RESEARCH ARTICLE

From Detection to Prediction: Next-Gen Tech for Food Safety and Quality Management

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ABSTRACT

The complexity of global food supply chains and rising consumer demands related to food safety and quality have increased the need for advanced food safety and quality management systems. While traditional testing methods are not becoming obsolete, they are increasingly supported by predictive and digital technologies, which enable early risk detection and proactive control. This paper examines the development of food safety and quality management through emerging technologies and internationally recognized standards. The review was qualitative, synthesizing evidence from international scientific, regulatory, and industry case studies on smart food safety technologies and quality assurance frameworks. It focuses on digital, automated, and non-thermal technologies used in food processing and distribution systems. The main findings indicate that high-sensitivity metal detectors and dual-energy X-ray scanners improve the detection of physical contaminants, while automation and robotics reduce handling and cross-contamination risks. IoT-based real-time monitoring helps control key parameters, and AI analytics can predict spoilage and microbial growth risks. Blockchain technology enhances traceability, enabling faster and more accurate recalls. Additionally, non-thermal interventions such as cold plasma are effective at inactivating pathogens without compromising food quality. The paper concludes that integrating these technologies into established frameworks such as GAP, GMP, GHP, GDP, GLP, and HACCP is essential for creating robust, transparent, and high-quality food systems. These insights are valuable for industry practitioners, regulators, and policymakers.

Keywords: *Food safety management systems, Smart food safety technologies, Predictive risk assessment, Supply chain traceability, Quality assurance standards*

INTRODUCTION

Food safety and quality assurance have become increasingly complex due to the globalisation of food supply chains, the diversification of raw materials, longer distribution channels, and rising consumer expectations for transparency and quality. The global food safety monitoring system market size was estimated at USD 24.73 billion in 2024 and is predicted to increase from USD 26.74 billion in 2025

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to approximately USD 53.94 billion by 2034, expanding at a CAGR of 8.11% from 2025 to 2034. The projected market size for the food safety monitoring system is shown in Figure 1. The increasing prevalence of foodborne diseases and growing awareness of food safety are driving growth in the food safety monitoring system market. These systems often identify hazards only after contamination has occurred, leading to product recalls, economic losses, and public health risks (Aslam *et al*., 2025). In recent years, technological advancements have enabled a paradigm shift from detection-oriented safety systems toward predictive and preventive food safety management. This shift is supported by digital technologies such as artificial intelligence, Internet of Things (IoT), advanced sensors, automation, and blockchain, which allow continuous monitoring and early risk identification across the food value chain (FAO, 2022; Liberty *et al*., 2025). These technologies complement established safety frameworks rather than replace them, strengthening the ability of HACCP-based systems to respond to emerging risks.

Recent literature emphasises a shift toward risk-based, technology-enabled food safety governance, where continuous monitoring and predictive analytics play a central role (Aslam *et al*., 2025; Liberty *et al*., 2025). These developments align with global policy priorities that advocate preventive food safety strategies over corrective actions (FAO, 2022). Moreover, consumer demand for transparency, traceability, and minimally processed foods has accelerated the adoption of smart technologies across the food sector. Studies indicate that digital traceability tools and real-time monitoring systems enhance consumer trust while supporting regulatory compliance and market access (Meliana *et al*., 2024).

The data on food processing sub-sectors in India are shown in Figure 2. In parallel, emerging non-thermal technologies and next-generation sequencing methods are redefining safety assurance by preserving food quality while improving microbial surveillance and outbreak response (Jagadeesan *et al*., 2019; Dhal & Kar, 2025). Despite these advancements, the adoption of next-generation technologies remains uneven, particularly among small and medium-sized food enterprises, due to financial, technical, and infrastructural constraints (FAO, 2022). Therefore, a comprehensive synthesis of technological innovations, their functional roles, benefits, and integration with established food safety systems is essential to inform industry practices and policy development. Therefore, this research aims to examine the transition from detection-based food safety and quality management to predictive and preventive approaches, identify and analyse the role of next-gen digital technologies, identify Indian food companies that are adopting these technologies, and highlight the significant challenges in their implementation.

