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ADVANCES IN FOOD SAFETY MANAGEMENT: CURRENT MONITORING STRATEGIES AND IMPLEMENTATION CHALLENGES IN FOOD PROCESSING UNITS

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Abstract

The implementation of food safety management systems (FSMS) is essential for ensuring food quality, consumer health, and regulatory compliance in food processing units. This review examines current monitoring practices, highlighting both established approaches such as Hazard Analysis and Critical Control Points (HACCP) and modern technologies like blockchain, Internet of Things (IoT) sensors, and real-time data analytics. These advancements enable more precise control, traceability, and risk management across the food supply chain. Despite technological progress, several barriers hinder effective FSMS implementation. Key challenges include insufficient staff training, limited financial resources, regulatory complexity, and difficulties in integrating advanced monitoring systems into existing workflows. Small and medium-sized enterprises (SMEs) are particularly affected due to constrained budgets and technical expertise. This review underscores the importance of overcoming these barriers through targeted interventions. Future research should focus on cost-effective, scalable solutions tailored to diverse food processing environments, ensuring that FSMS implementation becomes more efficient, sustainable, and globally standardized.

***Key words**: compliance challenges, food safety culture, risk assessment, technology integration, traceability systems.*

INTRODUCTION

Food safety is a critical public health concern, with the global food industry facing increasing pressure to ensure the quality and safety of food products (Lee et al., 2021). Due to the constant and persistent risks posed by foodborne illnesses and contamination, consumer awareness is increasing alongside regulatory demands (Yiannas, 2009; King, 2020).

Food safety, nutrition and food security are inextricably linked. It is estimated that 600 million 10% people in the world fall ill after eating contaminated food and 420 000 die every year. Foodborne illnesses are usually infectious or toxic in nature and caused by bacteria, viruses, parasites or chemical substances entering the body through contaminated food. Chemical contamination can lead to acute poisoning or long-term diseases, such as cancer (WHO, 2024).

Governments should make food safety a public health priority, as they play a pivotal role in developing evidence-based policies and risk-based, flexible regulatory frameworks and establishing and implementing effective food safety systems.

Food safety is a shared responsibility among different national authorities and requires a multisectoral, one health approach, to be addressed in all the steps of the food chain.

Food processing units are required to implement robust food safety management systems (FSMS) that not only meet compliance requirements but also support proactive risk mitigation (Unnevehr & Jensen, 1999; WHO, 2022).

The Hazard Analysis Critical Control Points (HACCP) framework is a crucial part of FSMS, playing a key role in identifying and controlling food safety hazards at critical points in the process (Mortimore & Wallace, 2013).

To maintain safe production environments, several other systems alongside HACCP are considered foundational to food safety, including Good Manufacturing Practices (GMP), ISO 22000 standards, and GFSI-recognized schemes (Wallace et al., 2018; ISO, 2018).

Modern food safety is increasingly shifting toward a continuous improvement mindset, centered on adaptability, learning, and evolution. This approach not only focuses on identifying hazards but also monitors performance, conducts internal audits and root cause analysis, and integrates corrective and preventive actions (Powell et al., 2011; Sampers et al., 2010).

Moreover, continuous improvement does more than strengthen the effectiveness of FSMS; it also supports and promotes a culture of safety and innovation within organizations (Griffith, 2010; Yiannas, 2009).

In parallel, the rise of digital technologies, such as Internet of Things (IoT) sensors, blockchain, and artificial intelligence offers new opportunities to enhance this improvement cycle. Real-time data analytics and cloud-based platforms such as Industry 4.0 and Manufacturing execution system (MES) allow food businesses to respond rapidly to deviations, enabling preventive action before hazards escalate (Trienekens & Zuurbier, 2008; Luning et al., 2015).

However, the benefits of these advancements are not fully realized without a strategic framework that promotes continuous learning and operational adaptation.

