

Industry 4.0 and Industry 5.0 in Food Processing and Preservation: A Comprehensive Review of AI, IoT, Robotics, and Blockchain Technologies

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Abstract: The food processing and preservation sector is undergoing a paradigm shift driven by the adoption of Industry 4.0 and the emerging principles of Industry 5.0. These frameworks emphasize the integration of advanced digital technologies with intelligent, human-centric, and sustainable manufacturing systems. Artificial intelligence (AI), the Internet of Things (IoT), robotics, and blockchain technologies are increasingly being employed to enhance processing efficiency, product quality, food safety, and supply chain transparency. AI enables predictive analytics, process optimization, and real-time quality assessment, while IoT-based sensor networks facilitate continuous monitoring of critical processing and storage parameters. Robotics and automation improve hygiene, precision, and operational efficiency, whereas blockchain enhances traceability, accountability, and trust across food supply chains. The transition toward Industry 5.0 further emphasizes resilience, sustainability, and human-machine collaboration. Despite the significant advantages, challenges related to cost, data interoperability, cybersecurity, and workforce skills persist. This review discusses the evolution, need, and scope of digital transformation in food processing and preservation within the Industry 4.0 and 5.0 paradigms, highlighting future opportunities for sustainable and resilient food systems.

Keywords: Industry 4.0, Industry 5.0, Food Processing and preservation, Artificial intelligence, Internet of things and Blockchain Technology

1. Introduction

1.1. Evolution of Food Processing and Preservation Technologies

Food processing and preservation technologies have evolved continuously to ensure food safety, extend shelf life, and retain nutritional and sensory quality. Early preservation methods such as drying, fermentation, salting, smoking, and chilling were developed primarily to inhibit microbial growth and enzymatic deterioration. With industrialization and urbanization, large-scale thermal processing techniques, including pasteurization, sterilization,



canning, and freezing, became dominant, enabling mass food production and long-distance distribution (Fellows, 2009; Sun, 2012). In the late twentieth and early twenty-first centuries, increasing consumer demand for minimally processed foods with enhanced nutritional value and fresh-like characteristics stimulated the development of advanced preservation technologies. These include high-pressure processing, pulsed electric fields, ultrasound, cold plasma, and modified atmosphere packaging, which offer improved microbial safety while minimizing thermal degradation of food quality attributes (Rastogi et al., 2007; Barbosa-Canovas et al., 2014). Despite their advantages, early implementations of these technologies relied largely on conventional control strategies and lacked real-time intelligence and adaptive process control.

Recent advances in digital technologies, including smart sensors, automation, data analytics, and networked systems, have enabled a paradigm shift from conventional processing toward intelligent and data-driven food processing systems. These developments facilitate enhanced process monitoring, traceability, predictive control, and sustainability across food processing and preservation operations (Zhang et al., 2017; Misra et al., 2020).

1.2. Concept of Industry 4.0 and Industry 5.0

Industry 4.0 represents the fourth industrial revolution and is characterized by the integration of cyber-physical systems, the Internet of Things (IoT), cloud computing, big data analytics, artificial intelligence, and robotics into manufacturing environments (Kagermann et al., 2013; Lasi et al., 2014). In food processing industries, Industry 4.0 enables interconnected production systems, real-time monitoring of processing parameters, automated quality control, and predictive maintenance, thereby enhancing operational efficiency, food safety, and product consistency (Verdouw et al., 2016; Kamilaris et al., 2019).

Industry 5.0 extends the Industry 4.0 paradigm by placing greater emphasis on human-centricity, sustainability, and system resilience. Rather than focusing solely on automation and productivity, Industry 5.0 promotes close collaboration between humans and intelligent machines, responsible resource utilization, and adaptability to disruptions such as climate change and supply chain volatility (Nahavandi, 2019; European Commission, 2021). Within the food sector, this approach supports ethical production practices, reduced environmental impact, and enhanced workforce participation through collaborative robotics, intelligent decision-support tools, and transparent digital systems.

1.3. Need for Digital Transformation in the Food Sector

The global food sector faces complex challenges, including population growth, climate variability, post-harvest losses, food safety incidents, and increasing consumer demand for transparency and sustainability. Conventional food processing and preservation systems often lack the flexibility, responsiveness, and intelligence required to effectively address these

challenges. Digital transformation through the adoption of AI, IoT, robotics, and blockchain technologies offers powerful solutions to overcome these limitations (Kamilaris et al., 2019; Klerkx et al., 2019). IoT-enabled sensor networks facilitate continuous monitoring of critical parameters—such as temperature, humidity, pressure, and gas composition—during processing, storage, and transportation, thereby improving cold-chain integrity and reducing spoilage (Aung and Chang, 2014; Badia-Melis et al., 2018). Artificial intelligence models analyze large and heterogeneous datasets to predict shelf life, optimize processing conditions, and detect anomalies in real time, supporting proactive quality and safety management. Blockchain technology further enhances transparency and trust by providing immutable and verifiable records of processing conditions, quality compliance, and logistics events. This capability strengthens traceability, improves recall efficiency, and supports regulatory compliance across complex food supply chains (Tian, 2017; Galvez et al., 2018). Collectively, these digital technologies are essential for building resilient, transparent, and sustainable food systems capable of meeting future global food security demands.

1.4. Scope and Objectives of the Review

The scope of this review is to critically examine the role of Industry 4.0 and Industry 5.0 technologies in transforming food processing and preservation systems. The specific objectives of this review are to:

- analyze the evolution of food processing and preservation technologies toward intelligent and automated systems;

- discuss the principles and applications of Industry 4.0 and Industry 5.0 within the food sector;

- evaluate the contributions of artificial intelligence, IoT, robotics, and blockchain technologies to food quality, safety, and sustainability; and

identify key challenges, research gaps, and future directions for digital food processing and preservation.

This review aims to provide a comprehensive and structured framework for researchers, industry stakeholders, and policymakers to support the development of smart, resilient, and human-centric food processing systems aligned with long-term global food security and sustainability goals.

2. Industry 4.0 and Industry 5.0 Frameworks in Food Systems

2.1. Key Principles of Industry 4.0 in Food Processing

Industry 4.0 represents the fourth industrial revolution and is defined by the comprehensive integration of digital technologies-such as the Internet of Things (IoT), artificial intelligence (AI), cyber-physical systems (CPS), robotics, big data analytics, and cloud computing-into industrial production environments (Kagermann et al., 2013; Lasi et al., 2014). In the context of food processing and preservation, Industry 4.0 facilitates the development of smart factories in which real-time data generated by embedded sensors are continuously acquired, analyzed, and used for adaptive process control. This enables consistent product quality, enhanced food safety, improved traceability, and reduced energy and material losses (Verdouw et al., 2016; Misra et al., 2020). The core principles of Industry 4.0 include connectivity through IoT-enabled networks linking machines, sensors, and control systems; automation supported by robotics and advanced control architectures; and data-driven intelligence enabled by machine learning and artificial intelligence algorithms. Digital twins-virtual representations of physical

processing systems-play a critical role by allowing simulation, optimization, and predictive analysis of food processing operations without disrupting production (Kritzinger et al., 2018; Verdouw et al., 2016). Cyber-physical systems form the technological backbone of this paradigm by tightly coupling physical machinery with computational intelligence, enabling closed-loop control, predictive maintenance, and early fault detection, which are essential for maintaining continuous quality and safety in food manufacturing lines (Lee et al., 2015).

Industry 4.0 also promotes the integration of quality assurance directly into processing operations through real-time monitoring of physicochemical, thermal, and microbiological parameters. Automated analytics and decision-support systems reduce reliance on manual inspection, minimize contamination risks, and improve compliance with food safety regulations, thereby enhancing productivity and operational reliability across food processing chains (Belaud et al., 2019; Misra et al., 2020).

2.2. Transition from Industry 4.0 to Industry 5.0

While Industry 4.0 primarily emphasizes automation, efficiency, and machine-to-machine communication, Industry 5.0 extends this paradigm by introducing human-centricity, sustainability, and system resilience as central objectives (Nahavandi, 2019; Breque et al., 2021). Rather than replacing Industry 4.0, Industry 5.0 builds upon its digital infrastructure by integrating ethical, social, and environmental considerations into intelligent manufacturing systems.

