Journal of Food Protection 88 (2025) 100621

Contents lists available at ScienceDirect

Journal of Food Protection

journal homepage: www.elsevier.com/locate/jfp

Review

Harnessing Artificial Intelligence to Safeguard Food Quality and Safety

Diwakar Singh

Jerome Cheese Company, ID 83338, USA

ARTICLE INFO

Keywords:
Artificial intelligence
Computer vision
Food safety
Machine learning
Natural language processing
Predictive analytics

ABSTRACT

Artificial Intelligence (AI) is reforming the food industry, particularly in food safety and quality control, by enhancing detection, predicting shelf life, and optimizing production processes. This review explores the innovative role of AI, focusing on the integration of machine learning (ML), computer vision, and natural language processing (NLP) in food safety systems. AI is transforming food safety by enabling real-time monitoring, predictive analytics, rapid contaminant detection, and automation throughout the food supply chain. These technologies reduce human error and allow quicker responses to safety threats, ultimately preventing foodborne illnesses and improving product quality. AI also helps to predict and manage climate-induced risks, such as chemical and microbiological hazards linked to extreme weather and temperature shifts. The review outlines the integration of digital tools such as biosensors and Internet of Things (IoT) devices and examines AI's convergence with blockchain and process analytical technologies to enhance traceability and strengthen food safety management systems. Despite its potential, the widespread adoption of AI is hindered by challenges such as data privacy concerns, workforce adaptation, and regulatory barriers, while critical gaps in digital infrastructure, data standardization, and policy support also need to be addressed to enable effective implementation. The review highlights the importance of ethical frameworks and interdisciplinary collaboration to guide responsible AI deployment. Emerging tools like neural networks and behavior-based safety assessments can boost food system resilience. The review concludes by calling for enhanced regulatory cooperation and technological investment to realize AI's full potential in creating safer, more sustainable, and efficient food systems.

Contents

E-mail address: dsndri33@gmail.com

https://doi.org/10.1016/j.jfp.2025.100621
Received 19 May 2025; Accepted 11 September 2025
Available online 16 September 2025

Abbreviations

AI	Artificial Intelligence
ML	Machine Learning
FSMS	Food Safety Management Systems
PAT	Process Analytical Technology
HACCP	Hazard Analysis and Critical Control Point
GMP	Good Manufacturing Practices
IoT	Internet of Things (IoT)
DL	Deep Learning
NLP	Natural Language Processing
ANNs	Artificial Neural Networks
CNNs	Convolutional Neural Networks
3D-FP	3D Food Printing
BDA	Big Data Analytics
VBA	Visual Basic for Applications
LSTMs	Long Short-Term Memory Networks
IP	Intelligent Packaging
AP	Active Packaging
RFID	Radio-Frequency Identification
HI	Hyperspectral Imaging
2DMs	2D nanomaterials
RASFF	Rapid Alert System for Food and Feed
XAI	Explainable AI
ADAT	Advanced Data Analytic Techniques
RNNs	Recurrent Neural Networks
RASAR	Read-Across-based Structure Activity Relationships
NIRS	Near-Infrared Spectroscopy
FTIR	Fourier-Transform Infrared
PFAS	Per and Polyfluoroalkyl Substances
NAMs	New Approach Methodologies
BNs	Bayesian Networks
NNs	Neural Networks
SVMs	Support Vector Machines
FSC	Food Safety Culture
EFSA	European Food Safety Authority
CEA	Controlled Environment Agriculture (CEA)
P-SAFETY	Privacy, Security, Accountability, Fairness, Explainability, Transparency
SERS	Surface-Enhanced Raman Scattering
GSRS21	Global Summit on Regulatory Science
PPE	Personal Protective Equipment
FSC	Food Supply Chain
CSFs	Critical Success Factors
QCA	Qualitative Comparative Analysis
TOEH	Technology, Organization, Environment, and Human
E-nose	Electronic nose
ASFs	Animal Source Foods
PPC	Postpasteurization contamination
FDA	Food and Drug Administration
PLS-DA	Partial Least Squares Discriminant Analysis

The food industry has become a significant focus due to its importance in global food production, distribution, processing, and packaging. Feeding the global population by 2050 requires balancing sustainability, food security, and safety. Key strategies include reducing food loss through source reduction and intelligent technologies, promoting circular food systems, shifting to plant-based diets, and optimizing protein sources like aquaculture and pastoral systems to improve efficiency and minimize environmental impact. Sustainable food security requires evidence-based decisions that avoid repeating past mistakes, ensure safety, and embrace innovation in food production and value chains to achieve a resilient and secure global food system (Vågsholm et al., 2020).

Current food safety and quality control systems in the food sector often fail to effectively prevent microbial and chemical contamination, eroding consumer trust. To address these challenges, food business operators and regulators must implement structured food safety management system (FSMS) based on continuous monitoring and control of critical parameters across the entire food supply chain. However, the sector remains fragmented, which impedes the adoption of innovative technologies. The integration of process analytical technology (PAT), information technologies, and data science offers a promising solution. By leveraging tools such as cloud computing, data mining, and artificial intelligence (AI), stakeholders can monitor and ensure food safety in real time. Additionally, virtualization in the food supply chain enhances traceability and transparency, supporting better decision-making. PAT enables online and postprocessing monitoring, while technologies such as Hazard Analysis and Critical Control Points (HACCP) and Good Manufacturing Practices (GMP) contribute to a comprehensive FSMS. Nonetheless, distribution and transportation remain weak links due to limited control and traceability. To overcome these barriers, the food industry must embrace digital transformation, promote interconnectivity, and invest in smart analytical tools. This approach not only ensures food safety and quality but also minimizes food waste and supports regulatory compliance, ultimately enhancing consumer confidence and sustainability in the global food system (Nychas et al., 2016). (See Table 1).

The integration of AI into food safety and quality control is reshaping global food systems by enabling proactive, data-driven approaches to risk management. Technologies such as machine learning (ML), computer vision, and Natural Language Processing (NLP) are enhancing FSMS, particularly in response to climate change, globalization, and increasingly complex supply chains. Technologies like drones, robotics, and smart packaging also contribute to this transformation. Overall, AI and ML present powerful opportunities to advance sustainable, safe, and resilient food systems capable of adapting to current and future challenges. However, their deployment is hindered by high costs, infrastructural limitations, and workforce skill gaps. These barriers restrict the integration of AI-based solutions essential for modern food safety systems.

This review aims to critically examine the growing role of AI, particularly ML, in enhancing food safety, quality control, and sustainability within the global food industry. The paper explores AI applications in food processing, packaging, and supply chain management, with emphasis on contaminant detection, shelf-life prediction, sensory evaluation, and real-time monitoring. The review attempts to analyze the use of AI tools such as biosensors, Internet of Things (IoT) devices, and predictive analytics in high-risk sectors like dairy and seafood. Additionally, the review aims to investigate AI's integration with digital technologies like blockchain and process analytical tools to support food safety management systems. This study builds on existing research to offer practical recommendations for improving efficiency, collaboration, and competitiveness in food safety. While current literature aims to highlight progress, it also reveals significant gaps, including limited real-world applicability and a lack of interdisciplinary integration. To unlock AI's full potential, more rigorous, scalable, and context-aware research is required for effective large-scale implementation. Thus, this review aims to analyze the available evidence, challenges, and perspectives on the possible role of AI in safeguarding

Table 1
AI-Powered Solutions in Food Safety and Quality Control

Subsection	Description	Digital Algorithms	Key References
Quality Assurance & Spoilage Detection	AI predicts spoilage, shelf-life, and product freshness with imaging, LSTM, and hyperspectral sensors.	CNNs, LSTMs	Ding et al., 2025; Singh et al., 2024
Food Safety Monitoring & Contaminant Detection	Sensors, NIRS, and ML models detect pathogens, toxins, allergens, and residues in real time.	ML, NIRS, RNNs, ANN, e-nose	Mahmudiono et al., 2022; Moholkar et al., 2023
Intelligent Packaging & Smart Labels	AI supports packaging with pH sensors, RFID, gas sensors, and visual freshness indicators.	CNNs, RFID, smart films, ANN, NLP	Nayak & Dutta, 2023; Shirzad & Joodaky, 2024
Traceability, Supply Chains & Blockchain	Blockchain and AI enhance traceability, predictive logistics, food recalls, and food fraud prevention.	Blockchain, AI, IoT, QCA, MCDA	Trollman, 2024; Cavalli et al., 2019
Biosensors, Microneedles & Real-Time Monitoring	Biosensors and smartphone-connected microneedle sensors track freshness and contamination.	CMS, CNNs, smartphone apps	Jiang et al., 2025; Zhang et al., 2022
Sustainable Food Systems & Climate Resilience	AI supports resilient food safety, waste reduction, climate-aware prediction, and circular packaging.	Predictive AI, smart sensors, satellite monitoring	Kuppusamy et al., 2024; Thorsen et al., 2025
Food Fraud, Authenticity & E-Nose Technology	Nondestructive AI tools detect adulteration and authenticity using ML, spectral data, and e-noses.	ML models, classification, PCA, e-nose	Funes et al., 2015; Anwar et al., 2023
Public Health Surveillance & Consumer Safety	Mobile AI and sensors enhance consumer safety, food alerts, recalls, and hygiene monitoring.	Mobile AI, cloud computing, LLMs	Marvin et al., 2017; Wang et al., 2025
Personalized Nutrition & Functional Foods	AI supports genome-based diets, allergen detection, and food personalization	AI-driven models, supervised ML	Theodore Armand et al., 2024; Pandey et al., 2023
Food Processing, 3D/4D Printing & Automation	AI optimizes sorting, food printing, robotics, fermentation, beverage QC, and automated safety checks.	CNNs, robotics, DL, neural nets, rheology models	Bedoya et al., 2022; Hassoun et al., 2023; Liu et al., 2024
Industry 4.0 & Workforce Transformation	AI, robotics, and smart tools enhance compliance, digitization, and workforce upskilling.	IoT, AI, digital twins, VBA, job tracking systems	Akyazi et al., 2020; Chen & Yu, 2021
Multi-Source Data Integration & Predictive Modeling	AI merges omics, sensor, weather, social, and logistics data for food risk prediction and management.	SVM, BNs, omics, DL, microbiome models	Taiwo et al., 2024; Wang et al., 2022

food Quality and Safety. By addressing technological, economic, and operational barriers, this paper outlines a pathway for leveraging AI to create a more resilient, transparent, and sustainable global food ecosystem.

Methodology

A systematic review was conducted to examine the role of AI in food systems. Peer-reviewed articles were sourced primarily from Google Scholar and ScienceDirect. Several inclusion and exclusion criteria were defined to set boundaries for the review to filter search results. Inclusion criteria focused on peer-reviewed articles that explored the application of AI in food safety, food packaging, quality assurance, sensory analysis, food processing, and food security. Studies involving AI tools, especially machine learning, blockchain, IOT, and predictive analytics within the food industry were included. Exclusion criteria eliminated non-English articles, opinion pieces, conference abstracts, and studies not directly related to AI or food safety. Articles were selected based on their relevance to the research objectives. A total of 153 articles were reviewed and analyzed to synthesize current findings and identify trends, challenges, and opportunities in the integration of AI across different stages of the food system.

Overview of artificial intelligence

Artificial Intelligence, a branch of computer science, focuses on developing systems capable of performing tasks that typically require human intelligence, such as reasoning, learning, and decision-making. A key subset of AI is ML, which enables systems to learn from data and make predictions or decisions without being explicitly programmed for every task. Over time, AI has evolved from rule-based systems, which rely on predefined “if-then” logic, to more sophisticated models like ML and deep learning (DL). While traditional ML methods often require manual feature engineering, deep learning overcomes this by automatically extracting complex patterns from raw data, making it especially valuable in areas such as food safety, where it supports contamination detection and product classification (Gbashi & Njobeh, 2024).

Blockchain technology complements AI by providing secure, tamper-proof records, particularly useful for ensuring traceability and data integrity throughout the food supply chain (Zhou et al., 2022). AI applications like NLP and Computer Vision further enhance operational efficiency. NLP enables machines to interpret and respond to human language, while Computer Vision allows analysis of visual data, useful in agriculture for monitoring livestock and evaluating production processes. Beyond food safety, AI empowers organizations across sectors to unlock hidden value, drive innovation, and make agile, data-driven decisions. For example, AI can combat misinformation by validating content and boosting consumer trust. It also supports personalized nutrition by analyzing dietary needs and recommending tailored food products. Through real-time data aggregation from various consumer touchpoints, AI enables precise production planning and supply chain optimization. These capabilities help businesses shift from hierarchical models to collaborative, data-centric cultures, fostering agility and resilience. As a cornerstone of digital transformation, AI bridges gaps between manufacturing and commercialization, ensuring long-term value creation and positioning companies for success in an increasingly digital marketplace.