This paper aims at analysing the monitoring strategies used in food processing units, taking into consideration both conventional systems and emerging digital tools.

It also explores the challenges of FSMS implementation, especially among small and medium-sized enterprises (SMEs), and emphasizes the importance of implementing continuous improvement techniques into food safety strategies for long-term stability and global food industry requirements.

MATERIALS AND METHODS

This article is based on an academic literature search and qualitative analysis of scientific publications, various technical books, regulatory guidelines, and case studies related to the implementation and evolution of food safety management systems (FSMS) in food processing environments.

In order to identify these sources, databases such as ScienceDirect, Scopus, Web of Science, and Google Scholar, were used along with academic publishers including Springer, Wiley, and Elsevier. The literature search used combinations of keywords such as "food safety management systems", "HACCP", "GMP", "ISO 22000", "GFSI", "continuous improvement in FSMS", "food safety culture", "blockchain traceability in food", "IoT sensors food safety", and "FSMS implementation challenges in SMEs".

To ensure relevance and quality, this paper prioritized peer-reviewed journal articles and scientific papers, academic books from professional experts and international regulatory and standards publications, such as ISO 22000:2018 and GFSI Benchmarking Requirements (2020).

Moreover, this article also reviewed official guidelines from global food safety authorities like the European Food Safety Authority (EFSA), Food and Agriculture Organization (FAO), and U.S. Food and Drug Administration (FDA).

Inclusion criteria

In order to conduct this analysis, we reviewed articles and books specifically addressing FSMS in food processing units.

Studies discussing monitoring tools, system integration, or performance evaluation were also a key part of this paper, together with research analysing regulatory frameworks, technological innovation, or continuous improvement.

We included crucial information from papers including real-world applications and comparative case studies.

Exclusion criteria

Publications focused solely on primary production or retail sectors and outdated frameworks not aligned with ISO 22000:2018 or current HACCP principles were excluded.

RESULTS AND DISCUSSIONS

Traditional Monitoring Strategies

Traditional monitoring in food safety and quality assurance refers to routine, scheduled activities that check whether control measures are operating as intended, primarily through visual inspections, measurements (e.g., time-temperature, pH, aw), microbiological sampling, record reviews, and internal audits.

In HACCP-based systems and modern Food Safety Management Systems (FSMS) frameworks, monitoring supplies real-time evidence for control at critical control points (CCPs) and supports verification across prerequisite programs (PRPs) such as sanitation, allergen control, pest management, and supplier management (FAO & WHO, 2023; USFDA, 2025; Mihafu et al., 2020).

a) *CCP monitoring (process controls)*
At CCPs, operators track critical limits using calibrated instruments and defined frequencies (e.g. continuous cook temperature charting or per-lot metal detection checks). The Codex General Principles of Food Hygiene (rev. 2020) require documented monitoring procedures that define what is measured, how, by whom, and when, with immediate corrective actions when limits are not met. ISO 22000:2018 integrates these HACCP principles and requires organizations to plan monitoring and measurement, maintain records, and ensure equipment is fit for purpose. Under FSMA's Preventive Controls (Panghal et al., 2018), monitoring of process preventive controls must be documented and reviewed. Typical tools used for CCP monitoring are calibrated thermometers/thermocouples, chart recorders or digital data loggers, flow meters, pH/aw meters, sieves/metal detectors/X-ray systems, and checklists tied to line clearance and start-up verification. Calibration/verification of monitoring devices is mandatory in ISO 22000 and expected by GFSI standards (e.g., BRCGS, IFS).

b) *PRP monitoring (GMPs and sanitation)*
Traditional PRP monitoring confirms the day-to-day hygiene and infrastructure controls: pre-op inspections, cleaning and sanitation sign-offs, allergen changeover checks, pest control service reports, glass and brittle plastic inspections, water/ice quality checks, and employee hygiene observations. Codex (2020) emphasizes robust GHP/PRP monitoring and adds explicit expectations for training and food safety culture that should be reflected in monitoring and review. U.S. CGMPs and preventive controls require monitoring of sanitation controls where necessary to significantly minimize hazards (IFS, 2023).