Industry 5.0 is increasingly described as a collaborative ecosystem in which humans and intelligent machines work synergistically, combining human creativity, contextual understanding, and ethical reasoning with machine precision, speed, and data-processing capabilities (Nahavandi, 2019; Longo et al., 2020). In food systems, this transition enables flexible and responsive production models capable of addressing dynamic consumer preferences, workforce well-being, and sustainability targets while maintaining high levels of safety and efficiency. Key technological enablers of Industry 5.0 include collaborative robots (cobots), advanced digital twins, edge and fog computing, augmented and virtual reality interfaces, and the Internet of Everything (IoE), which extends IoT by explicitly incorporating human interaction into data and decision loops (Longo et al., 2020; Xu et al., 2021). These developments shift food manufacturing away from rigid mass automation toward adaptive, customized, and socially responsible production systems.

2.3. Human-Centric, Sustainable, and Resilient Food Manufacturing

A defining characteristic of Industry 5.0 is its human-centric philosophy, which places workers at the core of intelligent manufacturing environments (Nahavandi, 2019; Breque et al., 2021). Unlike earlier industrial paradigms that prioritized automation and throughput, Industry 5.0 re-integrates human skills such as creativity, problem-solving, and ethical judgment into digitally enhanced food processing systems. This collaboration is enabled through intuitive human-machine interfaces, including augmented reality tools, decision-support dashboards, and interactive digital twins that allow operators to supervise, interpret, and optimize processes effectively (Longo et al., 2020). Sustainability represents another foundational pillar of Industry 5.0. Food manufacturing performance is increasingly

evaluated not only on economic outcomes but also on energy efficiency, resource optimization, carbon footprint reduction, and waste minimization (Galanakis, 2020; Breque et al., 2021). Advanced analytics enable real-time optimization of processing parameters—such as temperature, pressure, and residence

time—thereby reducing energy consumption in thermal processing, refrigeration, and cold storage operations. Circular economy principles further support the valorization of food by-products and reduction of environmental impacts throughout the processing lifecycle (Galanakis, 2020). Resilience refers to the ability of food manufacturing systems to withstand and adapt to disruptions such as supply chain interruptions, raw material variability, and climate-related stresses. Industry 5.0 enhances resilience through predictive analytics, anomaly detection, and modular production architectures that allow rapid system reconfiguration while maintaining human oversight and decision-making authority (Longo et al., 2020; Xu et al., 2021).

2.4. Role of Cyber-Physical Systems in Smart Food Industries

Cyber-physical systems are fundamental enablers of smart food industries and underpin both Industry 4.0 and Industry 5.0 paradigms. CPS integrate physical processing equipment, embedded sensors, communication networks, and computational intelligence to facilitate continuous interaction between digital and physical components (Lee et al., 2015). In food processing environments, CPS link unit operations—such as heating, cooling, mixing, drying, and packaging—with analytics platforms to enable real-time, closed-loop control based on continuous sensor feedback.

CPS also support the development of digital twins, which serve as virtual replicas of food processing lines and preservation systems. These models enable simulation, optimization, and evaluation of “what-if” scenarios without interrupting production, thereby improving efficiency and reducing operational risk (Kritzinger et al., 2018). In food preservation applications, CPS can autonomously adjust storage conditions—including temperature, humidity, and atmospheric composition—in response to real-time sensor data, contributing to extended shelf life and reduced post-harvest losses. The integration of CPS with AI and edge computing further enhances predictive maintenance, quality assurance, and food safety by enabling early detection of equipment failures, contamination risks, and process deviations. Within the Industry 5.0 framework, CPS evolve to support human-centered decision-making by providing transparent, interpretable insights that assist operators while maintaining automation for routine optimization tasks (Nahavandi, 2019; Breque et al., 2021).

3. Artificial Intelligence (AI) in Food Processing and Preservation

Artificial intelligence (AI) refers to a collection of computational techniques that enable machines to learn from data, recognize patterns, make decisions, and perform tasks that traditionally require human intelligence. In food processing and preservation, AI has emerged as a transformative tool for improving efficiency, quality consistency, safety assurance, and sustainability across the entire food supply chain (McCulloch et al., 2019; Misra et al., 2020). The convergence of AI with sensor networks, IoT platforms, big data analytics, and cloud–edge computing infrastructures has facilitated the development of intelligent food systems capable of real-time monitoring, optimization, and anomaly detection (Jha et al., 2019; Kamilaris and Prenafeta-Boldu, 2018).

AI-driven systems enable adaptive decision-making by integrating heterogeneous data streams generated during processing, storage, and distribution. These capabilities allow food manufacturers to move beyond conventional rule-based control toward predictive and prescriptive analytics that enhance product quality, reduce waste, and improve operational resilience (Ramesh et al., 2022; Zhang et al., 2024).

3.1. Machine Learning and Deep Learning Models in Food Processing

Machine learning (ML) and deep learning (DL) are core components of AI that provide algorithms capable of identifying complex relationships within large datasets without explicit programming. In food processing applications, ML techniques such as support vector machines (SVM), artificial neural networks (ANN), random forests, and ensemble learning models have been widely applied for quality classification, defect detection, and process modeling (Pathak et al., 2018; Jha et al., 2019). Deep learning models, particularly convolutional neural networks (CNNs), have demonstrated superior performance when handling high-dimensional data such as images, spectral signatures, and multivariate sensor outputs (LeCun et al., 2015; Liu et al., 2021).

CNN-based approaches are extensively used for visual quality assessment tasks, including detection of surface defects, foreign materials, and contamination in food products, often outperforming manual inspection in terms of speed, accuracy, and consistency (Mohanty et al., 2016; Liu et al., 2021). ML models are also employed for real-time monitoring of processing parameters by extracting meaningful features from sensor data generated across IoT-enabled production environments (Kamilaris and Prenafeta-Boldu, 2018). Through continuous learning from historical and

real-time data, these models support adaptive responses to process deviations, improving product uniformity while minimizing losses and rework.

3.2. AI-Based Process Optimization and Control

AI-based process optimization focuses on identifying optimal operational conditions that balance productivity, quality, and resource efficiency. Advanced algorithms such as reinforcement learning, genetic algorithms, particle swarm optimization, and Bayesian optimization have been investigated for adaptive control of food processing systems, particularly in complex multi-stage operations such as thermal processing, drying, fermentation, and freezing (Goyal et al., 2020; Ramesh et al., 2022).

Unlike conventional static control strategies, AI-driven optimization frameworks continuously learn from process feedback and dynamically adjust control parameters in response to variations in raw material properties or environmental conditions. For instance, AI-assisted thermal processing systems can determine optimal heating profiles that ensure microbial safety while minimizing nutrient degradation and energy consumption (Chen et al., 2020; Zhang et al., 2024). Such intelligent control strategies improve process robustness, enhance yield, and support sustainability goals by reducing energy use and operational variability.

3.3. Predictive Quality Assessment and Shelf-Life Modeling

Predictive quality assessment and shelf-life modeling are critical components of food preservation and distribution management. Traditional shelf-life determination methods-based on microbiological testing and chemical analysis-are time-intensive and unsuitable for real-time decision-making. AI-based models trained on multi-source datasets, including environmental conditions, physicochemical properties, and spectral information, enable rapid prediction of quality degradation and spoilage dynamics (Tsakanikas et al., 2021; Ramesh et al., 2022). Regression models, time-series analysis, and recurrent neural networks (RNNs) have been successfully applied to forecast shelf life by capturing the nonlinear influence of temperature, humidity, and storage duration on food quality attributes (Giannoglou et al., 2020; Tsakanikas et al., 2021). These models support proactive inventory management and dynamic

distribution strategies, thereby reducing food waste and economic losses while enhancing consumer safety.

Integration of AI-based shelf-life models with IoT platforms further enhances predictive accuracy by enabling continuous updates based on real-time environmental data. Such adaptive prediction systems are particularly valuable for cold-chain monitoring of perishable foods, where deviations from optimal storage conditions can significantly affect quality and safety (Badia-Melis et al., 2015; Misra et al., 2020).

