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Assessment of advancements and applications of robotics, artificial intelligence, and automated technology in the modern food sector

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ABSTRACT

The global food sector is under pressure to enhance production efficiency, safety, and quality due to growing consumer demands, labour shortages, and regulatory requirements. These challenges have driven the adoption of advanced technologies like robotics and AI. The food sector includes many operations, including manufacturing, processing, shipment, distribution, formation, conservation, and food service. The review paper explores the profound influence of robotics in various segments of the food enterprises, highlighting its applications across production, processing, packaging, and service stages. The main objective of this review is to provide a comprehensive overview of how robotics, AI, and automation are transforming food industry operations and addressing key challenges across the value chain. While various studies have explored specific robotics applications in food systems, few offer a holistic, cross-sectoral perspective that links robotics, AI, and automation technologies across different food categories and processing stages. Key findings include improved production efficiency, enhanced food safety, reduced labour dependency, and strengthened quality assurance driven by robotics and AI. Notably, collaborative robots (co-bots) are redefining human-robot interaction by working safely alongside humans to optimize workflow and productivity. This convergence of technologies is driving transformation in major food sectors such as dairy, meat, seafood, beverages, fruits, and vegetables, ensuring quality standards and operational excellence throughout the supply chain. The implications of this technological shift are substantial. Robotics and AI provide effective solutions to persistent industry challenges, including labour shortages and process variability, while laying the groundwork for a more resilient, data-driven, and intelligent food system. Unlike previous works that focus on specific tools or segments, this review distinguishes itself by examining the synergistic integration of robotics, AI, and automation across multiple food sectors. As industry demands continue to evolve, these technologies will remain central to enhancing efficiency, productivity, and competitiveness in the global food landscape.

1. Introduction

The food industry encompasses a huge range of accomplishments, including production, processing, packaging, distribution, preparation, preservation, and food service. Historically considered low-tech, the industry has experienced a shift towards increased technological integration, as documented by rising investments in research and development (RandD) relative to sales (Traill and Meulenberg, 2002). The implementation of technological innovations is steadily growing across various industrial applications. Automation is particularly crucial in the food and dairy industries as it helps them address numerous challenges and risks. (Caldwell, 2012). The programming of automation systems is heavily influenced by the specific nature of industrial operations. It is noteworthy that the food industry ranks among the top ten

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industries that extensively employ plant automation. The primary objective of automation is to supervise and optimize the various phases of processing while reducing labour costs, which account for around half of the total production costs (Singh, 2018). With aging populations and labour shortages, countries like Japan are actively pursuing automation to sustain profitability. The COVID-19 pandemic has further accelerated the adoption of automation across all phases of food production, emphasizing the critical role of automation in ensuring food safety and maintaining a stable food supply (Henry, 2020). The pandemic underscored a fundamental truth: robotics and automation are not merely about optimizing processes; they are about ensuring the resilience and reliability of an essential industry (Siderska, 2021). From production to packaging, distribution to delivery, automation emerged as a cornerstone of the food industry's response to the crisis. Currently, pick- and-place operations in the food business use industrial robotic arms to handle payloads and execute specific actions (Bader and Rahimifard, 2020) (Fig. 1).

Food manufacturing and processing facilities have shifted towards cost-effective automation solutions to increase production volumes, surpassing traditional methods. The dependence on manual labor is now considered outdated, with a growing preference for robotic handling and manufacturing systems. These encompass activities such as selecting, putting, packing, and palletising (Buckenhuskes and Oppenhauser, 2014). A significant advantage of robotics in the food sector is the capacity to automate repetitive and hazardous operations that may pose risks to human health, such as managing harmful substances or engaging in monotonous activities for prolonged durations. Automating these jobs enables food firms to enhance productivity and improve worker safety (Javaid et al, 2021). Typically, food processing facilities involve tasks such as manufacturing, processing, and packaging that necessitate direct interaction with food items. Dedicated machines, such as rice makers, dumpling makers, and automatic chocolate molding machines, are typically preferred for production and processing tasks that remain consistent without the need for frequent adjustment. These machines often do not require pick-and-place operations. However, packaging tasks often involve pick-and-place operations, which are also essential for transferring food products between different dedicated machines, thereby connecting various stages of processing (Wang et al, 2022). To enhance efficiency and adaptability in pick-and-place operations with diverse food products, robotic systems, comprising robotic manipulators, end-effectors, and sensors like cameras, are commonly deployed. Industrial robotic arms are currently the primary manipulators employed in the food industry, as they enable precise motion control and handle payloads during pick-and-place operations (Bader and Rahimifard, 2020) (Table 1).

