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Strategies for Integrating Technology into Hazard Analysis and Critical Control Points (HACCP) Systems to Optimize Food Safety

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ABSTRACT

This study aims to analyze strategies for integrating technology into Hazard Analysis and Critical Control Points (HACCP) systems to optimize food safety in food production businesses. The study addresses the challenge of conventional HACCP implementation, which often depends on manual documentation, delayed monitoring, and limited traceability. A qualitative case study approach was used in three food production businesses in Surabaya, East Java, Indonesia, from January to April 2025. Data were collected through semi-structured interviews, non-participant observation, and documentation involving business owners, production managers, quality control officers, production operators, and food safety documentation staff. The data were analyzed using thematic analysis supported by the interactive model of Miles, Huberman, and Saldaña. The findings reveal four main themes: digital monitoring as a response to manual HACCP limitations, traceability as a source of control and accountability, employee adaptation as a key condition for technology use, and managerial support as the foundation of sustainable digital HACCP. The study shows that technology improves monitoring accuracy, documentation, and corrective action, but its success depends on employee competence, organizational readiness, and food safety culture. The findings contribute to socio-technical understanding of digital HACCP and offer practical guidance for food businesses and policymakers in developing adaptive, realistic, and sustainable food safety systems.

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1. Introduction

Food safety has become a major concern in modern food production because food supply chains now involve longer distribution routes, more actors, and more complex control points. Hazard Analysis and Critical Control Points, or HACCP, remains one of the main preventive systems used to identify, evaluate, and control food safety hazards. However, many food businesses still implement HACCP through manual records, paper-based monitoring, and delayed corrective action reports. This condition creates problems in data accuracy, traceability, and rapid decision-making. Recent studies show that digital technologies can strengthen prerequisite programs and

HACCP activities, although adoption still faces financial, managerial, training, and system integration barriers (Sartoni et al., 2025).

In Indonesia, food safety management is closely related to public health, consumer trust, business competitiveness, and regulatory compliance. Food producers, especially small and medium-scale food industries, often face practical challenges in maintaining consistent temperature control, sanitation records, raw material traceability, and corrective action documentation. In field practice, HACCP is sometimes treated as a certification requirement rather than a daily risk control system. This weakens its preventive function because hazards may be identified only after production deviations occur. The issue becomes more important as consumers demand safer, more transparent, and better-documented food production processes.

Technology offers an opportunity to improve HACCP implementation. Internet of Things devices can support real-time monitoring of temperature, humidity, storage conditions, and processing parameters. Blockchain can improve traceability by recording product movement and supply chain transactions in a tamper-resistant system. Artificial intelligence can support predictive risk analysis, anomaly detection, and decision-making in food safety control. Kaur et al. (2022) explain that IoT and blockchain integration can help monitor food conditions and transportation problems in food supply chains. Gondal et al. (2023) also show that blockchain and IoT-enabled systems can improve transparency and shipment efficiency in perishable food supply chains.

Despite these benefits, technology integration into HACCP is not only a technical matter. It also involves organizational readiness, employee competence, work culture, cost allocation, leadership commitment, and acceptance of new procedures. In many food businesses, workers may feel burdened by digital documentation if they do not receive adequate training. Managers may also hesitate to invest in digital systems when the direct economic benefits are unclear. Dzwolak and Anim (2025) found that small food businesses face barriers in maintaining HACCP-based systems due to documentation burdens, limited financial resources, weak infrastructure, and operational constraints. These findings indicate that digital HACCP must be understood as a socio-technical process rather than a simple technology installation.

Previous studies have discussed digital food safety systems, blockchain traceability, IoT monitoring, and artificial intelligence in food quality management. However, many studies still focus on technical performance, system architecture, or supply chain efficiency. Limited research has explored how food industry actors experience, interpret, and negotiate the integration of technology into HACCP routines. This gap is important because technology adoption depends on how users understand its value, how they adapt work practices, and how organizations redesign control procedures. A qualitative approach can address this gap by examining meanings, experiences, barriers, and strategies from the perspective of actors directly involved in HACCP implementation.

This study is grounded in a socio-technical system perspective and food safety culture theory. The socio-technical perspective views technology, people, tasks, structures, and organizational environments as interconnected elements. In HACCP implementation, digital tools cannot work effectively without trained users, reliable procedures, managerial support, and a culture that prioritizes prevention. Food safety culture theory also emphasizes shared values, daily habits, communication, and leadership commitment in shaping safe food practices. Therefore, technology integration should not only improve monitoring accuracy but also strengthen awareness, responsibility, and evidence-based decision-making.

Based on this background, this study aims to analyze strategies for integrating technology into HACCP systems to optimize food safety in food production businesses. The study focuses on the types of technology used, actors' experiences in implementing digital HACCP, organizational barriers, and strategies used to maintain effective control of critical points. Theoretically, this study contributes to the development of socio-technical understanding in food safety management. Practically, it provides guidance for food businesses, auditors, regulators, and policymakers in designing digital HACCP systems that are realistic, adaptive, and suitable for field conditions.