3.4. Computer Vision for Food Inspection and Sorting

Computer vision is a prominent AI subfield that combines image acquisition, processing, and pattern recognition for automated inspection and sorting tasks. In food processing environments, vision systems equipped with high-speed cameras capture large volumes of images as products move along conveyor belts. AI models-especially CNNs-analyze these images to detect defects, color variations, texture irregularities, and foreign objects that may compromise quality or safety (Brosnan and Sun, 2004; Liu et al., 2021).

Automated grading and sorting systems have been successfully implemented for fruits, vegetables, grains, meat, and seafood, achieving accuracy levels exceeding those of manual inspection while operating continuously at industrial speeds (Cubero et al., 2016; Mohanty et al., 2016). Advanced computer vision systems integrated with hyperspectral and multispectral imaging further enable non-destructive assessment of internal quality attributes, such as moisture content, ripeness, and internal defects (ElMasry et al., 2012). These AI-driven vision systems reduce labor requirements, enhance consistency, and integrate seamlessly with robotic manipulators for automated pick-and-place and packaging operations, contributing to higher throughput and improved hygiene standards.

3.5. AI in Food Safety and Risk Assessment

AI plays a critical role in enhancing food safety by enabling predictive risk assessment, anomaly detection, and proactive hazard management. Machine learning models trained on historical contamination events, environmental conditions, and process deviations can identify patterns associated with increased safety risks, allowing early intervention before hazards reach consumers (Yang et al., 2020; Ramesh et al., 2022).

Deep learning techniques, including multilayer neural networks and hybrid models, are particularly effective in handling high-dimensional and heterogeneous food safety datasets, revealing subtle correlations related to pathogen

growth, chemical residues, and allergen contamination (Chen et al., 2020; Yang et al., 2020). These models support compliance with food safety regulations by enabling continuous monitoring and real-time alerts throughout processing and distribution networks. Furthermore, the integration of AI with digital traceability and blockchain-based systems enhances transparency and responsiveness during food safety incidents. AI-assisted analytics can rapidly identify affected batches and supply chain nodes, facilitating targeted recalls and minimizing public health risks (Casino et al., 2019; Tian, 2017). By combining predictive analytics with real-time monitoring, AI strengthens food safety governance and contributes to resilient, trustworthy food systems.

4. Internet of Things (IoT) for Smart Food Processing and Preservation

The Internet of Things (IoT) has emerged as a foundational technology enabling digital transformation in food processing and preservation systems. IoT refers to interconnected networks of sensors, devices, machines, and software platforms that enable real-time data

acquisition, communication, and intelligent control. In food systems, IoT supports continuous monitoring of critical parameters, enhances traceability, reduces post-harvest losses, and ensures compliance with food safety and quality standards (Aung and Chang, 2014; Badia-Melis et al., 2018). When integrated with advanced analytics and artificial intelligence, IoT enables adaptive, autonomous, and resilient food processing environments aligned with Industry 4.0 and Industry 5.0 paradigms.

4.1. IoT Architecture and Sensor Technologies in Food Systems

IoT architecture in food processing systems typically consists of three core layers: the perception layer, the network layer, and the application layer. The perception layer includes physical sensors and actuators that capture real-time data related to temperature, humidity, pressure, pH, gas composition, vibration, and microbial activity. Common sensor technologies used in food systems include thermistors, infrared sensors, electrochemical gas sensors, biosensors, and optical sensors, many of which are designed for food-grade and hygienic environments (Verdouw et al., 2016; Misra et al., 2020).

The network layer enables data transmission using wired and wireless communication technologies such as RFID, Bluetooth, Wi-Fi, ZigBee, LoRaWAN, and 5G networks. These technologies allow seamless connectivity between processing equipment, storage facilities, and cloud platforms. The application layer comprises data analytics, visualization dashboards, and decision-support systems that interpret sensor data to enable real-time monitoring, alerts, and control actions (Klerkx et al., 2019). Advances in low-power electronics and miniaturization have significantly improved the feasibility of deploying dense sensor networks in food processing plants and storage facilities. These developments allow continuous monitoring of large-scale operations with minimal energy consumption and maintenance requirements, supporting sustainable digital food infrastructures (Badia-Melis et al., 2018).

4.2. Real-Time Monitoring of Processing and Storage Parameters

Real-time monitoring is one of the most impactful applications of IoT in food processing and preservation. Continuous data acquisition enables precise control of critical processing variables such as temperature, time, moisture content, and atmospheric composition. For example, IoT-enabled thermal processing systems dynamically adjust heating profiles based on real-time sensor feedback, ensuring microbial safety while minimizing nutrient degradation (Aung and Chang, 2014).

In storage and preservation environments, IoT sensors monitor temperature fluctuations, humidity levels, and gas concentrations to prevent spoilage and quality deterioration. Deviations from predefined thresholds trigger automated alerts or corrective actions, reducing dependence on manual inspections and minimizing human error (Verdouw et al., 2016). Such systems are particularly valuable in cold storage, controlled atmosphere facilities, and fermentation units, where small deviations can have significant impacts on shelf life and safety.

The availability of continuous, high-resolution data also enables predictive analytics when combined with historical records. This facilitates early detection of equipment malfunctions, energy inefficiencies, and contamination risks, thereby improving operational reliability and compliance with food safety regulations (Misra et al., 2020).

4.3. Smart Cold Chain and Logistics Management

Cold chain management is critical for preserving the quality and safety of perishable foods during processing, storage, and transportation. IoT technologies have revolutionized cold chain

logistics by enabling end-to-end visibility and real-time monitoring across the supply chain. Temperature and humidity sensors placed in transport vehicles, storage units, and distribution centers continuously transmit data to centralized platforms, ensuring cold chain integrity from processing facilities to retail outlets (Aung and Chang, 2014; Badia-Melis et al., 2018).

IoT-based cold chain systems support proactive interventions by identifying temperature excursions and enabling immediate corrective actions. This reduces product losses, enhances shelf life, and improves consumer confidence. Additionally, IoT data can be integrated with traceability and blockchain systems to provide verifiable records of storage and transportation conditions, strengthening food safety assurance and recall efficiency (Tian, 2017). Recent developments incorporate predictive logistics models that analyze IoT data to optimize routing, storage duration, and inventory management. Such smart logistics frameworks improve energy efficiency, reduce carbon emissions, and enhance resilience against disruptions such as equipment failures or supply chain delays (Kamilaris et al., 2019).

4.4. IoT-Enabled Smart and Intelligent Packaging

Smart and intelligent packaging systems represent a rapidly growing application of IoT in food preservation. IoT-enabled packaging integrates sensors, indicators, and communication technologies directly into packaging materials to monitor product condition throughout its lifecycle. These systems include time-temperature indicators, freshness sensors, gas sensors, and RFID- or NFC-enabled tags that provide real-time information on product quality and safety (Kerry et al., 2006; Badia-Melis et al., 2018).

Intelligent packaging enhances transparency by allowing stakeholders-including processors, distributors, and consumers-to access real-time data regarding storage history and freshness status. Such systems support informed decision-making, reduce food waste, and improve consumer trust. In industrial settings, smart packaging data can be integrated with inventory management systems to optimize stock rotation and minimize spoilage losses. The integration of biosensors into packaging materials also enables early detection of microbial growth or chemical spoilage, offering significant potential for improving food safety monitoring without invasive testing methods (Kerry et al., 2006).

4.5. Integration of IoT with AI for Autonomous Decision-Making

The full potential of IoT in food processing and preservation is realized when it is integrated with artificial intelligence and advanced analytics. IoT systems generate vast volumes of real-time data, which AI algorithms analyze to extract actionable insights, predict outcomes, and enable autonomous decision-making. Machine learning models process sensor data to identify patterns associated with quality degradation, equipment inefficiencies, or safety risks, enabling systems to respond proactively (Misra et al., 2020; Kamilaris et al., 2019).

AI-IoT integration supports adaptive control strategies in processing lines, where operating parameters are continuously optimized based on real-time feedback. In preservation systems, AI models dynamically adjust storage conditions to extend shelf life and maintain quality under variable environmental conditions. This convergence enables self-learning systems that improve performance over time, aligning with Industry 4.0 and Industry 5.0 goals of intelligent, resilient, and sustainable food manufacturing. Moreover, autonomous decision-making systems reduce human workload and error while preserving human oversight through dashboards and decision-support interfaces. Such hybrid intelligence frameworks represent a

critical step toward fully smart food processing ecosystems capable of meeting future demands for safety, efficiency, and sustainability.