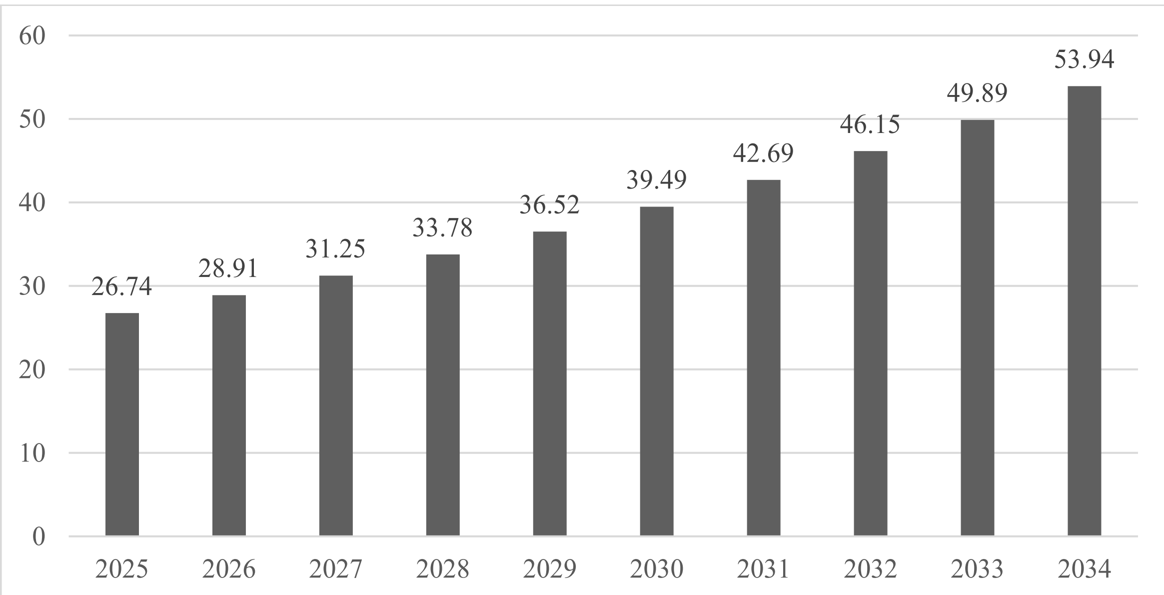

Figure 1. Projected global food safety monitoring system market size 2025 to 2034 (USD Billion).

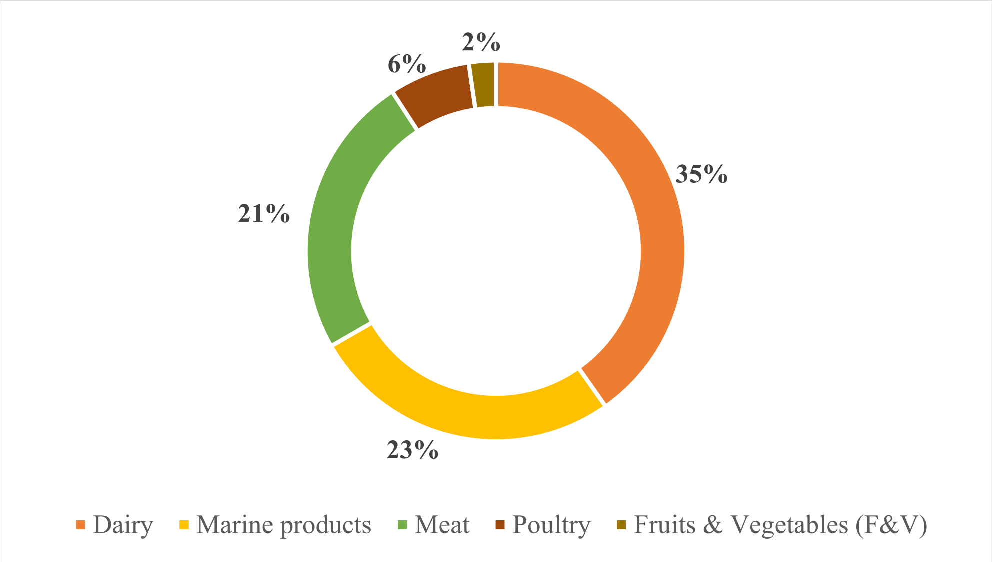

Figure 2. Food processing sub-sectors in India, 2019.