Role of AI in the food processing

Food is vital for survival, and food science plays a crucial role in ensuring health through agriculture, processing, and nutrition. Agriculture forms the foundation by supplying raw materials and eliminating hazards. Food processing must meet safety and quality standards, while nutritional evaluation supports healthy diets. AI is driving a transformation across the food sector, rejuvenating food science, agriculture, nutrition, and industry practices. Its integration into the entire food chain, from farm to fork, is reshaping how food is produced, processed, assessed, and consumed. Advanced AI techniques such as ML, DL, computer vision, and artificial neural networks (ANNs) are being employed to enhance efficiency, sustainability, and food safety at multiple levels (Esmaeily et al., 2024). In food science, AI enables better food safety and quality control through tools like electronic noses and tongues, and real-time sensory analysis. AI-based models assist in optimizing food formulation, processing, packaging, and distribution, resulting in greater consistency and lower waste. Evolutionary algorithms are being used for single- and multiobjective optimization in food processing systems, offering solutions to manufacturing problems with high efficiency (Enitan & Adeyemo, 2011). Emerging thermal modeling methods, including AI-driven simulations for estimating thermal conductivity and heat capacity, are proving valuable for designing safer, high-quality food processes.

AI also supports smart agriculture, facilitating soil analysis, crop prediction, pest control, and precision irrigation, significantly improving resource use and yields. This integration of AI and IoT devices creates intelligent systems that monitor environmental factors and optimize agricultural output while minimizing ecological impact (Addanki et al., 2022). In the domain of nutrition and health, AI plays a crucial role in advancing personalized nutrition. Applications include AI-driven dietary assessment, food recognition apps, and disease-specific diet planning. Personalized diet recommendations based on genetic, microbiome, and health data are emerging as powerful tools for disease prevention and management, particularly for conditions like diabetes, obesity, and cardiovascular disease (Theodore Armand et al., 2024). Metabolomics and biomarker-based AI models also contribute to disease diagnosis by linking dietary patterns with health outcomes.

AI and ML are further enhancing food processing and quality assurance. Technologies such as neural networks and convolutional neural networks (CNNs) support automation in food quality detection, sorting, shelf-life prediction, and fraud detection. In the dairy industry, AI optimizes processes like milking, pasteurization, and contamination monitoring. Smart packaging and noninvasive sensors driven by AI monitor milk quality and detect adulteration in real time (Alsaedi et al., 2024; Alves et al., 2021). AI's application extends to food safety and environmental monitoring. For example, ANN models assist in detecting pesticide residues via fluorescence spectroscopy and rapid screening of food contaminants, offering nondestructive, cost-effective solutions (Mahmudiono et al., 2022). In industries such as olive oil production, AI supports classification, adulteration detection, and optimization of chemical properties (Funes et al., 2015). Ultimately, AI is evolving the global food system by making it more efficient, personalized, sustainable, and secure. With increasing challenges from climate change, population growth, and complex global supply chains, AI offers scalable and adaptive solutions. However, while the potential is vast, much of the work remains in development stages, underscoring the need for further research, validation, and implementation (Ikram et al., 2024; Kakani et al., 2020).

The food industry has been reshaped by globalization, technological advancements, and changing consumer demands. AI and big data enhance food safety, production, and marketing, enabling food enterprises to improve product quality and meet consumer needs. The industry 4.0 technologies include smart agriculture, robotics, drones, and digital twins (Ding et al., 2023). The industry 4.0 technologies, such as AI, the Internet of Things, big data analytics, and automation, can be used in modernizing food production industries, including dairy, juice, bakery, and poultry sectors. These innovations are enhancing traceability and quality control, reshaping every stage of the food supply chain, from production to distribution, while improving efficiency, sustainability, and safety (George, 2024). Smart factories represent a key development within Industry 4.0, using interconnected systems to achieve real-time oversight and data-driven decision-making. By integrating sensors, digital twins, AI analytics, and ML algorithms, manufacturers can optimize operations, reduce waste, and improve productivity. Predictive maintenance, enabled by data from equipment and historical failure patterns, reduces unplanned downtime. AI vision systems detect defects more accurately than manual inspection, while robotic automation enhances consistency and speed in production. These tools allow companies to become more agile and responsive to market demands, ensuring product quality and operational resilience (George, 2024).

The transition to digital manufacturing in the food sector requires a workforce with new skill sets. As robotics, AI, and digital systems become integral to operations, there's a growing need for highly skilled professionals capable of managing and developing these technologies. Akyazi et al. (2020) highlight the importance of identifying current and future job roles through an automated database, which tracks competencies and evolving qualifications. This system, built using Visual Basic for Applications (VBA), supports tailored education and training programs to bridge skill gaps. Collaboration between academia and industry is vital to prepare a multiskilled workforce that can meet the challenges of the digital food economy. AI and big data are also uplifting food safety management. Kim and Kim (2022) described how AI enhances the prediction, detection, and management of foodborne risks. Technologies such as CNNs, next-generation sequencing, and omics-based profiling allow for real-time detection of pathogens and proactive risk management. In countries like South Korea, AI-driven platforms are used to track bacterial outbreaks like *E. coli* and *Salmonella* across the entire agri-food chain. Tools like R, MapReduce, and the Hadoop ecosystem process large-scale, high-velocity data, providing actionable insights for food safety operations.

The emergence of Food Safety 4.0 reflects the integration of intelligent biosensors with digital technologies like IoT, smart packaging, and AI. These biosensors enable real-time, noninvasive monitoring of contaminants, freshness, and spoilage across the supply chain. Innovations in quantum, wearable, and nanotech-based biosensors provide highly sensitive, multiplexed detection for environmental and food safety applications. They offer early hazard detection during food production, breeding, and processing, creating a transparent, responsive food system (Chen et al., 2024). In the dairy sector, termed Dairy 4.0, AI, robotics, IoT, and blockchain are transforming traditional operations, from milk collection to product packaging. Smart systems enable automated milking, real-time quality monitoring, and blockchain-enabled traceability (Hassoun et al., 2023). Similarly, in the beverage industry, robotics, biometrics, and computer vision are automating quality assessments, especially in hot and nonalcoholic drinks, replacing manual, time-intensive methods with faster, more accurate technologies (Gonzalez Viejo et al., 2019).

AI plays a pivotal role in ensuring food authenticity, safety, and transparency. Gbashi and Njobeh (2024) reported the use of computer vision, hyperspectral imaging, and predictive modeling for quality control and hazard detection. These tools combat challenges such as food fraud and contamination, while enhancing consumer trust and regulatory compliance. High accuracy in food grading and traceability boosts public health and confidence in food systems. AI is also central to the development of new food products and preservation methods. Thapa et al. (2023) discussed how AI algorithms, combined with advanced sensors, are used for freshness detection, pathogen identification, and food categorization. AI's learning and problem-solving capabilities assist in optimizing food formulations, quality assessment, and consumer preference modeling, leading to more tailored and efficient product development.

Liu et al. (2024) examined AI's impact on firm performance in China's food processing industry using panel data from Shanghai and Shenzhen (2010–2021). Their findings indicated that AI adoption improves productivity, increases demand for skilled labor, and enhances competitiveness by optimizing production technologies. This underscores the role of AI not just in technical operations but also in reshaping labor structures and boosting economic performance at the enterprise level. The integration of AI with 3D food printing (3D-FP) technologies is fostering innovation in personalized nutrition. Bedoya et al. (2022) highlighted the use of AI to design customized, nutrient-dense food products using alternative proteins from algae, insects, fungi, and plants. AI aids in optimizing viscosity, rheology, and texture for 3D printing processes, enabling the creation of foods tailored to individual dietary needs. Additionally, 4D printing introduces stimuli-responsive materials that adapt based on environmental conditions, supporting product innovation and sustainability.

AI and big data analytics (BDA) are also improving agricultural productivity and logistics. Sharma et al. (2021) explained how neural networks and ML algorithms are used for disease detection, yield prediction, supply chain optimization, and product authentication. In food processing, AI enhances drying processes for fruits and vegetables, optimizing parameters like airflow, moisture, and texture to maintain quality and extend shelf life (Przybył & Koszela, 2023). These AI-driven systems provide consistent quality, reduce costs, and support automation. AI supports food safety by minimizing human error and ensuring regulatory compliance. Bendre et al. (2022) and Kumar et al. (2021) described how AI automates processes like microbial control, sorting, and grading. By integrating chemical and biological sensors with AI systems, food manufacturers can ensure safety while boosting operational efficiency. These intelligent systems also improve hygiene, extend shelf life, and enhance waste management, offering end-to-end optimization.

ML algorithms can analyze vast datasets to identify patterns, predict quality issues, and automate decision-making. Goyache et al. (2001) emphasized that AI can convert human sensory expertise into structured models for training and evaluation. Abass et al. (2024) noted that with proper implementation, data preprocessing, model training, and real-time deployment, AI enables proactive quality control, minimizing recalls and aligning products with consumer expectations. The integration of AI and Industry 4.0 technologies is revamping the food sector, enabling smarter, safer, and more efficient food production and processing. These technologies support predictive maintenance, workforce upskilling, personalized nutrition, food safety monitoring, supply chain optimization, and quality assurance. As global food demand rises and supply chains grow more complex, embracing AI-driven innovation becomes not just an advantage but a necessity. Food manufacturers that invest in digital transformation today are positioning themselves as the leaders of tomorrow, resilient, adaptive, and aligned with the evolving demands of a digital, data-centric world.

Integrating AI with food packaging

Advanced packaging technologies play a significant role in enhancing food quality and safety. With rising global demand, innovation in intelligent packaging is vital. CRISPR-based biosensing is emerging as a promising tool for ultra-sensitive detection of pathogens and contaminants in food packaging, enabling real-time monitoring. AI, particularly deep learning technologies such as CNNs and Long Short-Term Memory Networks (LSTMs), has reformed food quality inspection and safety assurance. These tools enable the automated detection of defects, spoilage, and adulteration through hyperspectral imaging and spectral sensing, providing accuracy and consistency previously unattainable through manual inspection. AI-driven IoT packaging systems further enhance traceability, enabling real-time communication between producers, regulators, and consumers. Packaging machinery equipped with AI facilitates predictive maintenance and defect detection, leading to smoother, error-free production lines (Nayak & Dutta, 2023). Intelligent packaging systems, incorporating sensors, data carriers, and AI algorithms, are redefining how freshness, contamination, and shelf life are managed across the supply chain. These technologies allow for early anomaly detection and product classification, marking a significant advancement in food packaging technology (Abekoon et al., 2024).

The foundation of intelligent packaging lies in its ability to sense, record, and communicate vital information about food products in real time. Components such as Radio-Frequency Identification (RFID) tags, biosensors, gas sensors, and time–temperature indicators support these systems by constantly monitoring environmental conditions and internal product states. The synergy between Intelligent Packaging (IP) and Active Packaging (AP), the latter releasing antimicrobials or antioxidants, offers a powerful, adaptive response to varying storage or transportation conditions (Yam et al., 2005). The application of deep learning techniques (Xiong et al., 2024) in this context, especially when combined with multiple imaging modalities such as thermal, visual, and spectral imaging, significantly enhances freshness detection and spoilage prediction. For instance, AI models can accurately classify the decay stages of fruits based on microbial or volatile compound activity, reducing food waste and economic losses (Li et al., 2023; Singh et al., 2024). Such innovations are crucial in addressing global food safety challenges, especially in markets where real-time monitoring can reduce spoilage and boost consumer trust.

Active packaging has further extended the potential of AI in enhancing food safety and environmental sustainability. Materials embedded with antimicrobial or antioxidant agents, particularly nanomaterial-based films, can now be optimized using ML and ANN. These tools help formulate more effective and sustainable packaging compositions by analyzing real-time performance data and environmental conditions. Hyperspectral imaging, in combination with CNNs, allows for precise classification and detection of food spoilage, enabling dynamic responses throughout the supply chain (Hussain et al., 2024). In tandem, nanotechnology is also transforming biodegradable food packaging. AI aids in optimizing formulations and assessing the performance of biodegradable materials such as polylactic acid and nanocellulose, improving durability and functionality while minimizing environmental impact. Moreover, AI supports predictive toxicology and lifecycle analysis to ensure safe use of nanomaterials like silver or graphene oxide, whose potential health risks still require careful management (Adeyi et al., 2025).

Looking ahead, smart packaging technologies are expected to dominate the sustainable packaging landscape (Yakoubi, 2025). Consumer preferences are increasingly shifting toward intelligent, sustainable solutions, with innovations such as pH indicator films, moisture sensors, RFID-based traceability, and AI-driven labels becoming standard. These tools improve supply chain visibility, enable personalized consumer engagement, and reduce food and packaging waste (Ros-Lis & Serra, 2023; Nagaveni & Poosarla, 2024). Machine learning models are also being used in packaging evaluation and development. Natural language processing can analyze consumer reviews to detect packaging-related failures, while ML algorithms help predict material performance in new product development, such as optimizing the compression strength of ventilated corrugated paperboard (Shirzad & Joodaky, 2024; Esfahanian, 2024; Piotrowski, 2024). Given the 1.3 billion tons of food wasted annually, these technologies are vital. Advanced 2D nanomaterials (2DMs) like functionalized graphene oxide, integrated with AI systems, are being explored for intelligent spoilage detection and shelf-life extension, playing a crucial role in global efforts to reduce food insecurity and environmental harm (Moustafa et al., 2025).