5. Robotics and Automation in Food Processing and Preservation

Robotics and automation have become integral to modern food processing and preservation systems, driven by the need for higher productivity, improved product consistency, enhanced hygiene, and safer working environments. Automated robotic systems enable the execution of repetitive, high-precision, and physically demanding tasks, thereby reducing human exposure to occupational hazards and ensuring consistent handling at high throughput levels (Bogue, 2013; Alfian et al., 2020). The adoption of robotics across food systems supports Industry 4.0 objectives of intelligent automation while aligning with Industry 5.0 principles that emphasize flexibility, resilience, and human-centric manufacturing (Wakchaure et al., 2023; Longo et al., 2020).

Recent advances in industrial robots, collaborative robotic platforms, and intelligent automation technologies have significantly expanded their applicability across diverse food processing operations, including material handling, cutting, sorting, packaging, and sanitation. These developments contribute to improved operational efficiency, reduced

contamination risks, and enhanced traceability throughout food value chains (Bechar and Vigneault, 2016; Alfian et al., 2020).

5.1. Industrial and Collaborative Robots in Food Processing

Industrial robots—such as articulated arms, delta robots, and gantry systems—are widely deployed in food processing environments where speed, repeatability, and precision are critical. Early applications primarily focused on end-of-line operations, including packaging, palletizing, and case packing, where robots consistently handle large volumes of products with minimal variability (Bogue, 2013; Bechar and Vigneault, 2016). Delta robots, in particular, have gained prominence in high-speed pick-and-place applications due to their lightweight structure and rapid acceleration, making them well suited for packaging bakery items, confectionery, and ready-to-eat foods (Groover, 2020).

More recently, collaborative robots (cobots) have emerged as a flexible alternative to traditional industrial robots, especially in food processing environments characterized by high product variability and frequent changeovers. Cobots are equipped with advanced safety features—such as force and speed limitation, vision-based monitoring, and collision detection—that enable them to operate safely alongside human workers without extensive physical guarding (Villani et al., 2018; Matheson et al., 2019). Their ease of programming and redeployment makes cobots particularly attractive for small- and medium-scale food processors, where adaptability and cost efficiency are essential. Empirical studies indicate that collaborative robotic systems can improve throughput, reduce error rates, and shorten return-on-investment periods compared to conventional automation, while preserving human oversight and decision-making capabilities (Villani et al., 2018; Wakchaure et al., 2023).

5.2. Automation in Food Handling, Cutting, and Packaging

Robotic automation has expanded beyond packaging to encompass a wide range of food handling, cutting, portioning, and packaging operations. Advanced robotic systems equipped with specialized end-effectors, force sensors, and machine vision can manipulate delicate or irregularly shaped food products with minimal damage, addressing challenges associated with manual handling (Bechar and Vigneault, 2016; Sanfilippo et al., 2024).

In meat, poultry, and seafood processing, robotic cutting and portioning systems provide consistent product dimensions while reducing ergonomic strain and injury risks for workers exposed to repetitive manual cutting tasks (Rashidi et al., 2021). In packaging operations, robots integrated with computer vision systems can identify product orientation, compensate for variability, and execute precise pick-and-place actions at high speed. Intelligent control strategies, including reinforcement learning and adaptive algorithms, further optimize conveyor synchronization, gripping force, and cycle timing to enhance throughput and minimize product loss (Drijver et al., 2023). Beyond operational efficiency, robotic automation facilitates enhanced data acquisition and traceability by capturing real-time production metrics that can be integrated with manufacturing execution systems (MES) and enterprise resource planning (ERP) platforms. This data-driven capability supports quality management, predictive maintenance, and continuous process improvement initiatives.

5.3. Robotic Systems for Hygiene and Contamination Control

Hygiene and contamination control remain critical challenges in food processing environments, where microbial growth, allergen cross-contact, and foreign material contamination pose significant risks to consumer health. Robotic systems designed for hygienic operation and washdown conditions contribute to contamination prevention by reducing direct human contact with food and food-contact surfaces (Bogue, 2011; Bechar and Vigneault, 2016). Automated robotic cleaning and sanitation systems equipped with disinfectant spraying mechanisms, UV-C irradiation, or autonomous cleaning protocols can perform hygiene tasks more consistently and reproducibly than manual methods. These systems are particularly valuable in high-risk zones where frequent sanitation is required or where exposure to chemicals and extreme conditions may pose safety concerns for workers (Kumar et al., 2022).

Additionally, vision-guided robotic manipulators enable non-contact handling of food products within controlled environments, supporting compliance with Hazard Analysis and Critical Control Point (HACCP) principles and international food safety standards. Integration of sensors and real-time monitoring allows verification of sanitation effectiveness and facilitates continuous improvement of hygiene practices.

5.4. Human–Robot Collaboration in Industry 5.0 Food Systems

The Industry 5.0 paradigm emphasizes close collaboration between humans and intelligent machines, shifting the focus from full automation toward synergistic human–robot systems. In food processing environments, this

approach leverages human strengths-such as judgment, adaptability, and quality perception-alongside robotic capabilities in speed, precision, and endurance (Nahavandi, 2019; Longo et al., 2020).

Human-robot collaboration enhances operational flexibility by allowing workers to supervise, guide, or intervene in robotic tasks that require contextual understanding, while robots perform repetitive or hazardous operations such as sorting, stacking, trimming, or material transfer. Studies have shown that collaborative robotics can reduce ergonomic strain, improve workplace safety, and increase job satisfaction by enabling workers to focus on higher-value activities (Villani et al., 2018; Kılınç et al., 2025). Furthermore, modular and scalable automation architectures facilitate gradual digital transformation across food enterprises of varying sizes. By enabling incremental adoption of robotic technologies, Industry 5.0-aligned systems preserve human oversight while enhancing productivity, quality assurance, and resilience to market and supply chain fluctuations (Xu et al., 2021; Wakchaure et al., 2023).

6. Blockchain Technology in Food Processing and Preservation

Blockchain technology has gained considerable attention as a transformative digital tool capable of addressing long-standing challenges in food processing and preservation, particularly those related to traceability, transparency, safety, and trust across complex supply chains. Originally developed as the underlying technology for cryptocurrencies, blockchain has evolved into a versatile distributed ledger system with applications extending well beyond finance (Nakamoto, 2008; Tian, 2017). In food systems, blockchain enables immutable record-keeping, decentralized data management, and automated verification mechanisms that enhance coordination among stakeholders from primary production to consumption (Casino et al., 2019; Galvez et al., 2018). The adoption of blockchain in food processing and preservation is driven by increasing consumer demand for transparency, stricter regulatory requirements, and the need for rapid response to food safety incidents. By ensuring data integrity and auditability, blockchain supports improved quality assurance, efficient recalls, and enhanced confidence in food provenance and handling practices (Tian, 2017; Kamath, 2018).

6.1. Fundamentals of Blockchain in Food Supply Chains

At its core, blockchain is a distributed ledger technology that enables secure and transparent recording of transactions across a network of participants without reliance on a central authority. Each transaction is grouped into a block containing data, a timestamp, and a cryptographic hash linking it to the previous block, forming a chain that is computationally resistant to tampering once validated through consensus mechanisms (Nakamoto, 2008; Casino et al., 2019). This structure ensures immutability, traceability, and trust among participants who may not have prior relationships. In food supply chains, blockchain functions as a shared digital infrastructure that records information related to raw material sourcing, processing conditions, batch identification, storage, transportation, and distribution. Authorized stakeholders can access consistent and up-to-date information in real time, reducing data fragmentation and information asymmetry commonly associated with conventional, siloed record-keeping systems (Galvez et al., 2018; Kamath, 2018).

Blockchain architectures may be public, private, or consortium-based depending on requirements related to transparency, confidentiality, and performance. Private and consortium blockchains are particularly relevant for industrial food systems, as they offer higher transaction throughput and controlled access while maintaining core blockchain attributes such as immutability and auditability (Caro et al., 2018). When integrated with IoT sensors deployed in processing and storage environments, blockchain enables secure capture and verification of environmental data-such as temperature and humidity-enhancing real-time traceability and accountability for perishable foods (Badia-Melis et al., 2015; Casino et al., 2019).