MATERIALS AND METHODS

This study adopts a narrative qualitative review approach supported by secondary data analysis to examine next-generation technologies in food safety and quality management. Peer-reviewed journal articles, international organisation reports, regulatory documents, and industry publications published between 2021 and 2025 were systematically screened using keywords such as food safety technologies, predictive food safety, IoT in food systems, artificial intelligence in food quality, blockchain traceability, biosensors, non-thermal processing, and next-generation sequencing. Approximately 70-80 sources were reviewed, of which around 44 articles and reports were synthesised for this study. Secondary quantitative data from selected sources were used to develop descriptive tables and graphs to support trend analysis. No primary data collection or experimental validation was undertaken, and the review focuses on aligning technological advancements with established food safety frameworks such as HACCP, GMP, GHP, GDP, and ISO-based systems.

RESULTS AND DISCUSSION

Evolution of Food Safety and Quality Management Systems

Historically, food safety assurance relied heavily on visual inspection and microbiological testing of finished products. While effective at identifying unsafe products, this approach provided limited insight into process-related hazards and often led to delayed corrective actions. The introduction of Total Quality Management principles marked an important transition, emphasising process control, consistency, and continuous improvement in food manufacturing operations (Fayaz *et al*., 2020). The development of Hazard Analysis and Critical Control Point (HACCP) systems further strengthened preventive food safety management by systematically identifying hazards and establishing critical control points throughout processing. Supporting systems such as Good Manufacturing Practices (GMP), Good Hygiene Practices (GHP), and Good Distribution Practices (GDP) enhanced hygiene control and operational discipline.

However, these systems traditionally relied on manual monitoring, periodic documentation, and historical data, which limited their responsiveness to real-time risks. The integration of digital technologies into food safety management systems represents a natural evolution of these frameworks. Smart sensors, automation, and data analytics enhance monitoring frequency, accuracy, and decision-making speed, allowing food safety systems to move beyond compliance toward proactive risk management (Aslam *et al*., 2025). This convergence forms the foundation of next-generation food safety governance, and some recent technologies are given in Table 1.

Advanced Detection and Inspection Technologies in Food Processing

Advanced detection and inspection technologies have played a critical role in strengthening food safety systems by improving the

Table 1. Next-Generation Technologies Used in Global Food Safety and Quality Management

Next-Generation Technology	Key Application in Food Safety & Quality
Advanced sensors & biosensors	Rapid detection of pathogens, chemical residues, allergens, and spoilage indicators
Internet of Things (IoT)	Real-time monitoring of temperature, humidity, hygiene, and storage conditions
Artificial intelligence (AI) & Machine learning (ML)	Predictive risk assessment, microbial growth prediction, and shelf-life estimation
Automation & robotics	Reduction of manual handling, improved hygiene, and consistent processing
Blockchain technology	Enhanced traceability, transparency, and rapid recall management
Smart inspection systems (X-ray, vision systems)	Detection of physical contaminants and quality defects
Digital data platforms & analytics	Integration of monitoring data for decision support and compliance
Non-thermal technologies (e.g., cold plasma)	Microbial inactivation while preserving food quality

Source: FAO (2022), Thinking about the future of food safety: A foresight report.