c) *Environmental monitoring (EMP)*
Culture-based swabbing or contact plate sampling of food-contact and non-food-contact surfaces remains a cornerstone for ready-to-eat (RTE) operations, particularly for *Listeria* and *Salmonella*. ISO 18593:2018 provides standardized surface sampling methods (swabs, sponges, contact plates) and sampling scheme design; *Listeria* and *Salmonella* detection follow ISO 11290-1:2017 and ISO 6579-1:2017 respectively. Traditional EMPs use routine zones (1–4), rotating sites, and intensified "seek-and-destroy" sampling after positives. Multiple reviews reaffirm that relying only on finished-product testing is insufficient; proactive environmental monitoring is essential to detect harbourage and loss of control (De Oliveira et al., 2021; ISO 2017; ISO, 2018)
Program elements for traditional approach are: site list with zoning, frequencies (e.g., weekly/biweekly), defined organisms/indicators (e.g., *Listeria* spp., *Salmonella*, Enterobacteriaceae, APC), methods and labs, action levels, corrective actions (isolate, clean, sanitize, resample), and trending (IFS, 2023).

d) *Finished-product and in-process testing*
Traditional microbiological monitoring includes end-product or in-process sampling against microbiological criteria. Classical attribute plans (n/c) and three-class plans (n/c/m/M) from ICMSF underpin acceptance decisions; however, their statistical power to detect low-prevalence hazards is limited, making them more suitable as verification than as primary control. Contemporary literature underscores that finished-product testing is "too little, too late" for many hazards and should complement, not replace, process/EMP monitoring (Pérez-Lavalle et al., 2020; Zwietering et al., 2012).

e) *Supplier and incoming material monitoring*
Traditional approaches include approved supplier lists, certificates of analysis (COAs), audit results, and periodic incoming inspection/testing (identity, allergens, composition, microbiology). FSMA requires supply-chain programs where hazards are controlled by suppliers; EU Official Controls

provide the framework for competent authority verification. GFSI standards also require documented supplier assessment and monitoring with defined acceptance criteria (EU Regulation 2017/625).

f) *Internal audits and walkthroughs*
Routine internal audits verify that monitoring is done, records are complete, and the system is effective. ISO 19011:2018 provides the methodology for audit programs, auditor competence, and conducting audits that many FSMSs adopt. BRCGS and IFS expect scheduled internal audits, including factory hygiene inspections and GMP walks, with corrective actions and follow-up (ISO, 2018).
g) *Recordkeeping, review, and trend analysis*
Traditional programs rely on paper or basic electronic logs for CCPs, sanitation checks, EMP results, calibrations, maintenance, and training. Supervisors (and Preventive Controls Qualified Individuals under FSMA) review records to confirm timeliness, completeness, and corrective actions. Trend analysis - often using simple control charts or Pareto reviews - helps detect drift (e.g., rising APCs, escalating hold/release events) and triggers re-assessment of sampling frequencies or sanitation intensity. ISO 22000 requires planned evaluation of monitoring data and verification activities to feed management review (ISO, 2018).
An overview of traditional FSMS implemented in food processing units, reviewing their key features and limitations is presented in Table 1.

Table 1. Overview of traditional FSMS implemented in food processing units, reviewing their key features and limitations

FSMS Approach	Key Features	Limitations
Hazard Analysis and Critical Control Points (HACCP)	Systematic identification and control of food safety hazards at critical points.	Requires rigorous documentation; effectiveness depends on staff training and commitment.
Good Manufacturing Practices (GMP)	Guidelines ensuring products are consistently produced and controlled according to quality standards.	Often considered baseline; may not address all specific hazards without integration into broader FSMS.
ISO 22000 GFSI	International standard combining HACCP principles with prerequisite programs for comprehensive FSMS.	Implementation can be resource-intensive; may be challenging for SMEs to maintain certification.