2. Materials and Methods

In the method section, the author(s) should provide a detailed account of the procedures, materials, and equipment used in the research. This includes a comprehensive description of the study design, participants or subjects, materials used, procedures followed, and data analysis techniques employed. The goal is to offer sufficient information for other researchers to replicate the study, thereby ensuring the reproducibility and validity of the findings.

This study used a qualitative approach with a case study design. The case study design was selected because the research aimed to explore technology integration into HACCP systems within a real organizational setting. This design allowed the researcher to examine the interaction between digital tools, HACCP procedures, employee practices, managerial decisions, and food safety culture. A qualitative case study was considered suitable because the research did not aim to measure the statistical effect of technology, but to understand how actors experience, interpret, and manage the process of digital HACCP implementation.

The study was conducted in Surabaya, East Java, Indonesia, from January to April 2025. Surabaya was selected because it has a dense food industry ecosystem, including small and medium-scale food producers, catering businesses, processed food manufacturers, and distribution networks. The research site consisted of three food production businesses that had implemented HACCP principles and had begun using digital tools such as temperature sensors, spreadsheet-based monitoring, barcode traceability, digital audit forms, or cloud-based documentation systems. These sites were selected because they represented transitional conditions between conventional HACCP and technology-supported HACCP.

The participants consisted of business owners, production managers, quality control officers, production operators, warehouse staff, and personnel responsible for food safety documentation. Informants were selected through purposive sampling. The inclusion criteria were direct involvement in food production or food safety control, at least one year of work experience, familiarity with HACCP procedures, and involvement in digital monitoring or documentation activities. Snowball sampling was also used when initial informants recommended other individuals who had specific knowledge about system operation, audit preparation, corrective action records, or digital traceability. The final number of informants was determined based on data saturation, when new interviews no longer produced substantially new themes.

Data were collected through semi-structured interviews, non-participant observation, and documentation. Semi-structured interviews explored participants' experiences with HACCP implementation, perceived benefits of technology, barriers to digital adoption, changes in work routines, and strategies used to maintain monitoring accuracy. Observations were conducted in raw material receiving areas, storage rooms, production areas, packaging sections, and documentation points. Documentation analysis included HACCP plans, monitoring forms, standard operating procedures, temperature records, sanitation checklists, corrective action reports, training records, and audit documents. The combination of these techniques allowed the researcher to compare what participants said, what they did, and what was recorded in formal documents.

Data validity was ensured through source triangulation, method triangulation, member checking, and audit trail. Source triangulation was conducted by comparing information from owners, managers, quality control officers, and operators. Method triangulation was conducted by comparing interview data, observation notes, and company documents. Member checking was carried out by returning interview summaries and preliminary interpretations to selected informants for confirmation. An audit trail was maintained by documenting interview guides, field notes, coding decisions, analytic memos, data reduction steps, and theme development. These procedures strengthened the credibility, dependability, and confirmability of the findings.

Data were analyzed using thematic analysis supported by the interactive model of Miles, Huberman, and Saldaña. The analysis began with transcription of interview data and repeated reading of all field notes and documents. The researcher then conducted open coding to identify important meanings related to digital monitoring, traceability, employee adaptation, management support, infrastructure constraints, training needs, and corrective action practices. Similar codes were grouped into broader categories and then developed into themes. The final themes were verified by comparing them across participants, observation results, and documents. This process enabled the researcher to identify practical strategies for integrating technology into HACCP systems while preserving the contextual depth required in qualitative research.

3. Results and Discussions

The analysis produced four main themes: digital monitoring as a response to manual HACCP limitations, traceability as a source of control and accountability, human adaptation as the main condition for technology use, and managerial support as the foundation of sustainable digital HACCP. These themes show that technology integration was not understood only as the use of devices, but as a change in how food safety risks were identified, recorded, communicated, and corrected in daily production activities.

The first theme concerns the shift from manual monitoring to digital monitoring. Most participants stated that manual HACCP records often caused delays, incomplete forms, and difficulty in tracing deviations. Temperature monitoring, sanitation checks, and corrective action records were previously written by hand and reviewed only at the end of the shift. After the use of digital forms and temperature sensors, quality control officers could detect deviations faster. One quality control officer explained, “Before using the digital record, we often knew the problem after production ended. Now, when the temperature changes, we can respond earlier.” This finding indicates that digital tools helped HACCP become more preventive, not only administrative.

The second theme relates to traceability and data accountability. Participants reported that barcode records, spreadsheet-based batch tracking, and cloud documentation made it easier to trace raw materials, production dates, storage conditions, and distribution records. This system reduced dependence on individual memory and improved the ability to identify the source of potential hazards. A production manager stated, “If there is a complaint, we can check the batch, supplier, and storage record faster. We do not need to open many paper files.” This pattern supports recent findings that digitalisation can strengthen HACCP activities, especially documentation, monitoring, and corrective action processes.