identification of physical contaminants and quality defects. Traditional inspection methods relied heavily on visual examination and basic metal detection, which often failed to identify low-density or non-metallic contaminants. Studies have shown that adopting high-sensitivity metal detectors significantly improved the detection of ferrous, non-ferrous, and stainless-steel contaminants in high-speed processing environments. These systems were particularly effective reducing foreign-body contamination without disrupting production efficiency. Dual-energy X-ray inspection systems have further enhanced detection capabilities by enabling differentiation of materials based on density and atomic composition. X-ray systems effectively detected glass, stones, bones, and dense plastics, which are often missed by conventional detectors. In addition to safety assurance, X-ray inspection has supported quality control by identifying underfilled packages, missing components, seal defects, and product deformation. Machine vision technologies have also been increasingly adopted for automated inspection. Vision systems using high-resolution cameras and pattern recognition algorithms have detected surface defects, colour variations, and labelling errors with high accuracy. Research indicates that automated inspection reduces human error and improves consistency in compliance with food quality standards (Aslam *et al*., 2025). Collectively, these technologies have strengthened detection-based controls while laying the foundation for predictive safety systems.

Biosensors and Smart Detection Platforms for Chemical and Biological Hazards

Biosensors have emerged as important tools for the rapid detection of biological and chemical hazards in food systems. Unlike conventional microbiological assays, which require lengthy incubation periods, biosensors enable near-real-time detection of pathogens, toxins, allergens, and chemical residues. Kakumanu *et al*., (2023) found that biosensor-based systems significantly reduced detection time while maintaining high sensitivity and specificity. These advantages have supported early intervention and reduced the risk of contaminated products entering the market. Recent advancements in electrochemical and optical biosensors have further improved their applicability in food safety monitoring. Sakthivel *et al*., (2024) reported that electrochemical sensors achieved low detection limits for microbial and chemical contaminants and were suitable for on-site testing. Optical biosensors, including fluorescence- and colorimetric-based systems, have been widely used for allergen detection and freshness assessment. These technologies have increasingly been integrated with digital platforms to allow continuous data acquisition and remote monitoring.

Under this category, commonly applied tools have included: (1) Electrochemical biosensors for pathogen and residue detection, (2) Optical and fluorescence-based biosensors for allergen and spoilage monitoring, and (3) Smart biosensors integrated with IoT platforms for real-time surveillance. Meliana *et al*., (2024) demonstrated that biosensors integrated into innovative traceability systems improved early-warning capabilities and supported preventive food safety management. Overall, biosensor technologies have bridged the gap between laboratory-based analysis and real-time industrial monitoring.

Automation and Robotics for Hygienic and Consistent Food Processing

Automation and robotics have increasingly been adopted in food processing to enhance hygiene, reduce manual handling, and improve process consistency. Traditional food operations relied heavily on human labour, which increased the risk of cross-contamination and variability in processing conditions. Hassoun and Galanakis (2025) reported that robotic systems significantly reduced contamination risks by limiting direct human contact with food products during critical operations such as cutting, sorting, and packaging. Studies have shown that modern food-grade robots are designed according to hygienic engineering principles, including smooth surfaces, corrosion-resistant materials, and compatibility with clean-in-place systems.

Automation also ensured uniformity in processing parameters, which is essential for maintaining consistent product quality and compliance with safety standards. The integration of robotics within Industry 4.0 frameworks has further strengthened food safety systems. Automated processing lines equipped with sensors and data analytics have enabled real-time monitoring of operations and early detection of deviations. Although high initial investment costs remain a challenge, research has consistently shown that automation improves long-term safety performance, operational efficiency, and regulatory compliance (Aslam *et al*., 2025).

Internet of Things (IoT) for Real-Time and Continuous Food Safety Monitoring

The Internet of Things has transformed food safety monitoring by enabling continuous, real-time tracking of critical control parameters throughout the food supply chain. IoT systems use interconnected sensors to monitor temperature, humidity, gas composition, and sanitation conditions across processing, storage, and transportation stages. Eruaga (2024) demonstrated that IoT-based monitoring improved response time to deviations and reduced the likelihood of microbial growth and spoilage. IoT technologies have been particularly valuable in cold chain management, where temperature abuse is a significant cause of food quality deterioration and safety failures. IoT-enabled cold chain systems reduced spoilage losses and improved compliance with storage standards. Real-time alerts enabled rapid corrective actions, enhancing preventive control. Common IoT tools applied in food safety systems have included: (1) Wireless sensor networks for environmental monitoring, (2) RFID systems for tracking product movement and status, and (3) Cloud-based platforms for centralised data analysis and reporting. These systems have supported a shift from periodic inspection to continuous oversight, strengthening transparency, traceability, and preventive food safety management.