The most important system of food safety in processing units remains the Hazard Analysis and Critical Control Points (HACCP).
This system focuses on identifying hazards, determining critical control points (CCPs), and establishing monitoring procedures. Alongside HACCP, ISO 22000 and GFSI benchmarked standards provide a more structured, risk-based approach.

Emerging Technologies in FSMS
The integration of technology into FSMS has significantly improved traceability, monitoring precision, and real-time responsiveness (Figure 1).

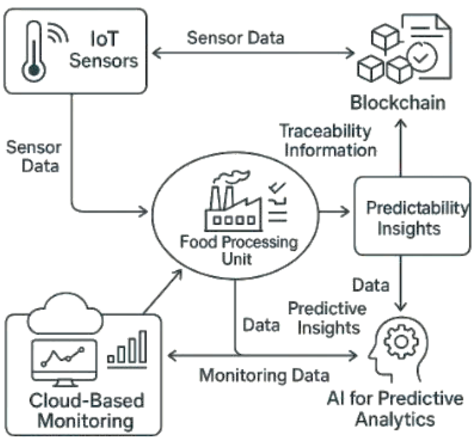

Figure 1. Integration of emerging technologies into FSMS, displaying how innovations like IoT sensors, blockchain, and AI contribute to enhanced food safety monitoring

a) *Genomics at scale: WGS & metagenomics*
Whole-genome sequencing (WGS) and metagenomics provide high-resolution typing for pathogens and root-cause analysis (RCA). Rapidly links environmental or product isolates to outbreaks, supports "seek-and-destroy," and strengthens verification. ISO 23418:2022 sets requirements for WGS in the food chain; EFSA/WHO/FDA endorse WGS for surveillance and outbreak response; FDA's GenomeTrakr is a global network sharing WGS data for real-time comparisons (EFSA, 2022; USFDA, 2025). This can be used in high-risk environments, persistent *Listeria/Salmonella* issues, supplier qualification (deep dives), and post-deviation RCA.

b) *Tech-enabled traceability & interoperable records*
Represents a digital capture of critical tracking events (harvest, pack, ship, receive, transform) and key data elements across partners; often the backbone for recall readiness. Why it matters. Faster traceback, narrower recalls, better stock segregation. FDA's FSMA Food Traceability Final Rule standardizes recordkeeping for foods on the Food Traceability List—part of the New Era of Smarter Food Safety blueprint that aims for end-to-end, tech-enabled traceability. (Compliance date currently proposed for extension (USFDA, 2024). It is used in any multi-node supply chain; start with FTL commodities and ingredients with complex transformations (Aswathi et al., 2022; Taiwo et al., 2024).
c) *AI & predictive analytics,* a machine-learning models that fuse process, environmental, and supply data to predict risk (e.g., pre-harvest contamination, EMP hot spots, cold-chain abuse). This turns monitoring data into leading indicators (e.g., "rising risk of *Listeria* in Zone 3 next shift"). Recent reviews show AI enhancing predictive microbiology and decision support; integration with sensor/Hyperspectral Imaging (HSI) is accelerating (Taiwo et al., 2024; Tarlak, 2023). EMP trend analysis, sanitation scheduling, dynamic sampling plans, and anomaly detection in continuous temperature/pH streams.

d) *Rapid & field-deployable diagnostics*
Is an isothermal amplification (e.g., LAMP), microfluidics, and CRISPR-based assays with lateral-flow or fluorescent readouts; often usable at line or receiving. It is hours-level results for holds and targeted sanitation, with lower equipment burden than qPCR. Reviews since 2022 document LAMP's performance in food matrices and the rise of CRISPR biosensors for foodborne pathogens (Moon et al., 2023; Nan et al., 2024). It is used in high-volume ingredients (rapid release), post-clean validations, and surge testing during investigations.