Role of AI in the food supply chain

Artificial intelligence is facilitating the food supply chain (FSC) by addressing critical challenges such as food safety, quality control, traceability, and waste reduction (Pallathadka et al., 2022). Despite its success in other sectors, AI adoption in FSCs, especially in developing economies like India, remains limited. Dora et al. (2022) highlighted the importance of critical success factors (CSFs) for AI integration using a conceptual model based on Technology, Organization, Environment, and Human (TOEH) dimensions and the rough SWARA technique. Key CSFs include technological readiness, cybersecurity, perceived benefits, regulatory alignment, and customer satisfaction. AI enables data integration, transparency, and enhanced coordination across the FSC, thereby reducing postharvest losses and improving traceability. Machine learning and predictive analytics assist in demand forecasting, spoilage reduction, and optimal storage, especially for perishable goods. These innovations underscore the need for context-specific policies and collaborative efforts among governments, tech providers, and practitioners to scale AI applications for global food safety and sustainability (Dora et al., 2022; Liu et al., 2023).

AI technologies such as neural networks, support vector machines, and computer vision are being applied to food safety risk management. These tools analyze large datasets to predict contamination and spoilage risks, enabling real-time detection through sensor-based monitoring systems (Singh, 2022). AI, when combined with the IoT and blockchain, offers end-to-end traceability and greater accountability across the supply chain. For example, RFID tags and wireless sensor networks can track temperature and humidity, supporting quality control in cold chain logistics for meat, produce, and dairy (Bouzembrak et al., 2019). In retail, AI enhances food safety through applications categorized as visual (e.g., automated inspections), analytical (e.g., risk prediction), and interactive (e.g., customer engagement), allowing faster, data-driven decisions (Friedlander & Zoellner, 2020). Although AI presents great potential, it must be applied to specific, well-understood problems with human oversight to ensure ethical and reliable outcomes (Qian et al., 2023).

Future-ready supply chains are increasingly adopting hybrid models that integrate AI, IoT, and blockchain technologies. Blockchain enhances transparency by securing transactions and reducing fraud, while AI augments predictive analytics and automation. This evolution, termed the shift from Supply Chain 4.0 to 5.0, includes human-robot collaboration, facial recognition, and distributed ledgers to enable smarter, safer food systems (Ahamed & Vignesh, 2022). Trollman (2024) suggested that a combination of AI and qualitative comparative analysis (QCA) can address data complexity and improve interpretability, aligning with the EU's Farm to Fork Strategy. These emerging tools can make food supply chains more resilient, adaptive, and aligned with consumer and regulatory expectations in a fast-evolving global landscape (Vegesna et al., 2024).

AI in contaminant detection and quality assurance

Food safety is a global public health priority, with the World Health Organization reporting 600 million foodborne illnesses and 420,000 deaths annually. AI presents potential in mitigating these risks by improving food quality control, contamination detection, and supply chain transparency. Tools such as electronic noses and tongues, computer vision, Near-Infrared Spectroscopy (NIRS) (Mavani et al., 2022), and even 3D printing are now being integrated with AI to automate and enhance food safety evaluations (Moholkar et al., 2023). AI systems are recognized for their speed, scalability, and precision, offering advantages over traditional inspection and testing methods. Their application spans across modeling, prediction, and sensory analysis, enabling industries to make real-time, data-driven decisions. However, widespread adoption hinges on cross-sector collaboration among regulators, researchers, and industry stakeholders to ensure ethical deployment and resilient implementation strategies.

AI technologies like CNNs and Recurrent Neural Networks (RNNs), particularly Long Short-Term Memory networks, have been widely applied in quality inspection, adulteration detection, and predictive monitoring of spoilage. CNNs are highly effective for image-based quality assessment, such as surface defect detection, while LSTMs handle sequential, time-series data, making them ideal for contamination risk prediction during storage and transport (Ding et al., 2025). These technologies significantly enhance operational efficiency, especially on production lines, where they automate inspection and risk flagging. In agriculture, AI applications span contamination prevention, biological hazard detection, and crop quality monitoring (Raki et al., 2023). Furthermore, Hyperspectral Imaging (HSI), combined with AI, enables nondestructive, high-dimensional analysis of food products, detecting contaminants, spoilage, and quality indicators like moisture content or ripeness (Nikzadfar et al., 2024). HSI systems powered by AI show promising applications in identifying egg fertility, nutritional profiling, and even microbial detection in real-time.

The integration of AI in food risk assessment continues to evolve with models leveraging big data (Sapienza, 2022) and explainable AI (XAI). For instance, tools like SHAP enhance model transparency by identifying key drivers of food safety alerts, such as the presence of aflatoxins or *Salmonella*, in datasets like the Rapid Alert System for Food and Feed (RASFF) (Sari et al., 2025). Data enrichment and augmentation improve model accuracy and help regulators make informed, timely decisions. AI-powered frameworks can proactively identify hazards across all supply chain stages, from production to distribution, especially in fruits and vegetables (Stoitsis et al., 2023). These systems are complemented by the Read-Across-based Structure Activity Relationships (RASAR) tool, which provides automated toxicity assessments for food additives with high reliability, significantly reducing the need for animal testing (Fu et al., 2023). In tandem with these technologies, cloud computing and IoT facilitate real-time contaminant monitoring, offering scalable and responsive food safety systems (Zhang, 2024).

The shift toward Controlled Environment Agriculture (CEA), such as vertical farming, has reduced reliance on external factors, yet microbial risks persist. While precision farming generates abundant data, the use of AI for risk mitigation remains limited due to model and data constraints (Motzer et al., 2024). Insights from the European Food Safety Authority emphasize the need for data-driven systems that leverage crowdsourcing, big data, and real-time analytics to transform exposure assessment and regulatory interventions (Authority et al., 2019). Traditional food safety practices like HACCP still form the foundation of risk management, but are increasingly enhanced by AI and automation technologies. For example, AI-integrated HACCP systems employ computer vision, light-based sensors, and isochoric freezing to prevent contamination, manage water quality, and maintain ISO 22000 standards (Awuchi, 2023). These hybrid systems represent the future of predictive food safety, merging proactive analytics with proven principles.

Technological convergence has further elevated food safety capabilities. IoT devices equipped with NIR spectrometers can now monitor food contamination in real-time during production. When combined with 5G, cloud computing, and blockchain, these systems create transparent, tamper-proof records and support swift product recalls when contamination is detected, such as undeclared allergens (Peddareddigari et al., 2024). AI also supports automated inspections and hygiene monitoring in retail and food service environments, bolstering public trust in food safety (Chavan et al., 2024). Advances in metabolomics, studying the chemical fingerprints of metabolic processes, when integrated with deep learning, offer enhanced microbial hazard detection. Metabolomic biomarkers, paired with deep neural networks, enable rapid and precise identification of foodborne pathogens, significantly improving the speed and accuracy of risk monitoring (Feng et al., 2024). These developments reflect AI's expanding role in moving the industry toward zero-contamination food systems.

Emerging dietary patterns and environmental shifts are reshaping the food safety landscape. Increased consumption of plant-based products raises concerns about natural toxins, pesticide residues, and chemical contaminants. Climate change further exacerbates these risks by influencing toxin levels and pest prevalence in crops. Additional complications arise from packaging materials, such as engineered nanomaterials and Per- and Polyfluoroalkyl Substances (PFASs), which may migrate into food. To tackle these complex issues, AI and New Approach Methodologies (NAMs) are being adopted for nonanimal, predictive toxicity testing, offering rapid and ethical alternatives (Liu et al., 2025). Big data platforms now aggregate diverse data types, from genomics and sensor data to social media alerts, enabling multi-dimensional risk assessments. Systems like WHO's FOSCOLLAB and

RASFF, along with automated surveillance platforms like MedISys, allow early outbreak detection and coordinated responses (Marvin et al., 2017). Mobile phone-based detection, omics data integration, and smart packaging collectively empower both consumers and regulators in maintaining food safety standards.

In conclusion, AI has become a cornerstone of modern food safety management, significantly enhancing the speed, accuracy, and resilience of safety systems. By automating risk assessment, improving traceability, and enabling real-time decision-making, AI reduces contamination risks and ensures safer food for global populations (Naseem and Rizwan, 2025). As outlined by Kuppusamy et al. (2024), AI supports sustainable agriculture and public health by optimizing food safety practices and mitigating environmental harm. Computer vision and deep learning are now being adopted for nondestructive inspection of fruits, vegetables, and other perishable goods (Khan et al., 2021). AI-driven food safety systems promise to modernize the global food supply chain, creating safer, more sustainable, and more responsive systems for the future.

AI-driven sensory evaluation

The increasing consumer demand for high-quality food has catalyzed the development of artificial sensory systems, such as electronic noses, tongues, and computer vision. These technologies replicate human senses to assess food characteristics like aroma, flavor, and appearance. Using sensors, including conductometric, potentiometric, and amperometric types, combined with data analysis tools like artificial neural networks and principal component analysis, artificial sensory systems now play a critical role in food quality control, authenticity verification, and production monitoring. Since their inception in the 1960s, these systems have evolved into reliable tools for evaluating freshness, detecting adulteration, and ensuring product consistency. For instance, electronic noses identify specific odor profiles by analyzing volatile compounds, while electronic tongues focus on the chemical composition of liquid foods. Their integration into automated quality assessment frameworks offers advantages over traditional sensory evaluations, including improved accuracy, speed, and objectivity (Sliwinska et al., 2014).

Beyond sensory replication, artificial intelligence is also addressing long-standing challenges in food modeling and design. The complex structure of food has traditionally limited its inclusion in predictive mathematical models, especially for nutritional properties and cooking transformations. AI-driven solutions now enable the creation of digital twins of foods, automated models capable of predicting changes such as texture and nutrient bioaccessibility, as demonstrated in studies of pasta during cooking (Mengucci et al., 2022). This approach significantly reduces dependence on costly, labor-intensive physical experiments. In parallel, electronic nose (e-nose) technologies, enhanced by machine learning algorithms, are advancing nondestructive food quality evaluation across industries, including meat, dairy, oils, seafood, tea, and coffee. These systems enhance accuracy, minimize human error, and offer scalable, cost-effective solutions. Despite these advancements, future efforts must focus on developing unified platforms for seamless data integration and real-time analysis (Anwar et al., 2023). Together, these innovations signal a transformative shift toward smarter, faster, and more sustainable food quality management.

AI in food safety evaluation and decision making

Food safety is critical in preventing foodborne illnesses and includes key practices such as cleanliness, proper food separation, thorough cooking, maintaining safe temperatures, and using safe water and raw materials. Key practices include maintaining temperatures below 5 °C or above 60 °C to inhibit bacterial growth, using safe water and ingredients, and ensuring staff training. These protocols protect public health and reduce contamination risks across the food chain. In recent years, AI and ML have emerged as transformative technologies in food safety, offering real-time monitoring, predictive analytics, and intelligent automation. AI algorithms enable rapid detection of pathogens and can predict potential risks based on environmental data, which significantly reduces response time and enhances preventive measures (Erkinjon & Feruz, 2024). Machine vision systems and sensors assist in quality control by identifying product defects more efficiently than human inspectors. AI also supports sorting, grading, and shelf-life estimation, which contributes to waste reduction. By integrating AI with technologies like blockchain and IoT, the food industry benefits from improved traceability, optimized inventory management, and predictive maintenance, resulting in enhanced food safety and supply chain resilience.

The integration of AI into food production and safety monitoring is part of a broader digital transformation that leverages big data, natural language processing, and deep learning for greater accuracy and speed in detecting and mitigating risks. These technologies allow for automated inspections, compliance monitoring, and early detection of safety concerns, helping industries meet regulatory standards and consumer expectations (Chhetri, 2024; Holzinger et al., 2023). In the era of big data, AI, and digital technologies are transforming food safety by enabling real-time monitoring, data visualization, and more efficient oversight (Chen, 2021). AI applications such as computer vision, robotics, and deep learning enhance key stages of food production, from sorting and grading (Filho et al., 2024) to packaging and supply chain optimization. These technologies improve product consistency, reduce waste, and support traceability through blockchain systems. AI-assisted quality control and predictive maintenance further streamline operations. Overall, integrating AI into food processing strengthens food security, promotes sustainability, and aligns production with evolving consumer and environmental demands (Mengistu & Ashe, 2024). AI's applications span across every stage of food production, from quality assurance in frozen and thawed meat to defect detection in high-value crops like Piarom dates (Qiao et al., 2024; Azimi & Rezaei, 2024). Through explainable and transparent algorithms, AI facilitates more sustainable food processing practices, aligning with global goals for responsible consumption and ecosystem preservation. Its integration into life sciences and environmental monitoring further expands its role in supporting long-term food security and safety.

AI's future in food safety also hinges on the quality and representativeness of data used in training algorithms. As highlighted by Altenburger and Ho (2019), high-quality datasets from sources like genomic surveillance, supply chain audits, and satellite imagery can enhance risk prediction and response. Advanced Data Analytic Techniques (ADATs), including machine learning and hyperspectral imaging, allow for early hazard identification and proactive intervention, transforming food safety into a data-driven science (Benefo et al., 2022). In agricultural innovation, AI-driven models support sustainable farming methods, alternative protein sources, and personalized nutrition (Lugo-Morin, 2024). The ongoing evolution of AI in the food industry promises smarter, more efficient, and sustainable approaches to quality control, risk management, and global food system resilience.