Artificial Intelligence and Machine Learning for Predictive Food Safety Management

Artificial intelligence and machine learning have increasingly been applied to analyse large, complex datasets generated by sensors, inspections, and historical records (Table 2). Traditional data analysis methods struggled to identify hidden patterns in such datasets. Liu *et al*., (2023) found that AI-based models effectively detected trends associated with contamination events, quality deterioration, and process failures. These findings highlighted the role of AI in predictive food safety management. Recent studies have demonstrated that machine learning algorithms improved microbial growth prediction, shelf-life estimation, and anomaly detection in food processing environments. Kuppusamy *et al*. (2024) reported that AI-enhanced contaminant analysis improved detection accuracy while supporting environmental protection goals.

Wang *et al*., (2025) showed that AI-based decision-support systems influenced safer operational behaviour in food manufacturing facilities. AI has increasingly been integrated with HACCP systems to prioritise risks and optimise control strategies. Rather than replacing existing safety frameworks, AI has strengthened them by enabling data-driven decision-making and early intervention. This integration has supported the transition from reactive hazard control to precision and predictive food safety systems.

Blockchain-Based Traceability and Transparency in Food Supply Chains

Traceability has become a core requirement in modern food safety systems

Table 2. AI-based technologies in food analysis and safety: An overview of technologies

Type of AI Application	Applications in Food Analysis	Applications in Food Safety	References
Machine Learning (ML)	Enhances spectroscopic techniques (e.g., NIR, Raman) for accurate chemical composition prediction and adulterant detection	Predictive modelling to forecast spoilage and contamination risks	Goyal *et al*., (2024); Teklemariam (2024)
Deep Learning (DL)	Image analysis for quality assessment, including defect detection and product classification	Enhances contaminant detection systems such as electronic noses	Hu *et al*., (2023); Lien & Zhao (2018)
Computer Vision	Automated inspection and grading based on visual attributes such as colour, size, and shape	Packaging inspection to ensure seal integrity and detect contaminants	Sivaranjani *et al*., (2021)
Natural Language Processing (NLP)	Analysis of quality reports, inspection records, and consumer feedback to identify trends related to product quality	Text mining of regulatory documents and inspection reports for compliance monitoring and risk identification	Zhang & El-Gohary (2011)
Fuzzy Logic	Sensory evaluation to model human perceptions and provide nuanced quality assessments	Risk assessment under uncertain or incomplete data conditions	Guillaume & Charnomordic (2004)

to enable rapid recalls and accountability. Traditional paper-based traceability systems often suffered from data fragmentation and delays. Blockchain technology has increasingly been adopted to address these limitations by providing immutable, transparent, and decentralised records of supply chain transactions. Liberty *et al*., (2025) reported that blockchain-enabled systems improved traceability accuracy and reduced response time during food safety incidents. Meliana *et al*., (2024) demonstrated that blockchain integrated with biosensors and IoT platforms enhanced real-time visibility across the supply chain. Such systems enabled precise identification of contamination sources, reducing the scale and cost of product recalls. Blockchain also strengthened trust among stakeholders by ensuring data integrity and preventing unauthorised modifications to records. From a regulatory perspective, blockchain aligns well with food safety standards that emphasise documentation, accountability, and traceability. When combined with AI and IoT systems, blockchain enables predictive, transparent food safety governance, contributing to safer, more resilient food systems.