6.2. Traceability and Transparency in Food Processing Operations

End-to-end traceability and transparency represent the most mature and widely adopted applications of blockchain in food systems. Blockchain-based traceability solutions record detailed product histories, including origin, processing dates, batch numbers, handling conditions, certification status, and logistics events, in a tamper-resistant digital ledger (Tian, 2017; Galvez et al., 2018). Once recorded, these data cannot be altered retroactively without network consensus, which significantly reduces opportunities for fraud, adulteration, and mislabeling.

Enhanced transparency benefits all supply chain participants by enabling rapid access to verified information. For food processors and regulators, blockchain improves visibility into upstream and downstream operations, facilitating compliance monitoring and quality audits. For consumers, blockchain-enabled interfaces-such as QR codes or mobile applications-allow verification of product provenance, production practices, and sustainability claims, strengthening trust and brand credibility (Kamath, 2018; Casino et al., 2019). Integration of blockchain with IoT

further enhances traceability by enabling real-time recording of sensor data related to processing and storage conditions. This integration ensures that environmental data influencing quality and shelf life are securely logged and protected from manipulation, supporting proactive quality management and risk mitigation throughout food processing and distribution networks (Badia-Melis et al., 2015; Galvez et al., 2018).

6.3. Blockchain for Food Safety, Quality Assurance, and Recalls

Blockchain's immutable and distributed data structure provides significant advantages for food safety management and quality assurance. By securely recording inspection results, hygiene logs, certification documents, and compliance records, blockchain enables stakeholders to verify that safety and quality standards have been met at each stage of processing and distribution (Tian, 2017; Kamath, 2018). This level of data integrity is critical for regulatory compliance and for maintaining confidence in food safety systems. In the event of contamination or quality failure, blockchain-enabled traceability dramatically improves recall efficiency. Conventional recall processes often require extensive manual investigation to identify affected batches, resulting in delays and broad product withdrawals. In contrast, blockchain systems allow rapid identification of the origin and distribution pathways of affected products, enabling targeted recalls that reduce economic losses and minimize risks to public health (Galvez et al., 2018; Casino et al., 2019).

Blockchain also supports continuous quality assurance by securely storing data related to processing parameters, cold-chain conditions, and handling practices that influence shelf life and sensory quality. These verifiable records provide objective evidence of compliance with quality thresholds and facilitate root-cause analysis when deviations occur, contributing to continuous improvement in food processing operations (Badia-Melis et al., 2015; Tian, 2017).

6.4. Smart Contracts for Compliance and Quality-Based Transactions

Smart contracts are programmable scripts embedded within blockchain platforms that automatically execute predefined actions when specified conditions are satisfied (Szabo, 1997; Christidis and Devetsikiotis, 2016). In food processing and preservation systems, smart contracts enable automation of compliance verification, quality assurance checks, and transactional processes without manual intervention. For example, smart contracts can be designed to verify that temperature-sensitive foods were maintained within acceptable limits during processing and transportation before authorizing transfer of ownership or releasing payment. When integrated with IoT sensors, smart contracts can automatically enforce quality-based agreements by triggering alerts, penalties, or recalls if deviations from predefined safety or quality parameters are detected (Caro et al., 2018; Casino et al., 2019).

Smart contracts also facilitate automated documentation and validation of certifications such as organic, fair-trade, or sustainability labels. By linking digital certificates to specific product batches on the blockchain, stakeholders—including regulators and consumers—can verify compliance claims transparently and efficiently. These mechanisms reduce administrative

overhead, minimize human error, and enhance accountability across food supply chains, supporting more efficient and trustworthy food processing and preservation systems (Christidis and Devetsikiotis, 2016; Kamath, 2018).

7. Cybersecurity and Data Management in Smart Food Systems

The digital transformation of food processing and preservation under Industry 4.0 and Industry 5.0 has led to extensive deployment of interconnected cyber-physical systems, Internet of Things (IoT) devices, cloud platforms, artificial intelligence tools, and blockchain networks. While these technologies significantly enhance operational efficiency, traceability, and decision-making, they also expose food systems to a broad spectrum of cybersecurity risks and data management challenges. Cybersecurity and robust data governance have therefore become critical enablers of safe, reliable, and resilient smart food systems (Boyes et al., 2018; Humayed et al., 2017). Ensuring data integrity, privacy, regulatory compliance, and secure interoperability is essential to maintaining stakeholder trust and safeguarding food safety outcomes.

7.1. Cyber Threats in Digitized Food Processing Environments

Digitized food processing environments increasingly depend on industrial control systems (ICS), supervisory control and data acquisition (SCADA) systems, and networked sensors for real-time monitoring and automation. When these operational technologies are connected to enterprise networks and cloud infrastructures, they become vulnerable to cyber threats such as malware, ransomware, denial-of-service attacks, unauthorized access, and data

manipulation (Cherdantseva et al., 2016; Humayed et al., 2017). Cyberattacks on food processing facilities can disrupt production, compromise product quality, and pose serious food safety risks if critical parameters—such as temperature, pressure, or sanitation controls—are maliciously altered.

IoT devices deployed in processing plants, storage facilities, and cold-chain logistics often possess limited computational resources and weak built-in security mechanisms, making them attractive targets for cyber attackers (Sicari et al., 2015). Inadequate authentication, unpatched firmware, and insecure communication protocols can enable unauthorized access to sensor networks and control systems. In food manufacturing environments, such breaches may result in falsified quality data, loss of traceability records, or manipulation of automated processing parameters, potentially leading to large-scale recalls and significant economic losses (Boyes et al., 2018). The growing reliance on AI-driven automation further amplifies cybersecurity risks, as compromised or poisoned data streams can mislead decision-support systems and predictive models. As food systems become increasingly autonomous, cyber resilience—defined as the ability to anticipate, withstand, recover from, and adapt to cyber incidents—has emerged as a core requirement of Industry 5.0 food manufacturing strategies (European Commission, 2021).

7.2. Data Integrity, Privacy, and Regulatory Compliance

Data integrity is fundamental to smart food systems, as decisions related to quality control, safety assurance, shelf-life prediction, and regulatory compliance depend heavily on accurate and trustworthy data. In digitally connected food processing environments, data are continuously generated by sensors, robotics, computer vision systems, and enterprise software platforms. Ensuring that these data remain accurate, complete, and unaltered throughout their lifecycle is a major challenge, particularly when data flow across multiple stakeholders and digital platforms (Roman et al., 2013; ISO/IEC, 2013).

Privacy and confidentiality are equally critical, especially when sensitive commercial information, proprietary processing parameters, and supplier data are exchanged across interconnected networks. Food companies must protect intellectual property while simultaneously enabling the transparency required for traceability and regulatory oversight. Legal frameworks such as the General Data Protection Regulation (GDPR) impose stringent requirements on data collection, storage, processing, and sharing practices within digital food systems (Voigt and von dem Bussche, 2017). From a regulatory perspective, food safety authorities increasingly require digital records for hazard analysis, process validation, and traceability. Cybersecurity failures that compromise data integrity can therefore lead not only to food safety risks but also to non-compliance with regulatory standards such as HACCP, ISO 22000, and food safety modernization frameworks (Boyes et al., 2018). Blockchain technology has been proposed as a mechanism to enhance data integrity by providing immutable and auditable records; however, its effectiveness depends on the reliability of data inputs and must be complemented by strong cybersecurity controls at the sensor and system levels (Tian, 2017).

7.3. Secure Data Sharing and Interoperability Challenges

Smart food systems depend on seamless data exchange among heterogeneous digital platforms, including IoT networks, cloud infrastructures, AI analytics engines, enterprise resource planning systems, and blockchain ledgers. Achieving secure and efficient data sharing across such diverse systems remains a significant challenge. Interoperability issues arise due to differences in data formats, communication protocols, proprietary architectures, and inconsistent cybersecurity practices across stakeholders (Klerkx et al., 2019). Secure data sharing requires standardized interfaces, encryption mechanisms, authentication protocols, and access control policies to ensure that only authorized entities can access or modify information. Technologies such as public-key infrastructure, secure application programming interfaces, and role-based access control models are increasingly adopted to address these challenges; however, their implementation across complex and multi-actor food supply chains remains uneven (Sicari et al., 2015). In addition, scalability, latency, and system integration constraints can limit the real-time performance of secure data exchange solutions in large-scale industrial environments.