A robot is a programmable, autonomous device consisting of electronic, electrical, or mechanical components. It is, in essence, a device that performs functions on behalf of a human operator. The International Organisation for Standardisation (ISO) defines a robot as "a consequently regulated, re-programmable, multi-purpose, manipulative

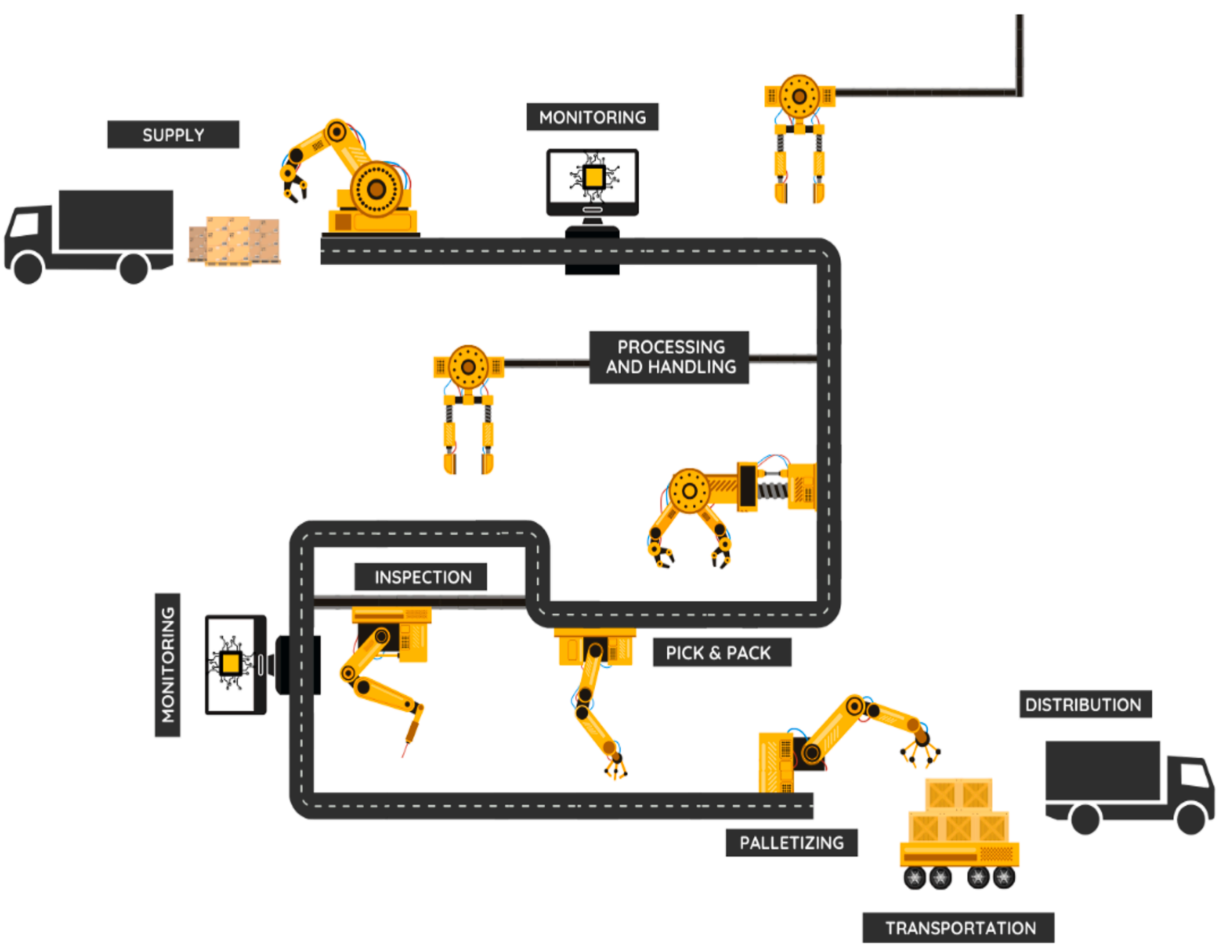

Fig. 1. Schematic representation of robotic integration across the food processing and supply chain. This diagram illustrates the progressive involvement of robotics at various key stages—beginning from the initial supply of raw materials, followed by monitoring, processing and handling, inspection, pick-and-pack, palletizing, and finally transportation and distribution to end users. Each robot-automated step highlights the transition toward smart manufacturing in the food sector. The use of intelligent systems and automation not only enhances operational precision but also ensures higher standards of hygiene, safety, traceability, and throughput. This integration helps address labour shortages and rising consumer expectations while supporting sustainable and scalable food production systems.

Table 1
Different robots their Utility and advantages of various robots used in food sector.