e) *Smart sensors, intelligent packaging & IoT,* networked data logger, RFID/BT trackers, time-temperature indicators (TTIs), gas/ VOC sensors, and smart labels that follow product conditions from pack to shelf. It provides continuous verification of cold-chain and real-time spoilage indicators; reduces waste and complaint risk. Recent reviews cover intelligent packaging sensors/TTIs and IoT-enabled freshness monitoring; pilots have tied package IDs to blockchain item records for authenticity and traceability (Mkhari et al., 2025; Ivy et al., 2024). It can be used for perishables (seafood, produce, dairy), long/complex distribution chains, private-label programs.
These technologies can be included in different parts of FSMS like: Hazard analysis & validation: WGS, HSI trials, and DT stress-tests inform which controls are truly effective; monitoring (IoT sensors, vision/HSI, and TTIs provide continuous control evidence; in rapid assays (LAMP/CRISPR) and targeted WGS close the loop after deviations or trend alarms; Digital records are aligned to FSMA 204 speed investigations and narrow product scope (Table 2).

Table 2. Challenges in Implementing Advanced FSMS Technologies summarizes common challenges faced by food processing units, particularly SMEs, in implementing advanced FSMS technologies

Challenge Category	Description
Technical Barriers	Difficulty integrating new technologies with existing systems; lack of technical expertise among staff.
Financial Constraints	High initial investment costs; ongoing maintenance expenses; limited access to funding, especially for SMEs.
Human Factors	Resistance to change; inadequate training; need for a cultural shift towards embracing new technologies.
Regulatory Complexity	Navigating diverse and evolving food safety regulations; ensuring compliance across different jurisdictions.

Sector-Specific Issues

Certain food sectors, like dairy or meat, face additional safety risks due to microbial sensitivity, while others like grains or packaged goods have different traceability concerns. Many SMEs are slower to adopt technology-based food safety systems due to limited support and high expense.

CONCLUSIONS

Robust Food Safety Management Systems (FSMS) are essential to safeguard public health, ensure product quality, and meet regulatory/commercial requirements; core frameworks remain HACCP, GMP/PRPs, ISO 22000, and GFSI schemes.

Traditional monitoring - CCP checks, PRP/GMP inspections, environmental monitoring (EMP), supplier control, internal audits, and record/trend reviews - provides the foundational control structure in processing plants.

Environmental monitoring is indispensable for detecting harborage and loss of control (e.g., *Listeria*, *Salmonella*); relying on finished-product testing alone is insufficient.

Finished-product and in-process microbiological testing are best used as verification tools; their ability to detect low-prevalence hazards is limited and should not replace process/EMP controls.

Emerging digital tools - IoT sensors, blockchain traceability, AI/analytics, MES/Industry 4.0 - shift FSMS from periodic, paper-based checks to continuous, data-driven control and faster response to deviations.

Whole-genome sequencing (WGS) and metagenomics strengthen outbreak linkage and root-cause analysis; international guidance (e.g., ISO 23418) and networks (e.g., GenomeTrakr) support adoption.

Rapid, field-deployable diagnostics (e.g., LAMP, CRISPR biosensors) enable hours-level decisions for holds, sanitation verification, and surge testing at receiving or line-side.

Smart sensors, intelligent packaging, TTIs, and IoT monitoring provide continuous cold-chain verification and freshness/spoilage indicators and can integrate with digital traceability.

Implementation barriers persist - insufficient staff training, limited finances, regulatory complexity, and system-integration challenges - with SMEs disproportionately affected. Targeted funding, harmonized regulation, and simplified solutions are needed.

Future work should deliver cost-effective, scalable FSMS models that integrate seamlessly with existing operations, support continuous improvement and food safety culture, and are adaptable across diverse processing sectors.

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