Industry 5.0 further emphasizes human-centric and collaborative data ecosystems in which humans, machines, and digital platforms interact seamlessly. Realizing this vision requires not only technical interoperability but also governance frameworks that clearly define data ownership, accountability, and ethical use. The development of harmonized standards and coordinated collaboration among technology providers, regulators, and food industry stakeholders will be essential to overcoming interoperability barriers and ensuring secure, resilient, and transparent smart food systems (European Commission, 2021; Klerkx et al., 2019).

8. Integration of AI, IoT, Robotics, and Blockchain

The full potential of digital transformation in food processing and preservation is realized not through isolated technologies, but through the strategic integration of artificial intelligence (AI), Internet of Things (IoT), robotics, and

blockchain into unified digital ecosystems. This convergence enables intelligent automation, real-time decision-making, enhanced traceability, and resilient food manufacturing systems aligned with Industry 4.0 and the emerging Industry 5.0 paradigm. Integrated digital architectures facilitate seamless data flow across processing,

preservation, storage, and distribution stages, thereby strengthening food safety, quality optimization, and operational sustainability (Klerkx et al., 2019; Misra et al., 2020).

8.1. Converged Digital Ecosystems in Food Processing

Converged digital ecosystems represent interconnected environments in which IoT sensors, robotic systems, AI-driven analytics platforms, and blockchain-based ledgers operate synergistically to support smart food processing operations. IoT devices continuously collect real-time data on critical processing parameters, including temperature, humidity, pressure, gas composition, and microbial indicators. These data streams are transmitted to centralized or distributed analytics platforms, where AI algorithms perform pattern recognition, predictive modeling, anomaly detection, and process optimization (Kamilaris et al., 2019; Misra et al., 2020). Robotic systems function as physical actuators within these ecosystems, dynamically responding to AI-generated insights by adjusting food handling, processing, packaging, or sanitation operations. Blockchain technology provides a secure and immutable digital backbone, ensuring that key process data, quality records, and compliance documentation are transparent, verifiable, and tamper-resistant across the food supply chain (Tian, 2017; Oyelami, 2024). Collectively, these technologies form cyber-physical-biological systems capable of adaptive control, enhanced traceability, and continuous process improvement. Such converged ecosystems improve operational efficiency by reducing manual intervention, minimizing process variability, and enabling proactive quality management. From an Industry 5.0 perspective, these systems also support human-centric manufacturing by augmenting human decision-making rather than replacing it, allowing operators to focus on supervision, strategic planning, and innovation (European Commission, 2021).

8.2. Digital Twins and Virtual Modeling of Food Processing Systems

Digital twin technology plays a pivotal role in integrating AI, IoT, and robotics within smart food processing and preservation environments. A digital twin is a virtual replica of a physical system that is continuously updated using real-time data from IoT sensors and operational feedback from processing equipment. In food processing, digital twins enable virtual modeling of thermal treatments, drying operations, fermentation systems, cold storage facilities, and packaging lines (Verdouw et al., 2016; Negri et al., 2017).

AI algorithms embedded within digital twin frameworks simulate system behavior under varying operational conditions, enabling predictive analysis and scenario evaluation without disrupting actual production. For example, digital twins can assess the influence of temperature fluctuations on microbial inactivation kinetics or shelf-life degradation, supporting optimized preservation strategies while minimizing energy consumption and nutrient loss (Zhang et al., 2022). Robotic systems linked to digital twins can also be virtually tested, programmed, and reconfigured prior to physical deployment, reducing commissioning time and operational downtime. The integration of blockchain technology further enhances the reliability of digital twins by ensuring that input data, model outputs, and operational records are securely stored and traceable. This combination strengthens regulatory compliance, process validation, and confidence in AI-assisted decision-support systems, particularly in safety-critical food processing environments.

8.3. Cloud and Edge Computing for Real-Time Food Data Analytics

The integration of AI-driven analytics with IoT-enabled food processing systems requires robust computing infrastructures capable of handling large volumes of heterogeneous data in

real time. Cloud and edge computing architectures provide complementary capabilities to meet these requirements. Cloud platforms offer scalable data storage, high-performance computing resources, and advanced analytics tools for long-term data analysis, machine learning model training, and system-wide optimization across multiple facilities (Shi et al., 2016; Misra et al., 2020).

Edge computing enables data processing closer to the source—within processing plants, storage facilities, or logistics nodes—thereby reducing latency and enhancing system responsiveness. This capability is particularly important for time-sensitive applications such as automated process control, robotic coordination, and real-time food safety monitoring. By executing AI models at the edge, food processing systems can maintain operational continuity even during network disruptions, thereby improving resilience and reliability (Shi et al., 2016).

Hybrid cloud-edge architectures support seamless integration of real-time operational decision-making with long-term strategic analytics. When combined with blockchain-based data integrity mechanisms, these architectures ensure secure data sharing, transparency, and regulatory compliance across distributed food processing networks.

Such integrated computing frameworks are essential for enabling the autonomous, adaptive, and sustainable food systems envisioned under Industry 4.0 and Industry 5.0 paradigms (European Commission, 2021; Kamilaris et al., 2019).

9. Sustainability, Resilience, and Ethical Considerations

Sustainability and resilience have become central priorities in modern food processing and preservation systems due to increasing resource constraints, climate change impacts, supply chain disruptions, and evolving societal expectations. Conventional food manufacturing practices are often energy-intensive and generate significant waste, contributing to environmental degradation and economic inefficiencies. The integration of Industry 4.0 and the emerging Industry 5.0 technologies offers transformative opportunities to enhance energy efficiency, optimize resource utilization, reduce waste generation, and promote ethical and socially responsible food manufacturing systems (Galanakis, 2020; Kamilaris et al., 2019). Industry 4.0 focuses on digital connectivity, automation, and data-driven optimization, while Industry 5.0 extends this paradigm by emphasizing human-centricity, sustainability, and system resilience. In the food sector, these combined approaches enable intelligent decision-making, adaptive production systems, and responsible use of natural resources while ensuring food safety and quality. However, alongside these benefits, digital transformation raises ethical, social, and workforce-related challenges that must be addressed to ensure inclusive, transparent, and sustainable food system development (European Commission, 2021; Klerkx et al., 2019).

9.1. Energy-Efficient and Resource-Optimized Processing

Food processing and preservation operations are among the most energy-intensive activities in the agri-food sector, particularly during thermal processing, drying, refrigeration, freezing, and cold storage. Industry 4.0 technologies such as IoT-enabled sensing, real-time monitoring, AI-based optimization, and advanced automation play a critical role in reducing energy consumption and improving resource efficiency. Continuous data acquisition from sensors allows processors to monitor energy use, water consumption, and equipment performance in real time, enabling rapid identification of inefficiencies and deviations from optimal operating conditions (Misra et al., 2020; Galanakis, 2020). Artificial intelligence and machine learning

models support intelligent control of processing parameters by dynamically adjusting operating conditions based on real-time product characteristics and environmental data. Predictive control strategies enable optimized heating, cooling, and drying cycles, minimizing energy input while maintaining microbial safety, nutritional quality, and sensory attributes of food products (Zhang et al., 2022). Digital twin technologies further enhance energy optimization by simulating alternative processing scenarios and identifying the most resource-efficient configurations without interrupting physical production processes (Verdouw et al., 2016; Negri et al., 2017). From an Industry 5.0 perspective, energy-efficient processing also contributes to system resilience and adaptability. Smart food processing systems can respond dynamically to energy price fluctuations, equipment failures, or variations in renewable energy availability, ensuring operational continuity while reducing environmental impacts. These capabilities directly support global sustainability targets and improve the long-term economic and environmental viability of food processing industries (European Commission, 2021).

9.2. Waste Reduction and Circular Economy Approaches

Food loss and waste remain critical challenges across global food systems, resulting in significant environmental, economic, and social consequences. Digital technologies integrated under Industry 4.0 frameworks provide powerful tools to reduce waste across processing, preservation, storage, and distribution stages. IoT-based monitoring systems and AI-driven forecasting models enhance inventory management, demand planning, and shelf-life prediction, thereby reducing overproduction, spoilage, and post-processing losses (Aung and Chang, 2014; Badia-Melis et al., 2018).