Innovative applications of machine learning in food safety

Machine learning is used in optimizing food processing by automating routine processes, improving food safety, packaging, and delivery systems. ML techniques, including supervised and unsupervised learning, data preprocessing, feature engineering, model selection, and optimization, are being leveraged to enhance production efficiency, reduce waste, and personalize consumer experiences. ML is widely used for packaging, labeling, ingredient optimization, and even predicting consumer behavior, allowing for smarter, more tailored food production strategies (Pandey et al., 2023). Particularly in fresh produce, ML identifies optimal storage conditions, preserving the quality of fruits and vegetables. Integration with nanotechnology enables precise data analysis, which supports quality control, defect detection, and the development of more effective packaging systems. Additionally, ML contributes to personalized nutrition labeling by categorizing ingredients, allergens, and nutrients, ensuring regulatory compliance and transparency. These innovations support better traceability, more responsive logistics, and the anticipation of market demand, ultimately leading to smarter and safer food systems.

Different ML models, such as Bayesian networks (BNs), neural networks (NNs), and support vector machines (SVMs), have demonstrated significant predictive capabilities in food safety applications. BN excels with structured data, while NN proves more effective for unstructured data like images (Wang et al., 2022). These models are further enriched by the integration of advanced technologies such as IoT sensors, social media data, and satellite imagery, enabling rapid and reliable food safety monitoring. The early−stage yet promising application of ML in risk prediction is enhanced by these expansive datasets, forming a robust foundation for food safety interventions. Tools that incorporate nontraditional data sources, such as crowdsourcing and online platforms, are already showing promise in real-time risk identification and are becoming central to food safety innovation (Mu et al., 2024).

The increasing complexity of food safety risks, driven by global trade, climate change, and emerging pathogens, necessitates intelligent, real-time monitoring systems. AI and ML now support early warning systems by analyzing structured and unstructured data from diverse sources, including weather trends, consumer sentiment, and logistics data. Predictive microbiology, a key discipline in food safety, has been reformed by ML models such as random forests and artificial neural networks (Taiwo et al., 2024). These technologies enable accurate shelf-life prediction, spoilage estimation, and microbial risk assessments by simulating complex microbial ecosystems and environmental variables. Combined with whole genome sequencing and metagenomics, ML enhances detection capabilities for emerging risks. Tools such as time–temperature indicators embedded with AI and IoT technologies help maintain cold chain integrity, providing real-time feedback that enhances food preservation and public health.

Big data are central to the transformation of food safety systems, with machine learning enhancing risk assessment and regulatory compliance. Principle-based models like P-SAFETY − Privacy, Security, Accountability, Fairness, Explainability, and Transparency ensure that ML applications in food safety maintain ethical and regulatory integrity (Sapienza & Vedder, 2023). Machine learning also advances beyond traditional detection methods like PCR and culture-based tests by increasing sensitivity and speed. ML can identify pathogens such as *E. coli* and *Pseudomonas aeruginosa*, trace sources of contamination, and even forecast outbreak potential (Onyeaka et al., 2024). When combined with IoT and blockchain, ML enables seamless traceability and enhances consumer trust. The European Food Safety Authority (EFSA) underscores the importance of advanced tools, such as AI, omics, and multicriteria decision analysis, for evidence-based regulatory decisions in an increasingly complex data landscape (Cavalli et al., 2019). Machine learning is upgrading the food supply chain by enhancing speed, accuracy, and decision-making, addressing challenges in safety, quality, and efficiency for scalable, cost-effective production (Kaviani et al., 2022).

In a globalized food economy, ML enhances productivity and resilience across the entire value chain. By automating inspection tasks, minimizing human error, and improving quality assessments, ML contributes to food safety, efficiency, and competitiveness (Kler et al., 2022). The use of ML in early warning systems enables regulatory bodies to act on risks before they escalate, reducing foodborne disease outbreaks and enhancing global public health protection (Röhrs et al., 2025). Data science plays a complementary role by integrating lab reports, supply chain data, and consumer feedback to detect inconsistencies and contamination (Whig et al., 2024). Moreover, techniques like surface-enhanced Raman scattering (SERS) have gained importance in food safety due to their sensitivity and compatibility with ML. Machine learning powered SERS enables the identification of chemical residues, pathogens, and even food additives with greater speed and accuracy (Dong et al., 2024), enhancing real-time food analysis and enabling nondestructive quality assurance.

Machine learning's scope continues to expand, particularly in tackling foodborne illnesses that affect millions globally. From predicting antibiotic resistance and tracking pathogens to assessing risks in ready-to-eat and thermally processed products, ML is increasingly embedded in food safety systems (Pujahari & Khan, 2022). AI also supports the creation of smart detection hardware and inspection systems tailored for USDA-FSIS-regulated foods. Applications of AI extend into regulatory frameworks by enabling predictive modeling, decision support, and risk assessment (Yu et al., 2024). Smart sensors, IoT, blockchain, and deep learning contribute to improved traceability, fraud prevention, and transparency. Technologies like hyperspectral imaging, automated visual inspection, and real-time data analytics are being integrated into food safety platforms, enhancing accuracy and reducing recall rates. As global food processing expands, widespread implementation of ML and AI will be essential for ensuring safety, enhancing quality, and supporting proactive risk intelligence (Stoitsis & Manouselis, 2023). These systems not only modernize traditional methods but also align food production practices with global standards and sustainability goals.

Impact of sensor and biosensor technologies on food safety

The integration of biosensors and ML has opened new frontiers in food safety assessment by enhancing sensitivity, speed, and real-time analysis. While biosensors have long been employed to detect microbial contamination, chemical residues, and allergens in food products, their standalone performance is often limited by accuracy and data complexity. The addition of ML algorithms, particularly supervised and unsupervised learning, enables improved signal processing and pattern recognition, allowing biosensors to perform multifactorial analyses in real-time. These smart systems can optimize food safety protocols and offer scalable, end-to-end monitoring capabilities. By analyzing biosensor data through ML, the system can detect anomalies more accurately and rapidly, supporting early interventions and quality assurance in food production (Zhou et al., 2024).

In parallel, the One Health approach, which integrates human, animal, and environmental health, complements the application of biosensor and ML technologies by emphasizing systemic, cross-sector collaboration. Traditional diagnostic tools like ELISA and PCR, while precise, are resource-intensive and time-consuming. Biosensors, ranging from whole-cell to affinity-based types, are now being deployed across agriculture, livestock, and packaging systems to enable real-time contaminant detection. These innovations align with the One Health framework's goals for cost-effective, scalable diagnostics and preventive health strategies. For instance, a smart spoilage monitoring system combining CNNs and sensor-based IoT technologies has proven effective in extending the shelf life of fresh produce. This system utilizes CNNs to classify fruits and vegetables with 95% accuracy, while embedded sensors adjust environmental conditions like humidity and temperature, sending real-time alerts to mobile devices (Grasso et al., 2022; Sonwani et al., 2022).

Further advancements in food safety have been driven by the convergence of AI, sensor technologies, and intelligent biosensors. Smartphone-enabled biosensing platforms, 3D-printed devices, and AI-driven neural networks are now enabling point-of-care food safety diagnostics that are both portable and cost-efficient. For instance, smartphone biosensors can perform real-time colorimetric analysis and data processing through cloud-based platforms. Additionally, biosensing systems like electronic noses and tongues replicate human senses to detect complex food mixtures. These tools are particularly valuable in low-resource settings, offering alternatives to conventional methods that often require sophisticated lab infrastructure. As demonstrated in the detection of Salmonella or allergens, AI-enhanced biosensors provide real-world solutions that reduce testing time, cut costs, and empower frontline decision-makers (Zhang et al., 2022).

AI, image processing, and sensor technologies are transforming quality assessment in the food industry by enabling nondestructive, real-time evaluations of product attributes such as size, shape, microbial presence, and defects. Advancements in nanotechnology and biotechnology have enhanced sensor precision, while digital tools like the IoT, blockchain, and data analytics ensure traceability, hazard detection, and efficient recalls across supply chains. AI-powered analytics improve early identification of food safety issues, while digital sensors maintain optimal storage conditions to prevent spoilage (Chen & Yu, 2021; Ali Eltabey, 2023). These innovations strengthen food safety, transparency, and efficiency from production to consumption.

Further breakthroughs include intelligent sensing systems using optical, electrochemical, and machine olfaction technologies integrated with machine learning and edge-cloud computing for enhanced accuracy, authenticity, and decision-making (Jiang et al., 2025). Novel solutions like the colorimetric microneedle sensor, paired with a CNN-enabled smartphone app, allow rapid, user-friendly meat freshness detection via pH-induced color changes (Wang et al., 2024). AI-based shelf-life prediction systems (Yang et al., 2025) using machine vision and spectroscopy outperform traditional methods, reducing waste and improving sustainability. As AI continues to evolve, it enables smarter, adaptive food safety management aligned with global public health and regulatory demands (Rashvand et al., 2025).

Food safety using integration with IoT, blockchain, and digital ecosystems

Technologies like AI, big data analytics, and blockchain are proving transformative in addressing safety risks across production, processing, distribution, and retail. AI tools, including machine learning and deep learning, are used for predictive analytics, anomaly detection, and decision support throughout the food lifecycle. Big data processes vast datasets from IoT sensors, genomic platforms, and social media to enable real-time traceability and contamination risk prediction. Blockchain ensures transparency through immutable records, strengthening stakeholder trust. These innovations are applied across the supply chain, from smart sensors monitoring farm conditions and AI tools optimizing processing and quality control, to IoT systems ensuring transport conditions and blockchain enhancing data integrity. Efficient infrastructure for data handling is vital, with NoSQL databases like MongoDB offering scalable storage solutions and tools like Apache Flume and ElasticSearch enabling rapid data flow and querying (Chhetri, 2024).

A promising model integrates blockchain, AI, IoT, and edge computing to modernize food safety. In a pilot study, this integrated system increased spoilage detection accuracy by 25% and improved response time by 30%, offering a scalable solution to longstanding food safety issues such as contamination, inefficiency, and fraud (Kamran & Sundarakani, 2024). These innovations are further supported by regulatory evolution, greater consumer awareness, and scientific advances. Technologies such as predictive AI, innovative preservation techniques, and functional ingredients like probiotics and bioactive peptides contribute not only to food safety but also to health promotion. Global regulatory bodies are adapting, and initiatives like the Global Summit on Regulatory Science (GSRS21) have highlighted the importance of real-world data and AI to enhance regulatory decision-making and global collaboration (Tan et al., 2025; Thakkar et al., 2023).

Broader global trends, climate change, urbanization, and shifting demographics are creating new challenges for food safety, such as increased pathogen risks, antimicrobial resistance, and disrupted supply systems. Addressing these requires risk-based, proactive strategies incorporating AI, biosensors, blockchain, and genomic surveillance. Precision agriculture and automated technologies offer earlier interventions, while food safety culture, shaped by leadership and employee engagement, ensures these measures are sustained. Evolving regulatory models now emphasize outcome-based frameworks and ethical data use. Importantly, resilience in global food systems demands context-specific approaches, particularly for low-income and smallholder farming communities. Harmonizing innovation, regulation, and cultural change is essential for building safe, sustainable, and equitable food systems globally (Thorsen et al., 2025).

Role of AI in behavioral monitoring and safety culture

Artificial intelligence is uplifting food safety by enhancing three core pillars: monitoring, evaluation, and intervention. AI-assisted monitoring systems enable precise, unobtrusive tracking of critical food safety behaviors such as hand hygiene and personal protective equipment (PPE) compliance, minimizing human error and ensuring consistent standards. Evaluation tools powered by AI and large language models provide advanced data analytics to assess food safety culture, producing actionable insights that empower companies to take proactive measures. These insights inform tailored AI interventions, including real-time feedback, personalized training, and communication tools, that promote behavior change and foster a strong food safety culture. Together, these AI-driven systems form a continuous improvement cycle, dynamically monitoring, assessing, and correcting behaviors to enhance public health outcomes and industry compliance (Wang et al., 2025).

Traditional food safety management systems often rely on lagging indicators that identify issues after they occur. AI, however, supports a shift toward leading indicators, which focus on predicting and preventing potential food safety failures. Through behavioral data analysis, such as observing workplace habits and cultural norms, AI can anticipate risks before they escalate. This shift to a data-driven approach enables early detection of deficiencies in human factors, contributing to stronger preventive measures and reduced instances of contamination and recalls. AI-powered prediction models can analyze behavioral trends across the workforce, enabling organizations to make more informed decisions and implement timely interventions. By combining AI capabilities with behavioral science, food safety systems can become more robust, adaptive, and responsive to emerging challenges (Kudashkina et al., 2022).

The growing complexity of global food supply chains has intensified the need for advanced tools to safeguard quality and safety. AI technologies, including machine learning, computer vision, robotics, and IoT devices, are significantly improving food safety through real-time monitoring, pattern recognition, and automated decision-making. For instance, computer vision detects contaminants, while machine learning can predict pathogen outbreaks. IoT sensors allow for continuous monitoring of environmental conditions throughout the supply chain. Moreover, causal inference techniques, such as Causal Directed Acyclic Graphs, enable deeper analysis by identifying actual cause-and-effect relationships rather than mere correlations. This emerging fusion of AI and causal modeling elevates food safety science to a more predictive and preventive discipline (Palakurti, 2022). In practice, AI tools like GPT models have also shown promise in enhancing the implementation of the HACCP system, offering tailored guidance across the food supply chain (Tzachor, 2024). Overall, these AI innovations signal a shift in food safety management, fostering more predictive, preventive, and resilient food systems worldwide.