Next-Generation Sequencing (NGS) and Microbial Surveillance

Next-generation sequencing (NGS) has emerged as a transformative tool in food safety by enabling rapid, high-resolution identification of foodborne pathogens and spoilage microorganisms. Unlike conventional culture-based or targeted molecular methods, NGS allows simultaneous detection of multiple microorganisms, providing detailed information on microbial diversity, virulence genes, antimicrobial resistance, and contamination sources within food matrices and processing environments (Jagadeesan *et al*., 2019; Macori & Fanning, 2023). NGS has also strengthened risk-based food safety management by supporting predictive microbial risk assessment. Whole-genome sequencing (WGS), a key NGS application, has been widely adopted for pathogen surveillance in meat, dairy, and ready-to-eat foods, improving differentiation among closely related strains and reducing uncertainty in epidemiological investigations (Imanian *et al*., 2022).

From a systems perspective, NGS plays a critical role within the One Health framework by linking data from food, environmental, and human health sources. This integrated approach supports early detection of emerging pathogens and enhances preparedness for foodborne disease outbreaks (Macori & Fanning, 2023). Although challenges such as high upfront costs, the need for bioinformatics expertise, and the complexity of data interpretation persist, technological advancements and declining sequencing costs are gradually enabling broader adoption of NGS in routine food safety monitoring (Imanian *et al*., 2022).

Non-Thermal Technologies for Quality-Preserving Safety Interventions

Non-thermal food processing technologies have attracted considerable attention as alternatives to conventional heat-based treatments, particularly for foods that require preservation of sensory and nutritional quality. Among these, cold plasma technology has shown strong potential for inactivating microbes on food surfaces without causing significant temperature increases. Cold plasma generates reactive oxygen and nitrogen species that disrupt microbial cell membranes, proteins, and nucleic acids, thereby reducing pathogen load (Dhal & Kar, 2025). Cold plasma is especially suitable for fresh produce, meat products, and ready-to-eat foods, where thermal treatments may negatively affect texture, colour, and nutritional value. Studies indicate that cold plasma treatments can significantly reduce surface contamination while maintaining product freshness and shelf life (Nychas & Tsezos, 2025). This aligns with consumer demand for minimally processed foods that retain high sensory quality and nutritional value.

In practical applications, cold plasma is often combined with conventional sanitation and hygiene practices rather than replacing them entirely. When integrated into existing food processing lines, it enhances overall safety performance and supports preventive control strategies within HACCP systems (Dhal & Kar, 2025). While industrial-scale implementation is still evolving, continued research and standardisation efforts are expected to facilitate wider adoption of non-thermal technologies in food safety management.

Benefits of Next-Generation Food Safety Technologies

The integration of next-generation technologies into food safety and quality management systems offers significant benefits across the food value chain. The Indian companies adopting next-gen technologies are listed in Table 3. Continuous monitoring using IoT sensors, biosensors, and automated inspection tools enables early detection of deviations in critical parameters, reducing the likelihood of contamination events (Aslam *et al*., 2025; Eruaga, 2024). Predictive analytics powered by artificial intelligence further strengthens preventive control by forecasting microbial growth, spoilage risks, and quality deterioration. Another significant benefit is improved traceability and transparency. Technologies such as blockchain, smart sensors, and digital data platforms enable real-time tracking of food products from production to distribution, enabling faster, more targeted recalls when safety incidents occur (Liberty *et al*., 2025; Meliana *et al*., 2024). This not only protects public

Table 3. Indian Food Companies Adopting Next-Gen Technologies

Company	Software/Platform	IoT/Sensor Technologies	Traceability/AI Technology	Source
Nestlé India	AWS IoT Core; SAP S/4HANA; SAP Quality Management	IoT edge devices (MQTT-enabled temperature & humidity sensors)	ERP-integrated IoT telemetry; SAP QM analytics	Farooq *et al.,* (2023)
ITC Ltd.	SAP ERP Central Component (ECC/ S/4HANA)	Industrial environmental sensors; PLC-interfaced sensors	RFID tags; automated reporting to SAP	Hassoun *et al*., (2024)
Amul (GCMMF)	Custom IoT data aggregator platforms (cloud)	Cold-chain IoT temperature sensors; telematics GPS sensors	Blockchain-enabled traceability blockchain layer	Khanna *et al*., (2022)
Britannia Industries	Jidoka Kompass; Jidoka Tigris	Machine-vision cameras (high-speed CCD/CMOS)	Automated line sorting & defect ejection	Zhu *et al*., (2021)
Hatsun Agro Product Ltd.	ERP-linked IoT monitoring dashboards	RFID animal and logistics sensors; refrigeration temp sensors	IoT-enabled cold-chain monitoring & telematics	Mustafa *et al.,* (2024)