Automation and robotics improve precision in sorting, cutting, grading, and packaging operations, minimizing raw material losses and reducing product defects. Blockchain-enabled traceability systems further support waste reduction by improving transparency and accountability across the food supply chain, allowing stakeholders to identify waste hotspots and implement targeted corrective actions (Tian, 2017; Galvez et al., 2018). Smart packaging technologies, including freshness indicators and sensor-based labels, provide real-time information on product quality and storage conditions, enabling informed decision-making by processors, retailers, and consumers. Circular economy principles are increasingly embedded within smart food systems, focusing on the valorization of by-products and waste streams. Digital tools facilitate the identification and optimization of valorization pathways, such as converting processing residues into functional ingredients, animal feed, bioenergy, or biodegradable packaging materials. These

approaches reduce environmental burdens while creating additional value streams, supporting sustainable and resource-efficient food manufacturing models (Galanakis, 2020; Mirabella et al., 2014).

9.3. Ethical, Social, and Workforce Implications of Industry 5.0

While automation and digitalization offer substantial efficiency gains, they also raise ethical and social concerns related to workforce displacement, data ownership, privacy, and equity. Industry 5.0 addresses these challenges by promoting human-centric manufacturing, where intelligent technologies are designed to complement and enhance human skills rather than replace them (European Commission, 2021). In food processing environments, collaborative robots, decision-support systems, and advanced human-machine interfaces assist workers by reducing physical strain, improving occupational safety, and supporting informed decision-making.

Workforce reskilling and upskilling are essential components of ethical digital transformation. As food industries increasingly adopt AI, IoT, and robotics, demand grows for digital literacy, data analytics capabilities, and interdisciplinary expertise. Inclusive training programs, lifelong learning initiatives, and continuous professional development are necessary to ensure that workers can adapt to evolving job roles and actively participate in smart food production systems (Klerkx et al., 2019; Longo et al., 2020). Ethical considerations also extend to data governance, algorithmic transparency, and accountability. AI-driven decision-making systems must be designed to avoid bias, ensure explainability, and protect sensitive commercial and personal data. Transparent data management frameworks and participatory governance mechanisms are critical for building trust among stakeholders and ensuring socially responsible adoption of digital technologies. By integrating sustainability, ethical principles, and social inclusion, Industry 5.0 provides a balanced and resilient pathway toward future-ready food processing and preservation systems.

10. Challenges and Limitations

Despite the substantial benefits offered by Industry 4.0 and Industry 5.0 technologies in food processing and preservation, their large-scale implementation faces multiple challenges and limitations. Economic constraints, technical complexity, workforce readiness, and regulatory uncertainties continue to impede widespread adoption, particularly among small and medium-sized food enterprises. Addressing these barriers is essential to ensure equitable, secure, and sustainable digital transformation across global food systems (Klerkx et al., 2019; European Commission, 2021).

10.1. Economic and Infrastructure Constraints

One of the primary challenges in adopting advanced digital technologies in food processing is the high initial investment required for infrastructure development. The deployment of IoT sensor networks, robotic systems, artificial intelligence platforms, secure cloud infrastructures, and blockchain-based traceability solutions involves significant capital expenditure. For small and medium-sized enterprises (SMEs), which constitute a major proportion of the global food industry, such investments may not be economically feasible without governmental support, subsidies, or policy incentives (Galanakis, 2020).

In addition to capital costs, operational and maintenance expenses associated with digital systems—including software licensing, cybersecurity upgrades, data storage, and system integration—further increase the financial burden. Many food processing facilities, particularly in developing economies, also lack reliable digital infrastructure such as high-speed internet connectivity, stable power supply, and advanced automation capabilities. These infrastructural limitations restrict the effective implementation of real-time monitoring, cloud-based analytics, and interconnected cyber-physical systems (Misra et al., 2020). Furthermore, the economic benefits of digitalization are often realized over the long term, whereas the costs are immediate. This imbalance can discourage technology adoption in highly competitive food markets characterized by low profit margins. Therefore, the development of scalable, modular, and cost-effective digital solutions tailored to diverse food processing contexts remains a critical industrial and research priority.

10.2. Technical and Interoperability Issues

The integration of heterogeneous digital technologies into unified smart food systems presents significant technical challenges. Food processing environments typically involve diverse

hardware platforms, proprietary software solutions, and multiple communication protocols, leading to interoperability issues that hinder seamless data exchange and system integration (Roman et al., 2013; Shi et al., 2016). The lack of standardized data formats and interfaces complicates the integration of IoT devices, AI-driven analytics

platforms, robotic systems, and blockchain ledgers into cohesive digital ecosystems. Cyber-physical systems deployed in food processing plants must operate reliably under harsh environmental conditions, including high humidity, temperature fluctuations, and stringent sanitation requirements. Ensuring long-term sensor accuracy, system robustness, and real-time responsiveness under such conditions remains a significant engineering challenge. Moreover, artificial intelligence models require large volumes of high-quality, representative datasets to function effectively. Data scarcity, inconsistency, and bias can adversely affect the accuracy of predictive models used for quality assessment, shelf-life estimation, and process optimization (Misra et al., 2020). Scalability and latency issues also arise when cloud-based analytics are applied to real-time control applications. While edge and fog computing architectures offer partial solutions, designing hybrid systems that balance computational efficiency, security, and responsiveness remains complex and resource-intensive.

10.3. Skill Gaps and Workforce Training Needs

The successful implementation of smart food processing technologies is highly dependent on the availability of a skilled workforce capable of operating, maintaining, and interpreting advanced digital systems. However, the food processing sector has traditionally relied on labor-intensive operations and may lack sufficient expertise in data analytics, artificial intelligence, robotics programming, and cybersecurity (Klerkx et al., 2019). This skills gap represents a major limitation to effective technology deployment and utilization.

Workforce-related challenges also include resistance to organizational change, concerns over job displacement, and limited digital literacy among employees. Without structured training programs and effective change management strategies, digital transformation initiatives may encounter low acceptance and operational inefficiencies. The Industry 5.0 paradigm emphasizes human-centric manufacturing, advocating collaborative human-machine systems that enhance productivity while preserving meaningful human roles (European Commission, 2021). Continuous professional development, interdisciplinary education, and strong collaboration between academia, industry, and policymakers are essential to address these challenges. Building digital competencies while retaining domain-specific food processing knowledge is critical for developing a resilient and future-ready workforce.

10.4. Regulatory and Standardization Challenges

Regulatory and standardization frameworks have not yet fully evolved to keep pace with rapid technological advancements in smart food processing systems. Existing food safety and quality regulations were largely designed for conventional processing methods and paper-based record-keeping, and may not adequately address digital data management, AI-driven decision-making, or blockchain-enabled traceability systems (Boyes et al., 2018). Such regulatory uncertainty can discourage investment and slow the adoption of innovative technologies.

Data governance and privacy regulations, including the General Data Protection Regulation (GDPR), impose strict requirements on data collection, storage, and sharing, creating compliance challenges for interconnected and data-intensive food supply chains (Voigt and von dem Bussche, 2017). Variations in regulatory frameworks across regions further complicate

cross-border data exchange and global food trade. In addition, the absence of universally accepted standards for interoperability, cybersecurity, digital twins, and AI validation limits system scalability and increases implementation risks. Addressing these regulatory and standardization challenges requires coordinated efforts among policymakers, standardization bodies, technology providers, and food industry stakeholders to establish harmonized guidelines that support innovation while ensuring food safety, data security, and consumer trust.

11. Future Perspectives and Research Directions

The rapid convergence of artificial intelligence, Internet of Things, robotics, blockchain, and cyber-physical systems is redefining the future of food processing and preservation. While Industry 4.0 has primarily focused on automation, efficiency, and data-driven optimization, Industry 5.0 introduces a paradigm shift toward human-centricity, sustainability, and system resilience. Future research and innovation efforts must therefore balance technological advancement with ethical, environmental, and societal considerations to ensure long-term food security and industrial sustainability (Breque et al., 2021; Klerkx et al., 2019).