The third theme shows that technology integration depended strongly on employee readiness. Some operators initially saw digital documentation as an additional workload. They were more familiar with paper forms and needed time to understand the logic of digital records. Observations showed that older workers often asked younger staff for help when uploading data or reading sensor alerts. One operator said, “The system is useful, but at first we were afraid of making mistakes. We needed repeated training.” This finding shows that digital HACCP requires continuous learning, simple system design, and internal assistance during the adaptation period.

The fourth theme concerns managerial support. Businesses that provided training, clear task division, and routine evaluation showed smoother technology adoption. Managers played an important role in explaining why digital records were needed, how data would be used, and who was responsible for responding to deviations. In contrast, weak managerial support caused confusion because employees used digital tools only to meet audit requirements. This condition confirms that barriers to HACCP maintenance often relate to documentation burden, limited resources, weak infrastructure, and operational constraints in small food businesses.

Overall, the results show that technology integration into HACCP produced practical benefits, but its success depended on the alignment between tools, users, procedures, and organizational culture. Digital systems improved speed, accuracy, traceability, and data visibility. However, technology did not automatically solve food safety problems. It worked effectively only when employees understood its function, management supported its use, and HACCP procedures were redesigned to fit daily production routines.

Discussion

The findings support the socio-technical system perspective. Technology integration into HACCP cannot be separated from human behavior, work routines, organizational structure, and food safety culture. Sensors, digital forms, and traceability systems improved monitoring capacity, but employees still made key decisions in interpreting alerts, recording deviations, and applying corrective actions. This finding aligns with Sartoni et al., who found that digitalisation can support prerequisite programs and HACCP activities, but also faces managerial and technological constraints such as financial impact, resistance to change, training needs, system fragmentation, and data entry burdens.

The results also strengthen previous studies on IoT and blockchain in food supply chains. Kaur et al. explain that IoT and blockchain can improve monitoring, transparency, and traceability in food supply chain management. In this study, similar benefits appeared in simpler forms, such as barcode tracking, digital batch records, and cloud-based documentation. This shows that small and medium food businesses do not always need advanced technology at the beginning. They can start with low-cost digital tools as long as the system supports critical control point monitoring, corrective action, and traceability.

The finding on employee adaptation offers an important contribution. Many technical studies emphasize the capacity of AI, IoT, and blockchain to improve food safety. However, this study shows that the main challenge is not only technological readiness, but also user confidence and work culture. Wang et al. argue that AI can support monitoring, evaluation, and action in food safety behavior. This study adds that such potential will not be achieved if employees feel that digital tools only increase workload or create fear of error.

The study also differs from research that presents digital technology as a direct solution for food safety management. In the observed cases, technology improved documentation and early detection, but several limitations remained. Internet instability, limited devices, uneven digital skills, and unclear responsibilities still affected implementation. This means that digital HACCP should be introduced gradually through training, workflow redesign, and leadership commitment. Dzwolak and Anim's findings on small food businesses support this interpretation because HACCP maintenance can be hindered by resource limitations, infrastructure problems, and operational pressures.

The theoretical implication of this study lies in its emphasis on digital HACCP as a socio-technical practice. HACCP digitalisation should not be treated only as system automation. It should be understood as a process that reshapes how food safety knowledge is produced, shared, and used in daily work. The practical implication is that food businesses need a staged strategy: identify the most critical manual weaknesses, select suitable digital tools, train users, assign clear responsibilities, evaluate data quality, and connect digital records with corrective action decisions.

Future research can expand this study by comparing different food sectors, such as catering, dairy, bakery, meat processing, and frozen food industries. Further studies can also combine qualitative and quantitative methods to measure how digital HACCP affects deviation response time, audit performance, employee compliance, and product safety outcomes. A broader study across regions in Indonesia would also help explain how local infrastructure, regulatory support, and business scale influence the adoption of technology in HACCP systems.

4. Conclusions

This study concludes that technology integration into HACCP systems strengthens food safety management by improving monitoring accuracy, traceability, documentation, and response to critical control point deviations. The findings show that digital HACCP is not only a technical process, but also a socio-technical practice shaped by employee readiness, managerial support, training, infrastructure, and food safety culture. The study contributes to the literature by explaining how technology changes daily HACCP routines and how food industry actors adapt to digital monitoring, corrective action, and data-based decision-making.

Theoretically, this study reinforces the socio-technical system perspective in food safety management. Practically, the findings suggest that food businesses should adopt technology gradually, beginning with the most critical manual weaknesses, supported by clear procedures, user training, and regular evaluation. From a policy perspective, regulators and industry associations need to support small and medium food businesses through technical guidance, affordable digital tools, and capacity-building programs. Future research should examine digital HACCP implementation across different food sectors and combine qualitative findings with quantitative indicators such as response time, audit performance, and compliance rates.

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