Role of AI in food security

Artificial intelligence is rapidly transforming food safety, quality, and security by enabling real-time contamination detection, predictive risk modeling, and enhanced compliance monitoring. AI-driven technologies automate defect detection, shelf-life prediction, and product consistency verification, leading to improved food quality and safety standards. Additionally, AI supports food security by optimizing resource use, forecasting crop yields, and streamlining supply chains, thus reducing losses and operational costs. Integration with advanced food processing techniques, like high-pressure processing, ultraviolet treatment, and cold plasma, further enhances microbial safety and product quality. Beyond these applications, AI facilitates food valorization by converting food waste into valuable resources and mitigating risks in dynamic and complex environments (Dhal and Kar, 2025). Moreover, AI contributes to sustainable food systems through production and safety innovations in alternative proteins such as edible insects and microalgae, addressing population growth and environmental challenges (Rugji et al., 2024).

The increasing impact of climate change on food systems (Ejedegba, 2024) has underscored the need for predictive tools that can address emerging food safety, quality, and availability risks. Rising temperatures and extreme weather events exacerbate microbiological hazards, requiring sophisticated modeling and risk prediction across the entire food chain. AI, combined with other advanced technologies, enhances resilience by integrating diverse data streams, from crop and livestock production to postharvest management and waste reduction. It supports precision agriculture, real-time monitoring, and smart farming, aligning with global sustainability goals such as Zero Hunger. AI also improves crop management, soil irrigation, pest control, and operational efficiency, especially in vulnerable regions like Sri Lanka, helping mitigate resource depletion and shrinking agricultural land challenges (Kutyauripo et al., 2023; Chamara et al., 2020). By automating farming tasks, optimizing crop health, and enabling demand-driven supply chains, AI reduces environmental impacts and promotes healthier food systems, representing a pivotal opportunity to reshape global food security sustainably (Kaur et al., 2023).

AI's application across supply chain management, food production, sensory science, and personalized nutrition is propelling the food industry with smarter, more efficient, and consumer-tailored solutions. Key AI methodologies, including expert systems, fuzzy logic, artificial neural networks, and genetic algorithms, support predictive maintenance, quality assurance, product innovation, and waste reduction. The integration of AI with advanced sensors enables real-time monitoring, intelligent packaging, and accurate shelf-life prediction, which enhances food safety and operational efficiency. For example, AI frameworks combining Radial Basis Function neural networks with Genetic Algorithms effectively forecast nonlinear sales patterns in perishables like fresh milk, reducing waste and lost sales while improving sustainability (Doganis et al., 2006; Zatsu et al., 2024). AI-powered robotics and machine vision streamline food handling and quality assurance, supporting the four pillars of food security: availability, access, utilization, and stability. These technologies facilitate data-driven automation, improved decision-making, and resilience throughout the food supply chain. Commercial applications, such as greenhouse monitoring and logistics optimization, highlight AI's potential to create adaptable, sustainable food systems that meet global demands efficiently and responsibly (Sahni et al., 2021).

Field applications of AI in food safety

Artificial intelligence is advancing food safety by enabling real-time detection of pests, diseases, and contaminants through advanced technologies such as spectral analysis, machine vision, and predictive analytics. AI-powered sensors and ML algorithms enhance traceability and regulatory compliance, while blockchain ensures data transparency across the supply chain. At the consumer level, tools like edge computing and colorimetric sensors offer on-the-spot assessments of food freshness (Yin et al., 2025). AI applications are increasingly tailored to specific food safety challenges, addressing issues like pesticide residue detection, pathogen identification, and spoilage forecasting. Public health is also benefiting from AI innovations. For example, Menichetti et al. (2023) developed an ML algorithm to classify levels of food processing, revealing that over 73% of the U.S. food supply is made up of ultra-processed foods, strongly associated with chronic conditions like cardiovascular disease, type 2 diabetes, and accelerated aging. Their findings suggested that even modest dietary shifts toward minimally processed foods can significantly improve health outcomes. AI-enabled labeling systems and access to real-time processing data can help guide healthier consumer choices, supporting preventative healthcare strategies (Menichetti et al., 2023).

Animal-source foods (ASFs) have also seen significant improvements with AI integration into HACCP systems. Techniques like near-infrared (NIR), Fourier-transform infrared (FTIR), and Raman spectroscopy, paired with ML, enable real-time detection of anomalies in meat, dairy, and seafood (Revelou et al., 2025). Smartphone sensors and hyperspectral imaging offer precise traceability and fraud detection. Convolutional neural networks and LSTM networks process image data, while interpretable ML models like SVMs and random forests ensure explainable, reliable outcomes. Global databases such as WHO's GEMS and the EU's RASFF are now feeding into early warning systems. Additionally, AI-based image-processing systems, utilizing preprocessing and segmentation algorithms, are being deployed for automated spoilage detection and quality grading (Hemamalini et al., 2022).

Advancements in food inspection systems are further driven by the fusion of spectroscopy, chromatography (Yi et al., 2024), mass spectrometry, and biosensors with ML, enhancing both speed and precision (He et al., 2024). Portable, interpretable, and hybrid AI models are increasingly prioritized. Foerster et al. (2024) stressed the need for interdisciplinary collaboration to ensure regulatory compliance and data standardization. Furthermore, Li et al. (2025) highlighted the importance of deep learning, meta-learning, and better data structuring for achieving AI's full potential in food systems. AI's role within Industry 4.0 and the emerging Quality 4.0 framework, incorporating digital twins and smart sensors, further underscores its impact on safety, sustainability, and resilience in the global food supply (Bisht et al., 2025).

Postpasteurization contamination (PPC) by gram-negative bacteria continues to challenge the dairy industry, affecting the shelf life of HTST- and vat-pasteurized milk. The study of Murphy et al. analyzed fluid milk spoilage data from 23 facilities (2015–2017) and surveyed quality management practices to rank PPC risk factors using multimodel inference and conditional random forest. Key factors associated with increased PPC included poor cleaning and sanitation, weak GMP adherence, container type, lack of in-house product testing, and absence of a dedicated quality department. These findings highlight critical intervention points and demonstrate how machine learning can manage correlated, unbalanced data for improved food safety and decision-making (Murphy et al., 2021). da Silva Pereira et al. (2024) explored the use of a portable NIR spectrometer to screen for subclinical mastitis in milk, a condition that affects milk quality and safety. Milk samples collected across five Brazilian regions over two years were analyzed using PCA, Partial Least Squares Discriminant Analysis (PLS-DA), RF, and SVM models. Lactose content was the key differentiator between mastitis and nonmastitis milk. PLS-DA achieved 78% accuracy. RF had the highest sensitivity (78%), while SVM excelled at detecting nonmastitis milk (81%). Applying the

Isolation Forest algorithm improved RF and SVM precision by up to 25%, enhancing overall model performance.

Artificial intelligence is evolving food safety and inspection services, particularly within USDA-FSIS, by offering transformative tools that enhance public health protection (Cheng, 2024). Its integration highlights both complexity and opportunity, as researchers and industry leaders pursue innovative solutions to strengthen food system resilience. AI applications, such as predictive analytics, supply chain tracking, and automated sanitation monitoring, improve safety outcomes and regulatory compliance. Furthermore, AI supports the development of safer food additive alternatives. While U.S. Food and Drug Administration (FDA) workforce reductions present challenges for regulatory oversight, they also offer the industry a chance to adopt responsible AI strategies. Companies embracing AI will better navigate regulations and prevent foodborne illnesses (Minsk et al., 2025). FDA is enhancing traceability to swiftly identify contaminated food sources, enabling faster recalls and stronger prevention (FDA, 2024). Through FSMA Section 204, it promotes harmonized data, digital technologies, transparency, and predictive analytics. The FDA is also deepening its understanding of AI to boost regulatory efficiency, exploring machine learning for targeting high-risk seafood imports, adverse event detection, synthetic dataset testing, and drug application timeline predictions (FDA, 2022a). In phase three of its AI-Imported Seafood Pilot, the FDA uses AI and ML to address global supply chain risks (FDA, 2022b). Additionally, new guidance supports iterative, safe AI-enabled device software function improvements (FDA, 2023).

Recent advancements demonstrate the growing role of AI and deep learning in managing perishable food products. Gong et al. (2023) developed a portable smartphone-based sensing platform using a colorimetric indicator bar and a CNN model, achieving 96.2% accuracy in real-time meat freshness prediction. The system, built on VGG16 architecture and a watershed algorithm, delivers results in under 30 s. Similarly, Javanmardi and Ashtiani (2025) employed CNNs with transfer learning to assess mushroom freshness, achieving accuracies of 94.10% (white button), 89.11% (oyster), and 86.36% (shiitake) using ResNet-50 and MobileNet-V2 models. These nondestructive, efficient methods enhance postharvest quality control and reduce spoilage. Moreover, Şimşek (2024) highlighted AI's broader application in perishable goods management, from demand forecasting to quality monitoring, with proven success in companies like Coles, Walmart, and Migros. Integrating AI with blockchain may further boost transparency and sustainability. The Casino Food Co-op's processing facility in Australia is using AI and UV sanitization to enhance worker hygiene and reduce contamination risks. The plant makes hygiene and quality assurance critical, where AI-driven systems monitor staff compliance with handwashing, PPE use, and foreign object control. Automated sensors and UV equipment further ensure sanitation. This aims to improve hygiene outcomes through continuous monitoring and refinement (McDonald, 2024).

Limitations and constraints in applying AI to the food industry

The widespread adoption of artificial intelligence and machine learning in the food industry is fraught with a broad array of challenges that span technical, financial, ethical, regulatory, and societal dimensions. Financial challenges are among the foremost barriers, particularly for small and medium-sized enterprises and stakeholders in low- and middle-income countries. High upfront costs for AI system acquisition, integration, and maintenance, combined with limited access to advanced infrastructure and skilled personnel, create substantial obstacles. Data quality and availability further hinder AI adoption; food systems often rely on fragmented, inconsistent, or nondigital data sources, complicating model training and interoperability. Concerns over privacy, intellectual property, and data misuse also deter collaboration and data sharing. Ethical concerns such as algorithmic bias, lack of transparency, and potential misuse of AI systems, especially in high-risk domains like food safety, impact public trust and regulatory confidence. Resistance to technological change, digital illiteracy, and workforce shortages deepen the implementation gap. Regulatory challenges compound these issues; many jurisdictions lack cohesive AI guidelines, while differing global data privacy laws inhibit cross-border collaboration and scalability.

AI adoption in the food industry faces several technical challenges, including poor data quality, limited model generalizability, high computational demands, and outdated infrastructure. The opaque nature of deep learning models raises trust and compliance concerns, especially under strict legal frameworks like FSMA and GDPR. Many AI systems also struggle to scale or adapt to evolving food safety risks. Small and medium enterprises are particularly burdened by potential job displacement and the need for retraining. While AI adoption is growing globally, regional progress varies widely due to differences in infrastructure, regulations, and economic and policy priorities. Technical integration is also difficult. Legacy systems are not always compatible with modern AI tools, and advanced methods like Explainable AI or federated learning require substantial computational resources. Sensor-based systems face reliability issues due to environmental variability and a lack of standardization.

As AI becomes integral to food safety operations, companies must address legal and ethical risks tied to AI failures. Faulty AI decisions, such as misjudging contamination or shelf-life, can lead to foodborne illness, product recalls, financial loss, regulatory penalties, lawsuits, and reputational harm. Accountability often lies with the food company using the AI, especially in the absence of due diligence (e.g., lack of validation or oversight). To mitigate liability, firms should validate AI tools, ensure human oversight, document processes, and follow regulatory updates from agencies like the FDA and EFSA. Clear legal frameworks and standards are essential for safe, responsible AI implementation in food safety. Furthermore, many AI innovations remain confined to academic research, failing to scale due to reproducibility issues and regulatory uncertainty. Cybersecurity threats and unresolved liability concerns pose additional risks. Without clear legal frameworks, accountability for AI-driven decisions remains ambiguous. Lastly, limited collaboration between the public and private sectors and a lack of shared platforms and goals hinder coordinated progress. Overcoming these multifaceted constraints will require strategic investments, regulatory reform, ethical foresight, inclusive innovation, and sustained stakeholder engagement to fully realize AI's potential in transforming food systems.

Prospects and pathways for future research

The future of artificial intelligence and machine learning in food safety and quality assurance offers opportunities that promise to reform the industry. The future of AI in food systems promises transformative advances in safety, sustainability, and personalization. AI-powered sensors and IoT devices will enable continuous, high-resolution monitoring of food environments, allowing for early detection of microbial, chemical, and spoilage risks. This shift from reactive to proactive food safety management will significantly enhance public health protection. Coupled with blockchain and federated learning, AI will ensure secure, transparent, and traceable food supply chains, strengthening consumer trust through tamper-proof data integrity. In agriculture, AI-driven technologies like drone surveillance, intelligent machinery, and precision farming will optimize inputs, detect crop diseases in real time, and enhance environmental monitoring. Adaptive, intelligent packaging will dynamically respond to storage conditions, extending shelf life and reducing food waste. Personalized nutrition, supported by biometric data analysis, will enable tailored dietary recommendations, improving public health outcomes.