11.1. Emerging Trends in Smart Food Processing Technologies

Emerging trends in smart food processing technologies are increasingly centered on system integration, autonomy, and intelligence. Artificial intelligence techniques such as deep learning, reinforcement learning, and hybrid modeling approaches are expected to evolve from decision-support tools to self-adaptive control systems

capable of real-time optimization under dynamic processing conditions (Zhang et al., 2021). The increasing availability of high-resolution sensor data from IoT-enabled processing environments will further enhance predictive analytics, digital twins, and process transparency. Advanced sensing technologies, including hyperspectral imaging, biosensors, and nano-enabled sensors, are anticipated to play a critical role in non-destructive quality assessment and early detection of contamination or spoilage (ElMasry et al., 2012; Pu et al., 2015). In parallel, edge and fog computing architectures will gain prominence by enabling low-latency analytics, reducing dependence on centralized cloud systems, and improving data security and reliability in food processing operations (Shi et al., 2016). Another notable trend is the increasing adoption of intelligent and active packaging systems that integrate sensors, indicators, and connectivity features to monitor product quality throughout the supply chain. These technologies are expected to improve shelf-life management, reduce food waste, and enhance consumer trust through transparent information sharing (Realini and Marcos, 2014).

11.2. Role of Industry 5.0 in Sustainable Food Security

Industry 5.0 places sustainability and human well-being at the core of technological development, offering significant opportunities to address global food security challenges. By integrating advanced automation with human expertise, Industry 5.0 enables flexible, resilient, and inclusive food production systems that can adapt to disruptions such as climate change, pandemics, and supply chain shocks (Brequé et al., 2021). Future food processing systems are expected to prioritize energy-efficient operations, resource optimization, and circular economy principles. AI-driven optimization of water, energy, and raw material usage can significantly reduce the environmental footprint of food processing facilities (Galanakis, 2020). Furthermore, the integration of digital traceability systems with sustainability metrics will enable more informed decision-making across the food value chain, from raw material sourcing to consumption. Industry 5.0 also emphasizes the preservation of human creativity and

craftsmanship, particularly in artisanal and traditional food sectors. Collaborative human–robot systems can support skilled labor, improve ergonomics, and enhance product consistency without eliminating human involvement, thereby contributing to socially sustainable food systems (Nahavandi, 2019).

11.3. Policy Frameworks and Innovation Strategies

Supportive policy frameworks and innovation strategies are essential to accelerate the adoption of smart food processing technologies. Governments and regulatory bodies play a crucial role in fostering innovation by providing financial incentives, research funding, and infrastructure development, particularly for small and medium-sized enterprises (SMEs) (OECD, 2020). Public–private partnerships can further facilitate technology transfer and commercialization of research outcomes. Future policy efforts must also address regulatory harmonization and standardization to support interoperability, data sharing, and cross-border food trade. Clear guidelines for AI validation, data governance, and blockchain-based traceability are required to reduce uncertainty and build industry confidence (Boyes et al., 2018). Additionally, ethical frameworks governing the use of AI and automation in food systems should be integrated into policy design to ensure transparency, accountability, and consumer protection.

Innovation strategies should encourage open innovation ecosystems that connect food manufacturers, technology providers, research institutions, and startups. Such ecosystems can accelerate interdisciplinary collaboration and enable the co-development of scalable, context-specific solutions for diverse food processing environments (Chesbrough, 2020).

11.4. Opportunities for Interdisciplinary Research

The complexity of smart food processing systems presents substantial opportunities for interdisciplinary research spanning food engineering, computer science, data analytics, materials science, social sciences, and policy studies. Future research should focus on developing hybrid models that combine data-driven AI approaches with mechanistic food processing knowledge to improve robustness, interpretability, and trustworthiness of digital systems (Zhang et al., 2021). Human–machine interaction, explainable AI, and ethical AI design represent critical research frontiers in Industry 5.0 food systems. Understanding how operators interact with intelligent systems and how trust is established in automated decision-making processes is essential for successful implementation (Nahavandi, 2019). In addition, socio-economic research is needed to assess the impacts of digital transformation on employment, skills development, and rural livelihoods. Finally, long-term, system-level studies integrating sustainability assessment, life cycle analysis, and resilience modeling will be crucial for evaluating the true benefits and trade-offs of digitalization in food processing and preservation. Such interdisciplinary efforts will support the development of resilient, equitable, and future-ready global food systems.

12. Conclusion

The digital transformation of food processing and preservation is rapidly accelerating through the adoption of Industry 4.0 and Industry 5.0 technologies. The integration of artificial intelligence, Internet of Things, robotics, blockchain, and cyber-physical systems is reshaping conventional food manufacturing into intelligent, adaptive, and data-driven ecosystems. This review highlights the technological progress achieved to date, examines their implications for the global food industry, and outlines future pathways toward sustainable and resilient food systems.

12.1. Summary of Key Technological Advances

Recent advancements in smart food processing have been driven by the convergence of artificial intelligence, advanced sensing technologies, automation, and digital connectivity. Artificial intelligence and machine learning have enabled predictive quality assessment, real-time process optimization, and shelf-life modeling, significantly improving processing efficiency and product consistency (Misra et al., 2020; Zhang et al., 2021). Computer vision and hyperspectral imaging systems have further enhanced non-destructive inspection, sorting, and contamination detection across diverse food products (ElMasry et al., 2012). The Internet of Things has played a critical role in enabling continuous monitoring and control of processing, storage, and distribution parameters. IoT-based sensor networks facilitate real-time data acquisition, traceability, and decision-making throughout the food supply chain, improving transparency and operational efficiency (Verdouw et al., 2016). Robotics and automation have contributed to improved hygiene, precision, and labor efficiency in food handling, packaging, and sanitation, while collaborative robotic systems have enabled safer and more flexible human-machine interactions (Bogue, 2016). Blockchain technology has emerged as a transformative tool for enhancing traceability, data integrity, and trust in food processing and distribution networks. By providing immutable and transparent records, blockchain-based systems support rapid recall management, quality assurance, and regulatory compliance (Casino et al., 2019). Together, these technological advances form the foundation of intelligent and interconnected food processing systems.

12.2. Implications for the Global Food Industry

The widespread adoption of Industry 4.0 and Industry 5.0 technologies has profound implications for the global food industry. Digitally enabled food processing systems enhance productivity, reduce waste, and improve food safety, contributing to more resilient and competitive food supply chains (Galanakis, 2020). Improved traceability and transparency strengthen consumer confidence and facilitate compliance with increasingly stringent food safety and sustainability regulations. From a socio-economic perspective, the transition toward smart food systems necessitates changes in workforce structure and skill requirements. While automation may reduce reliance on manual labor, Industry 5.0 emphasizes human-centric manufacturing, promoting collaboration between humans and intelligent machines rather than workforce displacement (Nahavandi, 2019). This shift underscores the importance of continuous education, upskilling, and interdisciplinary training to prepare the workforce for digitally integrated food production environments. Globally, digital food processing technologies also offer opportunities to enhance food security by improving resource efficiency, reducing post-harvest losses, and enabling localized and flexible production systems. However, equitable access to digital infrastructure and supportive policy frameworks is essential to prevent widening technological disparities between developed and developing regions (Klerkx et al., 2019).

12.3. Pathways Toward Intelligent and Sustainable Food Systems

Future pathways toward intelligent and sustainable food systems will require a holistic and integrated approach that aligns technological innovation with environmental stewardship, ethical considerations, and social responsibility. The adoption of Industry 5.0 principles encourages the design of food processing systems that prioritize sustainability, resilience, and human well-being alongside economic performance (Breque et al., 2021). Key research and

development priorities include the integration of AI-driven digital twins, energy-efficient processing technologies, and circular economy strategies to minimize environmental impact across the food value chain. Enhanced interoperability, standardized data governance frameworks, and secure digital infrastructures will be critical for enabling seamless system integration and large-scale deployment of smart technologies (Boyes et al., 2018). Ultimately, collaboration among industry stakeholders, researchers, policymakers, and technology providers will be essential to realize the full potential of intelligent food processing and preservation systems. By fostering innovation ecosystems and evidence-based policy development, the global food industry can progress toward resilient, transparent, and sustainable food systems capable of meeting future societal and environmental challenges.

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Abstract:

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