Table 4. Adoption Challenges of Next-Gen Food Safety Technologies

Technology	Key Barriers	Sources
Biosensors	High cost of advanced sensors and need for calibration expertise	Kakumanu *et al*., (2023); Sakthivel *et al*., (2024); Meliana *et al*., (2024)
IoT Monitoring	Infrastructure gaps, uneven digital connectivity, and data security concerns	Eruaga (2024)
Artificial Intelligence	Requires a skilled workforce, complex data integration, and a high initial investment	Liu *et al*., (2023); Kuppusamy *et al*., (2024); Wang *et al*., (2025)
Blockchain	Interoperability issues, resistance to adoption, and policy/regulatory uncertainty	Liberty *et al*., (2025); Meliana *et al*., (2024)
Next-Gen Sequencing (NGS)	High sequencing costs, shortage of bioinformatics expertise, and data interpretation complexity	Jagadeesan *et al*., (2019); Macori & Fanning (2023); Imanian *et al*., (2022)
Non-Thermal Technologies	Limited industrial-scale adoption, equipment cost, and lack of standardised protocols	Dhal & Kar (2025); Nychas & Tsezos (2025)

health but also minimises economic losses and reputational damage for food businesses. Additionally, technology-enabled food safety systems enhance regulatory compliance and consumer confidence. Digital documentation, automated monitoring, and data-driven reporting support adherence to international standards such as HACCP, GMP, and ISO-based systems. Overall, next-generation technologies contribute to safer food systems, reduced food waste, and more resilient supply chains.

Implementation Challenges and Policy Support

Despite their advantages, adopting next-generation food safety technologies faces several practical challenges, as shown in Table 4. High capital investment requirements, limited access to technical expertise, and infrastructure constraints pose significant barriers, particularly for small and medium-sized food enterprises (FAO, 2022). Data security, interoperability between digital systems, and standardisation of emerging technologies further complicate implementation. Workforce readiness is another critical concern, as advanced systems such as AI-based analytics, IoT networks, and NGS platforms require skilled personnel for operation and interpretation. Without adequate training and capacity building, the effectiveness of these technologies may be limited. Resistance to change and stakeholders' lack of awareness can also slow adoption, especially in traditional food processing sectors.

To address these challenges, international organisations and regulatory agencies have emphasised the need for policy support for technology-enabled food safety systems. Global strategies promote risk-based and preventive approaches, encouraging digitalisation, innovation funding, and public–private partnerships. Government initiatives that support research, training, and infrastructure development are essential to ensuring the inclusive and sustainable adoption of next-generation food safety technologies.

CONCLUSION

Next-generation technologies are fundamentally transforming food safety and quality management by enabling a shift from reactive detection systems to predictive, data-driven frameworks. Advanced tools such as biosensors, IoT-based monitoring, artificial intelligence, blockchain traceability, next-generation sequencing, and non-thermal interventions strengthen early hazard detection and preventive control across the food supply chain. When integrated with established food safety standards such as HACCP, GMP, and GHP, these technologies enhance system resilience, transparency, and effectiveness. Although challenges related to cost, expertise, and infrastructure remain, coordinated efforts involving industry, regulators, and policymakers can accelerate adoption. Overall, next-generation technologies offer a robust pathway toward ensuring safe, high-quality food in an increasingly complex global food system.

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Author Contributions:

Rakshitha B contributed to the idea and prepared the original draft; Balaji Parasuraman provided guidance and supervision; Balaji Parasuraman, Gangaiselvi R, Jayasuriya S and Mugilan K contributed to the review and editing of the manuscript.

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