Advancements in explainable AI will improve the transparency of automated decision-making, building trust among regulators, industry stakeholders, and consumers. In low- and middle-income countries, mobile AI applications and crowdsourced data will democratize access to food safety tools, supporting local capacity building and timely responses to emerging threats. Global collaboration and harmonized data standards will be essential to closing food safety gaps and promoting equitable access. AI will also enhance regulatory compliance through automated inspections and standardized testing protocols, while supporting the transition to circular food economies by optimizing resource use and minimizing waste. Deep learning and computer vision will advance quality control, incorporating consumer feedback through sensory analysis technologies like emotion detection. As AI continues to evolve, ethical implementation − rooted in fairness, inclusivity, and transparency − will be critical to its success. With continued investment, cross-sector collaboration, and adaptive regulation, AI and machine learning will become foundational to building resilient, sustainable, and future-ready global food systems.

Conclusion

AI applications are proving essential in tackling critical food safety issues such as microbial contamination, chemical residues, and spoilage, particularly under the strain of climate change, globalization, and increasingly complex supply chains. These global pressures are intensifying vulnerabilities within food systems, making them more susceptible to microbial contamination, chemical residues, spoilage, and food fraud. As traditional safety frameworks struggle to keep pace, AI provides the advanced capabilities needed for proactive and predictive food safety management. AI technologies, such as machine learning, deep learning, computer vision, and natural language processing, are enabling food systems to shift from reactive models to data-driven, preventive strategies. These tools can analyze vast datasets, detect anomalies, recognize emerging hazards, and generate real-time insights. In high-risk sectors like the dairy industry, where products are highly perishable and sensitive to temperature changes, AI proves particularly impactful. Integrated with IoT devices, biosensors, and imaging technologies, AI facilitates real-time monitoring, automated quality control, and predictive maintenance. For example, by analyzing temperature fluctuations and microbial test results, AI can forecast spoilage risks, optimize shelf-life predictions, and reduce waste. Computer vision systems further enhance visual inspections by identifying contamination and quality defects faster and more accurately than manual methods.

Throughout the supply chain, AI enables continuous environmental and process monitoring, helping producers maintain food safety standards and regulatory compliance. In processing, AI improves efficiency through automation, fault detection, and process optimization. Smart packaging technologies powered by AI monitor freshness and can detect early signs of spoilage, offering both safety and convenience to consumers. In quality assurance, AI's use of computer vision and sensor data allows for the precise identification of microbial, chemical, and physical hazards. AI-driven sensory evaluation systems ensure consistent product quality by analyzing flavor, color, and texture attributes. The integration of AI with IoT, blockchain, and federated learning systems enhances traceability, data sharing, and trust among stakeholders. This creates more transparent and resilient food ecosystems, where real-time data flow supports rapid responses to potential safety threats. AI also contributes to strengthening food safety culture through behavioral monitoring, which helps assess worker compliance and identify unsafe practices. On a broader level, AI plays a critical role in promoting food security. It improves resource efficiency, reduces postharvest losses, and helps producers adapt to climate variability by enabling smarter agricultural and distribution strategies. The concept of Food Safety 4.0 encapsulates this digital transformation, highlighting the convergence of AI and digital technologies to create intelligent, adaptive food systems.

However, realizing the full potential of AI in food safety comes with its own set of challenges. Key issues include data privacy, algorithmic bias, lack of regulatory clarity, and uneven access to technology, particularly in developing regions. AI systems must be transparent, auditable, and inclusive in their design and implementation. Ethical deployment and equitable access are essential to prevent the deepening of existing inequalities within the global food system. To address these challenges, significant investments are needed in digital infrastructure, education, and innovation. Cross-sector collaboration between governments, industry, academia, and civil society will be crucial to develop responsible AI frameworks. With coordinated global efforts, AI can help build a food future that is not only safer and more efficient but also sustainable, inclusive, and resilient to emerging threats.

In conclusion, this review underscores the pivotal impact of artificial intelligence and machine learning in reshaping the modern food landscape. From enhancing safety protocols and optimizing quality assurance to promoting sustainability, intelligent technologies are driving significant advancements across the supply chain. By integrating innovations such as biosensors, IoT platforms, and predictive systems, the industry is better equipped to manage risks, ensure freshness, and streamline operations. Additionally, the convergence of AI with blockchain and analytical frameworks offers new avenues for achieving transparency and accountability. Despite its promise, AI adoption faces hurdles requiring collaboration and focused interdisciplinary research efforts. This review not only highlights the current capabilities of AI-driven solutions but also presents a forward-looking perspective on constructing a more robust, data-informed, and eco-conscious global food infrastructure.

Disclaimer

The statements, opinions, and data presented in this publication are solely those of the author and are based on the analysis of previously published research. They do not reflect the views or positions of the author's affiliated institution.

CRediT authorship contribution statement

Diwakar Singh: Writing – review & editing, Writing – original draft, Validation, Resources.

Declaration of competing interest

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abass, T., Itua, E. O., Bature, T., & Eruaga, M. A. (2024). Concept paper: Innovative approaches to food quality control: AI and machine learning for predictive analysis. *World Journal of Advanced Research and Reviews, 21*(3), 823–828.

Abekoon, T., Buthpitiya, B. L. S. K., Sajindra, H., Samarakoon, E. R. J., Jayakody, J. A. D. C. A., Kantamaneni, K., & Rathnayake, U. (2024). A comprehensive review to evaluate the synergy of intelligent food packaging with modern food technology and artificial intelligence field. *Discover Sustainability, 5*(1), 160.

Addanki, M., Patra, P., & Kandra, P. (2022). Recent advances and applications of artificial intelligence and related technologies in the food industry. *Applied Food Research, 2*(2)100126.

Adeyi, T. A., Jaiyeola, C. O., Oresegun, O. I., & Dolapo, A. (2025). AI and nanotechnology integration in the development of biodegradable food packaging materials. *International Journal of Science and Research Archive, 14*(1), 726–736.

Ahamed, N. N., & Vignesh, R. (2022). Smart agriculture and food industry with blockchain and artificial intelligence. *Journal of Computer Science, 18*(1), 1–17.

Akyazi, T., Goti, A., Oyarbide, A., Alberdi, E., & Bayon, F. (2020). A guide for the food industry to meet the future skills requirements emerging with industry 4.0. *Foods, 9*(4), 492.

Ali Eltabey, R. (2023). Utilizing digital technologies to ensure food safety. *International Journal of Artificial Intelligence and Emerging Technology, 6*(2), 42–65.
Alsaedi, A. W. M., Al-Hilphy, A. R., Al-Mousawi, A. J., & Gavahian, M. (2024). Artificial neural network modeling to predict electrical conductivity and moisture content of milk during non-thermal pasteurization: New application of Artificial Intelligence (AI) in food processing. *Processes, 12*(11), 2507.
Altenburger, K. M., & Ho, D. E. (2019). Artificial Intelligence and food safety: Hype vs. Reality. *Food Safety Magazine*. https://www.food-safety.com/articles/6416-artificial-intelligence-and-food-safety-hype-vs-reality.
Alves, R. O. R., Tomé, O. C., Pereira, P. C., Villanoeva, C. N. B. C., & Silva, V. M. D. (2021). Artificial neural networks in the prediction of fraud in integral milk powder by adding whey powder. *Ciência Rural, 52*(4)e20210109.
Anwar, H., Anwar, T., & Murtaza, S. (2023). Review on food quality assessment using machine learning and electronic nose system. *Biosensors and Bioelectronics: X, 14*, 100365.
Authority, E. F. S., Bronzwaer, S., Kass, G., Robinson, T., Tarazona, J., Verhagen, H., Verloo, D., Vrbos, D., & Hugas, M. (2019). Food safety regulatory research needs 2030. *EFSA Journal, 17*(7)e170622.
Awuchi, C. G. (2023). HACCP, quality, and food safety management in food and agricultural systems. *Cogent Food & Agriculture, 9*(1)2176280.
Azimi, N., & Rezaei, D. M. (2024). *Automated defect detection and grading of piarom dates using deep learning*. arXiv preprint arXiv:2410.18208. https://arxiv.org/abs/2410.18208.
Bedoya, M. G., Montoya, D. R., Tabilo-Munizaga, G., Pérez-Won, M., & Lemus-Mondaca, R. (2022). Promising perspectives on novel protein food sources combining artificial intelligence and 3D food printing for food industry. *Trends in Food Science & Technology, 128*, 38–52.
Bendre, S., Shinde, K., Kale, N., & Gilda, S. (2022). Artificial intelligence in food industry: A current panorama. *Asian Journal of Pharmacy and Technology, 12*(3), 242–250.
Benefo, E. O., Karanth, S., & Pradhan, A. K. (2022). Applications of advanced data analytic techniques in food safety and risk assessment. *Current Opinion in Food Science, 48*, 100937.
Bisht, B., Rawat, K., Vohat, A., Jangid, N., Singh, N., Nishinari, K., Vlaskin, M. S., Kurbatova, A., & Kumar, V. (2025). Industry 4.0 digital transformation: Shaping the future of food quality. *Food Control, 170*, 111030.
Bouzembrak, Y., Klüche, M., Gavai, A., & Marvin, H. J. (2019). Internet of things in food safety: Literature review and a bibliometric analysis. *Trends in Food Science & Technology, 94*, 54–64.
Cavalli, E., Gilsenan, M., Van Doren, J., Grahek-Ogden, D., Richardson, J., Abbinante, F., Cascio, C., Devalier, P., Brun, N., Linkov, I., Marchal, K., & Verhagen, H. (2019). Managing evidence in food safety and nutrition. *EFSA Journal, 17*, e170704.
Chamara, R. M. S. R., Senevirathne, S. M. P., Samarasinghe, S. A. I. L. N., Premasiri, M. W. R. C., Sandaruwani, K. H. C., Dissanayake, D. M. N. N., De Silva, S. H. N. P., Ariyaratne, W. M. T. P., & Marambe, B. (2020). Role of artificial intelligence in achieving global food security: A promising technology for future. *Sri Lanka Journal of Food and Agriculture, 6*(2).
Chavan, Y., Paul, K., & Kolekar, N. (2024). Food safety and hygiene: Current policies, quality standards, and scope of artificial intelligence. In *Food production, diversity, and safety under climate change* (pp. 319–331). Cham: Springer Nature Switzerland.
Chen, X. (2021). Research on visual analysis method of food safety big data based on artificial intelligence. In *2021 International Conference on Aviation Safety and Information Technology* (pp. 815–819).
Chen, Y., Wang, Y., Zhang, Y., Wang, X., Zhang, C., & Cheng, N. (2024). Intelligent biosensors promise smarter solutions in food safety 4.0. *Foods, 13*(2), 235.
Chen, T. C., & Yu, S. Y. (2021). The review of food safety inspection system based on artificial intelligence, image processing, and robotic. *Food Science and Technology, 42*, e35421.
Cheng, D.W. (2024). Development and application of AI for food processing and safety regulations. Available at: *Development and application of AI for food processing and safety regulations | food safety*. Accessed 22 July 2025.
Chhetri, K. B. (2024). Applications of artificial intelligence and machine learning in food quality control and safety assessment. *Food Engineering Reviews, 16*(1), 1–21.
da Silva Pereira, E., Cruz-Tirado, J. P., Lourenço Crippa, B., Martins Morasi, R., Milagres de Almeida, J., Fernandes Barbin, D., Barbon Junior, S., & Cristina Cirone Silva, N. (2024). Portable near infrared (NIR) spectrometer coupled with machine learning to classify milk with subclinical mastitis. *Food Control, 163*, 110527.
Dhal, S. B., & Kar, D. (2025). Leveraging artificial intelligence and advanced food processing techniques for enhanced food safety, quality, and security: A comprehensive review. *Discover Applied Sciences, 7*(1), 1–46.
Ding, H., Hou, H., Wang, L., Cui, X., Yu, W., & Wilson, D. I. (2025). Application of convolutional neural networks and recurrent neural networks in food safety. *Foods, 14*(2), 247.
Ding, H., Tian, J., Yu, W., Wilson, D. I., Young, B. R., Cui, X., Xin, X., Wang, Z., & Li, W. (2023). The application of artificial intelligence and big data in the food industry. *Foods, 12*(24), 4511.
Doganis, P., Alexandridis, A., Patrinos, P., & Sarimveis, H. (2006). Time series sales forecasting for short shelf-life food products based on artificial neural networks and evolutionary computing. *Journal of Food Engineering, 75*(2), 196–204.
Dong, Y., Hu, Y., Jin, J., Zhou, H., Jin, S., & Yang, D. (2024). Advances in machine learning-assisted SERS sensing towards food safety and biomedical analysis. *TrAC Trends in Analytical Chemistry*.
Dora, M., Kumar, A., Mangla, S. K., Pant, A., & Kamal, M. M. (2022). Critical success factors influencing artificial intelligence adoption in food supply chains. *International Journal of Production Research, 60*(14), 4621–4640.
Ejedegba, N. E. O. (2024). Innovative solutions for food security and energy transition through sustainable fertilizer production techniques. *World Journal of Advanced Research and Reviews, 24*(3), 1679–1695.
Enitan, A. M., & Adeyemo, J. (2011). Food processing optimization using evolutionary algorithms. *African Journal of Biotechnology, 10*(72), 16120–16127.
Erkinjon, R., & Feruz, K. (2024). The role of artificial intelligence in enhancing food safety and quality control. *Western European Journal of Modern Experiments and Scientific Methods, 2*(5), 233–236.
Esfahanian, S. (2024). Implementing artificial intelligence in the evaluation of packaging distribution and label design modeling (*Doctoral dissertation, Michigan State University*). https://search.proquest.com/openview/54fe8c37622b006817131887d5c7fb1e/1?pq-origsite=gscholar&cbl=18750&diss=y.
Esmaeily, R., Razavi, M. A., & Razavi, S. H. (2024). A step forward in food science, technology and industry using artificial intelligence. *Trends in Food Science & Technology, 143*, 104286.
U.S. Food and Drug Administration (2022a). *Focus area: artificial intelligence*. Available at: Focus area: Artificial intelligence | FDA. Accessed 22 July 2025.
U.S. Food and Drug Administration (2022b). *The FDA moves into third phase of artificial intelligence imported seafood pilot program*. Available at: The FDA moves into third phase of artificial intelligence imported seafood pilot program | FDA. Accessed 22 July 2025.
U.S. Food and Drug Administration (2023). *Marketing submission recommendations for a predetermined change control plan for artificial intelligence-enabled device software functions*. Docket no. 2022-D-2628. Available at: Marketing submission recommendations for a predetermined change control plan for artificial intelligence-enabled device software functions | FDA. Accessed 20 August 2025.
U.S. Food and Drug Administration (2024). *New era of smarter food safety blueprint, modern approaches for modern times*. Available at: https://www.fda.gov/food/new-era-smarter-food-safety/new-era-smarter-food-safety-blueprint. Accessed 24 July 2025.
Feng, Y., Soni, A., Brightwell, G., Reis, M. M., Wang, Z., Wang, J., Wu, Q., & Ding, Y. (2024). The potential new microbial hazard monitoring tool in food safety: Integration of metabolomics and artificial intelligence. *Trends in Food Science & Technology*104555.
Filho, E. V., Lang, L., Aguiar, M. L., Antunes, R., Pereira, N., & Gaspar, P. D. (2024). Computer vision as a tool to support quality control and robotic handling of fruit: A case study. *Applied Sciences, 14*(21), 9727.
Foerster, S., Brosinsky, A., Koch, K., & Eckardt, R. (2024). Hyperedu online learning program for hyperspectral remote sensing: Concept, implementation and lessons learned. *International journal of applied earth observation and geoinformation, 131*, 103983. https://www.sciencedirect.com/science/article/pii/S1569843224003376.
Friedlander, A., & Zoellner, C. (2020). Artificial intelligence opportunities to improve food safety at retail. *Food Protection Trends, 40*(4).
Fu, Y., Luechtefeld, T., Karmaus, A., & Hartung, T. (2023). The use of artificial intelligence and big data for the safety evaluation of US food-relevant chemicals. In *Present Knowledge in Food Safety* (pp. 575–589). Academic Press.
Funes, E., Allouche, Y., Beltrán, G., & Jiménez, A. (2015). A review: Artificial neural networks as tool for controlling food industry process. *Journal of Sensor Technology, 5*(01), 28.
Gbashi, S., & Njobeh, P. B. (2024). Enhancing food integrity through artificial intelligence and machine learning: A comprehensive review. *Applied Sciences, 14*(8), 3421.
George, A. S. (2024). Leveraging industry 4.0 for efficiency gains in food production. *Partners Universal International Research Journal, 3*(1), 86–108.
Gong, W., Yao, H. B., Chen, T., Xu, Y., Fang, Y., Zhang, H. Y., Li, B. W., & Hu, J. N. (2023). Smartphone platform based on gelatin methacryloyl (GelMA) combined with deep learning models for real-time monitoring of food freshness. *Talanta, 253*, 124057.
Gonzalez Viejo, C., Torrico, D. D., Dunshea, F. R., & Fuentes, S. (2019). Emerging technologies based on artificial intelligence to assess the quality and consumer preference of beverages. *Beverages, 5*(4), 62.
Goyache, F., Bahamonde, A., Alonso, J., López, S., Del Coz, J. J., Quevedo, J. R., Ranilla, J., Luaces, O., Alvarez, I., Royo, L. J., & Díez, J. (2001). The usefulness of artificial intelligence techniques to assess subjective quality of products in the food industry. *Trends in Food Science & Technology, 12*(10), 370–381.
Grasso, G., Zane, D., & Dragone, R. (2022). Field and remote sensors for environmental health and food safety diagnostics: An open challenge. *Biosensors, 12*(5), 285.
Hassoun, A., Garcia-Garcia, G., Trollman, H., Jagtap, S., Parra-López, C., Cropotova, J., Bhat, Z., Centobelli, P., & Aït-Kaddour, A. (2023). Birth of dairy 4.0: Opportunities and challenges in adoption of fourth industrial revolution technologies in the production of milk and its derivatives. *Currentresearch in Food Science, 7*, 100535.
He, Q., Huang, H., & Wang, Y. (2024). Detection technologies, and machine learning in food: Recent advances and future trends. *Food Bioscience*105558.
Hemamalini, V., Rajarajeswari, S., Nachiyappan, S., Sambath, M., Devi, T., Singh, B. K., & Raghuvanshi, A. (2022). Food quality inspection and grading using efficient image segmentation and machine learning-based system. *Journal of Food Quality, 2022*(1)5262294.
Holzinger, A., Keiblinger, K., Holub, P., Zatloukal, K., & Müller, H. (2023). AI for life: Trends in artificial intelligence for biotechnology. *New biotechnology, 74*, 16–24.
Hussain, S., Akhter, R., & Maktedar, S. S. (2024). Advancements in sustainable food packaging: From eco-friendly materials to innovative technologies. *Sustainable Food Technology, 2*(5), 1297–1364.
Ikram, A., Mehmood, H., Arshad, M. T., Rasheed, A., Noreen, S., & Gnedeka, K. T. (2024). Applications of artificial intelligence (AI) in managing food quality and ensuring global food security. *CyTA-Journal of Food, 22*(1)2393287.

