually reinforce one another.

Despite these promising results, this study is subject to certain limitations, including the limited scope of implementation, short-term evaluation period, and the absence of advanced predictive analytics and comprehensive economic assessment. These limitations open opportunities for future research to expand the system's application across different halal product categories, incorporate intelligent data analytics, and evaluate long-term economic and organizational impacts.

Overall, this study contributes to the growing body of knowledge on Industry 4.0 adoption in halal food systems by providing a practical and scalable model tailored to island-based SMEs. The findings offer valuable insights for researchers, practitioners, and policymakers seeking to promote sustainable digital transformation, enhance halal assurance, and improve the competitiveness of halal SMEs in remote and island regions.

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