Javanmardi, S., & Ashtiani, S. H. M. (2025). AI-driven deep learning framework for shelf life prediction of edible mushrooms. *Postharvest Biology and Technology, 222*, 113396.

Jiang, W., Liu, C., Liu, W., & Zheng, L. (2025). Advancements in intelligent sensing technologies for food safety detection. *Research, 8*, 0713.

Kakani, V., Nguyen, V. H., Kumar, B. P., Kim, H., & Pasupuleti, V. R. (2020). A critical review on computer vision and artificial intelligence in food industry. *Journal of Agriculture and Food Research, 2*, 100033.

Kamran, R., & Sundarakani, B. (2024). Combining blockchain, IoT and AI for food safety assurance: A systemic approach. *In 2024 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD)* (pp. 1-7). IEEE. https://ieeexplore.ieee.org/abstract/document/10878247/.

Kaur, K., Priyanka, Kaur, G., Singh, B., Sehgal, S., & Trehan, S. (2023). Artificial intelligence (AI) as a transitional tool for sustainable food systems. *In Sustainable Food Systems (Volume II) SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity* (pp. 305–328). Cham: Springer Nature Switzerland. https://link.springer.com/chapter/10.1007/978-3-031-46046-3_15.

Kaviani, M., Dara, R., & Farber, J. M. (2022). Machine learning application in food safety, production, and quality. *Harnessing Big Data in Food Safety*, 1–21.

Khan, R., Kumar, S., Dhingra, N., & Bhati, N. (2021). The use of different image recognition techniques in food safety: A study. *Journal of Food Quality, 2021*(1) 7223164.

Kim, S. S., & Kim, S. (2022). Impact and prospect of the fourth industrial revolution in food safety: Mini-review. *Food Science and Biotechnology, 31*(4), 399–406.

Kler, R., Elkady, G., Rane, K., Singh, A., Hossain, M. S., Malhotra, D., Ray, S., & Bhatia, K. K. (2022). [Retracted] Machine learning and artificial intelligence in the food industry: A sustainable approach. *Journal of Food Quality, 2022*(1)8521236.

Kudashkina, K., Corradini, M. G., Thirunathan, P., Yada, R. Y., & Fraser, E. D. (2022). Artificial Intelligence technology in food safety: A behavioral approach. *Trends in Food Science & Technology, 123*, 376–381.

Kumar, I., Rawat, J., Mohd, N., & Husain, S. (2021). Opportunities of artificial intelligence and machine learning in the food industry. *Journal of Food Quality, 2021* (1)4535567.

Kuppusamy, S., Meivelu, M., Praburaman, L., Alam, M. M., & Al-Sehemi, A. G. (2024). Integrating AI in food contaminant analysis: Enhancing quality and environmental protection. *Journal of Hazardous Materials Advances, 16*, 100509.

Kutyauripo, I., Rushambwa, M., & Chiwazi, L. (2023). Artificial intelligence applications in the agrifood sectors. *Journal of Agriculture and Food Research, 11*, 100502.

Li, C., Li, J., & Wang, Y. Z. (2025). Data integrity of food and machine learning: Strategies, advances and prospective. *Food Chemistry*143831.

Li, X., Liu, D., Pu, Y., & Zhong, Y. (2023). Recent advance of intelligent packaging aided by artificial intelligence for monitoring food freshness. *Foods, 12*(15), 2976.

Liu, C., Wang, D., Rietjens, I. M., & Zheng, L. (2025). Current and emerging issues in chemical food safety. *Current Opinion in Food Science, 101284*.

Liu, H., Wang, Y., & Yan, Z. (2024). Artificial intelligence and food processing firms productivity: Evidence from China. *Sustainability, 16*(14), 5928.

Liu, Z., Wang, S., Zhang, Y., Feng, Y., Liu, J., & Zhu, H. (2023). Artificial intelligence in food safety: A decade review and bibliometric analysis. *Foods, 12*(6), 1242.

Lugo-Morin, D. R. (2024). Artificial intelligence on food vulnerability: Future implications within a framework of opportunities and challenges. *Societies, 14*(7), 106.

Mahmudiono, T., Saleh, R. O., Widjaja, G., Chen, T. C., Yasin, G., Thangavelu, L., Altimari, U. S., Chupradit, S., Kadhim, M. M., & Marhoon, H. A. (2022). A review on material analysis of food safety based on fluorescence spectrum combined with artificial neural network technology. *Food Science and Technology, 42*, e118721.

Marvin, H. J., Janssen, E. M., Bouzembrak, Y., Hendriksen, P. J., & Staats, M. (2017). Big data in food safety: An overview. *Critical Reviews in Food Science and Nutrition, 57* (11), 2286–2295.

Mavani, N. R., Ali, J. M., Othman, S., Hussain, M. A., Hashim, H., & Rahman, N. A. (2022). Application of artificial intelligence in food industry—a guideline. *Food Engineering Reviews, 14*(1), 134–175.

McDonald, A. (2024). AI and UV driving new approaches to personal hygiene. Available at: *AMPC News. AI and UV driving new approaches to personal hygiene*. Accessed 20 August 2025.

Mengistu, D., & Ashe, G. (2024). Review of artificial intelligence powered food processing: Enhancing safety and sustainability. *Journal of Agroalimentary Processes & Technologies, 30*(2).

Mengucci, C., Ferranti, P., Romano, A., Masi, P., Picone, G., & Capozzi, F. (2022). Food structure, function and artificial intelligence. *Trends in Food Science & Technology, 123*, 251–263.

Menichetti, G., Ravandi, B., Mozaffarian, D., & Barabási, A. L. (2023). Machine learning prediction of the degree of food processing. *Nature Communications, 14*(1), 2312.

Minsk, A., Dona L., Davis C., & Gluck G. (2025). Welcome to the machine: AI and potential implications for the food industry. Available at: *Welcome to the machine: AI and potential implications for the food industry | food safety*. Accessed 20 August 2025.

Moholkar, G., Bhoite, V., & Todmal, A. (2023). *Empirical study on investigation of applications of artificial intelligence in food safety*. https://abhivruddhi.mituniversity.ac.in/wp-content/uploads/2023/08/Applications-of-AI-in-Food-Safety-final.pdf.

Motzer, C., El-Moghazy, A., Allende, A., Isabel Gil, M., Weesepoel, Y., van Overbeek, L., van de Zedde, R., Bouzembrak, Y., Nitin, N., Ivanek, R., & Wiedmann, M. (2024). Food safety related data analytics, digital, and artificial intelligence needs and opportunities in controlled environment agriculture. *Food protection trends, 44*(6).

Moustafa, H., Hemida, M. H., Nour, M. A., & Abou-Kandil, A. I. (2025). Intelligent packaging films based on two-dimensional nanomaterials for food safety and quality monitoring: Future insights and roadblocks. *Journal of Thermoplastic Composite Materials, 38*(3), 1208–1230.

Mu, W., Kleter, G. A., Bouzembrak, Y., Dupouy, E., Frewer, L. J., Radwan Al Natour, F. N., & Marvin, H. J. P. (2024). Making food systems more resilient to food safety risks by including artificial intelligence, big data, and internet of things into food safety early warning and emerging risk identification tools. *Comprehensive Reviews in Food Science and Food Safety, 23*(1)e13296.

Murphy, S. I., Reichler, S. J., Martin, N. H., Boor, K. J., & Wiedmann, M. (2021). Machine learning and advanced statistical modeling can identify key quality management practices that affect postpasteurization contamination of fluid milk. *Journal of Food Protection, 84*, 1496–1511.

Nagaveni, S., & Poosarla, V. G. (2024). Future trends in intelligent packaging solutions. In *Intelligent Packaging* (pp. 383–411). Academic Press.

Naseem, S., & Rizwan, M. (2025). The role of artificial intelligence in advancing food safety: A strategic path to zero contamination. *Food Control*111292.

Nayak, A., & Dutta, D. (2023). A comprehensive review on CRISPR and artificial intelligence based emerging food packaging technology to ensure "safe food". *Sustainable Food Technology, 1*(5), 641–657.

Nikzadfar, M., Rashvand, M., Zhang, H., Shenfield, A., Genovese, F., Altieri, G., Matera, A., Tornese, I., Laveglia, S., Paterna, G., Lovallo, C., & Di Renzo, G. C. (2024). Hyperspectral imaging aiding artificial intelligence: A reliable approach for food qualification and safety. *Applied Sciences, 14*(21), 9821.

Nychas, G. J. E., Panagou, E. Z., & Mohareb, F. (2016). Novel approaches for food safety management and communication. *Current Opinion in Food Science, 12*, 13–20.

Onyeaka, H., Akinsemolu, A., Miri, T., Nnaji, N. D., Emeka, C., Tamasiga, P., Pang, G., & Al-sharify, Z. (2024). Advancing food security: The role of machine learning in pathogen detection. *Applied Food Research, 100532*.

Palakurti, N. R. (2022). AI applications in food safety and quality control. *ESP Journal of Engineering & Technology Advancements, 2*, 48–61.

Pallathadka, H., Jawarneh, M., Sammy, F., Garchar, V., Sanchez, D. T., & Naved, M. (2022). A review of using artificial intelligence and machine learning in food and agriculture industry. In *2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)* (pp. 2215–2218). IEEE.

Pandey, V. K., Srivastava, S., Dash, K. K., Singh, R., Mukarram, S. A., Kovács, B., & Harsányi, E. (2023). Machine learning algorithms and fundamentals as emerging safety tools in preservation of fruits and vegetables: A review. *Processes, 11*(6), 1720.

Peddareddigari, S., Vijayan, S. V. H., & Annamalai, M. (2024). IoT, Blockchain, Big Data and Artificial Intelligence (IBBA) framework—for real-time food safety monitoring. *Applied Sciences, 15*(1), 105.

Piotrowski, N. (2024). Machine learning approach to packaging compatibility testing in the new product development process. *Journal of Intelligent Manufacturing, 35*(3), 963–975.

Przybył, K., & Koszela, K. (2023). Applications MLP and other methods in artificial intelligence of fruit and vegetable in convective and spray drying. *Applied Sciences, 13*(5), 2965.

Pujahari, R. M., & Khan, R. (2022). Applications of machine learning in food safety. *In artificial intelligence applications in agriculture and food quality improvement* (pp. 216-240). IGI global. https://www.igi-global.com/chapter/applications-of-machine-learning-in-food-safety/307427.

Qian, C., Murphy, S. I., Orsi, R. H., & Wiedmann, M. (2023). How can AI help improve food safety? *Annual Review of Food Science and Technology, 14*(1), 517–538.

Qiao, J., Zhang, M., Wang, D., Mujumdar, A. S., & Chu, C. (2024). AI-based R&D for frozen and thawed meat: Research progress and future prospects. *Comprehensive Reviews in Food Science and Food Safety, 23*(5)e70016.

Raki, H., Aalaila, Y., Taktour, A., & Peluffo-Ordóñez, D. H. (2023). Combining AI tools with non-destructive technologies for crop-based food safety: A comprehensive review. *Foods, 13*(1), 11.

Rashvand, M., Ren, Y., Sun, D. W., Senge, J., Krupitzer, C., Fadiji, T., Miró, M. S., Shenfield, A., Watson, N. J., & Zhang, H. (2025). Artificial intelligence for prediction of shelf-life of various food products. Recent advances and ongoing challenges. *Trends in Food Science & Technology*104989.

Revelou, P. K., Tsakali, E., Batrinou, A., & Strati, I. F. (2025). Applications of machine learning in food safety and HACCP monitoring of animal-source foods. *Foods, 14*(6), 922.

Röhrs, S., Nagy, K., Kreutzer, M., Stadler, R., Rohn, S., & Pfeifer, Y. (2025). Identifying food safety risks with a novel digitally-driven food safety early warning tool–a retrospective study on the pesticide ethylene oxide. *Food Control, 168*, 110939.

Ros-Lis, J. V., & Serra, M. B. (2023). Recent advancements in smart and intelligent packaging technologies: An overview. *Postharvest Management of Fresh Produce*, 241–263.

Rugji, J., Erol, Z., Taşçı, F., Musa, L., Hamadani, A., Gündemir, M. G., Karalliu, E., & Siddiqui, S. A. (2024). Utilization of AI–reshaping the future of food safety, agriculture and food security–a critical review. *Critical Reviews in Food Science and Nutrition*, 1–45.

Sahni, V., Srivastava, S., & Khan, R. (2021). Modelling techniques to improve the quality of food using artificial intelligence. *Journal of Food Quality, 2021*(1)2140010.

Sapienza, S., & Vedder, A. (2023). Principle-based recommendations for big data and machine learning in food safety: The P-SAFETY model. *AI & SOCIETY*, 1–16.

Sapienza, S. (2022). *Big data, algorithms and food safety* (pp. 1–214). Springer Cham. https://link.springer.com/content/pdf/10.1007/978-3-031-09367-8.pdf.

Sari, O. F., Amer, E., Bader-El-Den, M., Ince, V., & Leadley, C. (2025). AI-driven risk assessment in food safety using EU RASFF database. *Food and Bioprocess Technology*, 1–22.

Sharma, S., Gahlawat, V. K., Rahul, K., Mor, R. S., & Malik, M. (2021). Sustainable innovations in the food industry through artificial intelligence and big data analytics. *Logistics, 5*(4), 66.

Shirzad, K., & Joodaky, A. (2024). Enhancing sustainable food packaging design: A machine learning approach to predict ventilated corrugated paperboard strength. *Biosystems Engineering, 247*, 26–41.

Şimşek, A. B. (2024). AI in managing perishable goods inventory. In *Modern management science practices in the age of AI* (pp. 29–70). IGI Global.

Singh, S. K. (2022). AI applications in food safety. *International Journal of Gender, Science and Technology, 11*(01).

Singh, R., Nickhil, C., Upendar, K., Jithender, B., & Deka, S. C. (2024). A comprehensive review of advanced deep learning approaches for food freshness detection. *Food Engineering Reviews*, 1–34.

Sliwinska, M., Wisniewska, P., Dymerski, T., Namiesnik, J., & Wardencki, W. (2014). Food analysis using artificial senses. *Journal of Agricultural and Food Chemistry, 62* (7), 1423–1448.

Sonwani, E., Bansal, U., Alroobaea, R., Baqasah, A. M., & Hedabou, M. (2022). An artificial intelligence approach toward food spoilage detection and analysis. *Frontiers in Public Health, 9*, 816226.

Stoitsis, G., & Manouselis, N. (2023). The use of big data in food safety management: Predicting food safety risks using big data and artificial intelligence. In *Food Safety Management* (pp. 513–520). Academic Press.

Stoitsis, G., Papakonstantinou, M., Karvounis, M., & Manouselis, N. (2023). The role of big data and artificial intelligence in food risk assessment and prediction. In *Present knowledge in food safety* (pp. 1032–1044). Academic Press.

Taiwo, O. R., Onyeaka, H., Oladipo, E. K., Oloke, J. K., & Chukwugozie, D. C. (2024). Advancements in predictive microbiology: Integrating new technologies for efficient food safety models. *International journal of microbiology, 2024*(1)6612162.

Tan, M., Jin, M., Daglia, M., Capanoglu, E., & Abd El-Aty, A. M. (2025). Perspective on current advances and future directions in food safety and health. *Food Safety and Health*.

Thakkar, S., Slikker, W., Jr, Yiannas, F., Silva, P., Blais, B., Chng, K. R., Liu, Z., Adholeya, A., Pappalardo, F., Soares, M. D. L. C., Beeler, P. E., & Tong, W. (2023). Artificial intelligence and real-world data for drug and food safety–a regulatory science perspective. *Regulatory Toxicology and Pharmacology, 140*, 105388.

Thapa, A., Nishad, S., Biswas, D., & Roy, S. (2023). A comprehensive review on artificial intelligence assisted technologies in food industry. *Food Bioscience, 56*, 103231.

Theodore Armand, T. P., Nfor, K. A., Kim, J. I., & Kim, H. C. (2024). Applications of artificial intelligence, machine learning, and deep learning in nutrition: A systematic review. *Nutrients, 16*(7), 1073.

Thorsen, M., Hill, J., Farber, J., Yiannas, F., Rietjens, I. M., Venter, P., Lues, R., & Bremer, P. (2025). Megatrends and emerging issues: Impacts on food safety. *Comprehensive Reviews in Food Science and Food Safety, 24*(3)e70170.

Trollman, H. (2024). Feature extraction for artificial intelligence enabled food supply chain failure mode prediction. *Discover Food, 4*(1), 22.

Tzachor, A. (2024). Enhancing food safety in supply chains: The potential role of large language models in preventing campylobacter contamination. *arXiv preprint arXiv:2406.06049*. https://arxiv.org/abs/2406.06049.

Vågsholm, I., Arzoomand, N. S., & Boqvist, S. (2020). Food security, safety, and sustainability—getting the trade-offs right. *Frontiers in Sustainable Food Systems, 4*, 487217.

Vegesna, V. V., Prabhakaran, S. M., & Whig, P. (2024). AI for food safety: Leveraging artificial intelligence to ensure a safe and reliable food supply. In *Nutrition Controversies and Advances in Autoimmune Diseas* (pp. 501–524). IGI Global Scientific Publishing.

Wang, X., Bouzembrak, Y., Lansink, A. O., & Van Der Fels-Klerx, H. J. (2022). Application of machine learning to the monitoring and prediction of food safety: A review. *Comprehensive Reviews in Food Science and Food Safety, 21*(1), 416–434.

Wang, K., Mirosa, M., Hou, Y., & Bremer, P. (2025). Advancing food safety behavior with AI: Innovations and opportunities in the food manufacturing sector. *Trends in Food Science & Technology*105050.

Wang, J., Xia, L., Liu, H., Zhao, C., Ming, S., & Wu, J. (2024). Colorimetric microneedle sensor using deep learning algorithm for meat freshness monitoring. *Chemical Engineering Journal, 481*, 148474.

Whig, P., Dhamodharan, B., Molli, V. L. P., & Dutta, P. K. (2024). Food and supplement safety using data science and ML ensuring quality and compliance. *In Nutrition Controversies and Advances in Autoimmune Disease* (pp. 547-571). IGI Global. https://www.igi-global.com/chapter/food-and-supplement-safety-using-data-science-and-ml-ensuring-quality-and-compliance/353808.

Xiong, F., Kühl, N., & Stauder, M. (2024). Designing a computer-vision-based artifact for automated quality control: A case study in the food industry. *Flexible Services and Manufacturing Journal, 36*(4), 1422–1449.

Yakoubi, S. (2025). Sustainable revolution: AI-driven enhancements for composite polymer processing and optimization in intelligent food packaging. *Food and Bioprocess Technology, 18*, 82–107.

Yam, K. L., Takhistov, P. T., & Miltz, J. (2005). Intelligent packaging: Concepts and applications. *Journal of food science, 70*(1), R1–R10.

Yang, H., Jiao, W., Zouyi, L., Diao, H., & Xia, S. (2025). Artificial intelligence in the food industry: Innovations and applications. *Discover Artificial Intelligence, 5*(1), 60.

Yi, L., Wang, W., Diao, Y., Yi, S., Shang, Y., Ren, D., Ge, K., & Gu, Y. (2024). Recent advances of artificial intelligence in quantitative analysis of food quality and safety indicators: A review. *TrAC Trends in Analytical Chemistry*117944.

Yin, B., Tan, G., Muhammad, R., Liu, J., & Bi, J. (2025). AI-Powered Innovations in food safety from farm to Fork. *Foods, 14*(11), 1973.

Yu, W., Ouyang, Z., Zhang, Y., Lu, Y., Wei, C., Tu, Y., & He, B. (2024). Research progress on the artificial intelligence applications in food safety and quality management. *Trends in Food Science & Technology*104855.

Zatsu, V., Shine, A. E., Tharakan, J. M., Peter, D., Ranganathan, T. V., Alotaibi, S. S., Mugabi, R., Muhsinah, A. B., Waseem, M., & Nayik, G. A. (2024). Revolutionizing the food industry: The transformative power of artificial intelligence-a review. *Food Chemistry: X*101867.

Zhang, F. (2024). Research on food safety information supervision based on artificial intelligence and big data. In Proceedings of the International Conference on Modeling, *Natural Language Processing and Machine Learning* (pp. 81–85). https://dl.acm.org/doi/abs/10.1145/3677779.3677792

Zhang, J., Huang, H., Song, G., Huang, K., Luo, Y., Liu, Q., He, X., & Cheng, N. (2022). Intelligent biosensing strategies for rapid detection in food safety: A review. *Biosensors and Bioelectronics, 202*, 114003.

Zhou, Z., Tian, D., Yang, Y., Cui, H., Li, Y., Ren, S., Han, T., & Gao, Z. (2024). Machine learning assisted biosensing technology: An emerging powerful tool for improving the intelligence of food safety detection. *Current Research in Food Science, 8*, 100679.

Zhou, Q., Zhang, H., & Wang, S. (2022). Artificial intelligence, big data, and blockchain in food safety. *International Journal of Food Engineering, 18*(1), 1–14.