Type of robot	Use	Industry sector	Advantages	References
Sorting and Grading Robot	Sorting and grading food items	Fruits, Vegetables, Meat, Seafood	• Enhanced accuracy and consistency • Reduced manual labour	Dairath et al. (2023)
Dough Kneading Robot	Kneading and mixing dough	Bakeries, Pizza shops, Bread production	• Precision in kneading • Minimized manual effort	Derossi et al. (2023)
Processing Robot	Slicing, dicing, mixing and cooking	Meat, Seafood, Prepared foods, Baking	• Improved safety • Minimized repetitive tasks • Increased throughput	Wakchaure et al. (2023)
Cheese Cutting Robot	Precise cutting of cheese	Dairy, Cheese production	• Ensured uniform cuts • Reduced cheese handling labour	Meshram et al. (2022)
Autonomous Mobile Robot	Material handling and transportation	Warehouses, Distribution centers, Large-scale production	• Streamlined material handling • Minimized manual lifting	Sgarbossa et al. (2022)
Quality Control Robot	Inspecting food products	Various food industries like dairy, meat, seafood	• Ensured thorough inspections • Reduced human errors	Brito et al. (2020)
Picking and Packing Robot	Picking items and packing them	Snack food, Frozen food, Confectionery	• Reduced labor-intensive tasks • Increased efficiency	Dube et al. (2018)
Packaging Robot	Packaging finished products	Food packaging across industries	• Increased packaging speed • Reduced labour costs	Wang et al. (2022)
Cleaners and Sanitizing Robot	Cleaning and sanitizing	Food processing facilities	• Safeguard thorough sanitation • Minimized labor in cleaning	Yin et al. (2020)

machine with multiple degrees of freedom, which may be either stationary or mobile for industrial automation applications." Robots are particularly advantageous for specific tasks because, unlike humans, they do not experience fatigue, can work in uncomfortable or hazardous environments, function in a vacuum, are not affected by repetitive work, and remain focused on the assigned task (Agrawal et al, 2010; Nayik et al, 2015). RAS (Robotic Autonomous Systems) is not a novel concept; it finds applications in various industries. In tourism, it is used for check-ins and deliveries (Ivanov et al, 2019). The construction industry employs it for high-rise building construction (Cai et al, 2019) while self-driving trucks are employed in transportation (Sanders et al, 2019). The phrase 'Agri-food 3.0′ originated in the late 20th century within the agri-food sector to describe RAS (Miranda et al. 2019). Instances encompass automated milking systems (Driessen and Heutinck, 2015) and on-farm monitoring systems such as moisture in the soil monitors (Fentanes et al, 2020). The advancement of RAS is propelled by its application in perilous settings, superior efficiency, economic viability, alleviation of tiredness, and facilitation of interaction between humans and robots (McCarthy et al, 2018).

Automation eliminates the need for constant human oversight, often outperforming humans in accuracy and speed. While automation is common in manufacturing industries with well-defined processes, applying robotics in the food industry presents unique challenges. Objects in food processing vary in size, shape, weight, and position, requiring intelligent sensing. Delicate and often slippery or sticky items demand careful handling to prevent damage during rapid, secure lifting. Additionally, hygiene, quality, and customer safety are paramount concerns. Modern robots address these challenges effectively (Ahmad Nayik, 2015). To address the extensive diversity and fluctuating attributes of food items, it is essential to build diverse robotic end-effectors. The deficiency of efficient robotic end-effectors is seen as a primary obstacle to the swift integration of robotics into the food sector (Chua et al, 2003). In recent years, robotics technology has profoundly altered several areas of the food business, encompassing meat, dairy products, seafood, beverage, and packaging (Demir and Dincer, 2020) (Fig. 2). The growing prevalence of wireless communication systems has led to increased adoption of Sensor network systems within the food industry, offering benefits across various aspects. One of the most formidable challenges in the food industry is ensuring food safety by preventing contamination throughout the entire food supply chain (Gungor et al, 2010). To address this, intelligent sensor networks are widely employed to facilitate traceability. Nearly all sectors of the food industry have begun utilizing PDAs (Personal Digital Assistants) and other variable mobile devices to enhance traceability and logistics (Wadalkar et al, 2019).

As our society ages and faces labor shortages, the food industry is experiencing a surge in robotic technology adoption. Robots are increasingly taking on routine tasks that were traditionally performed by human workers. This trend opens up a plethora of opportunities for researchers and businesses across various domains, including robotic manipulators, end-effectors, computer science, artificial intelligence, and system integration (Bader and Rahimifard, 2020). Despite these advancements, several research gaps remain unaddressed, including the need for more flexible and adaptable robotic systems capable of handling diverse food products, the integration of advanced sensors for real-time monitoring, and the development of AI-driven systems for decision-making in complex environments. This paper aims to explore the necessity of automation in the food industry by identifying key areas where automation tools such as robotics, online sensors, and machine vision technologies are being employed. Furthermore, it highlights the current research gaps in these domains and outlines objectives to address these challenges. This paper aims to bridge the gap between existing technological advances and practical implementation challenges in the food industry. To achieve this, the review is structured to (i) assess the state-of-the-art in robotic technologies in food processing and packaging, (ii) identify current limitations and potential solutions, and (iii) examine the broader impacts of automation on productivity, food safety, and labour efficiency.

2. Methodology

This review was conducted using a structured and thematic approach to comprehensively capture the current state and future prospects of robotics, artificial intelligence (AI), and automation across various segments of the food industry. Given the interdisciplinary nature of the topic, which spans engineering, food science, AI, and industrial applications, a narrative thematic review was deemed most appropriate. This approach allows for an in-depth discussion of sector-specific applications and cross-cutting technologies while enabling the synthesis of emerging trends that may not be captured through quantitative meta-

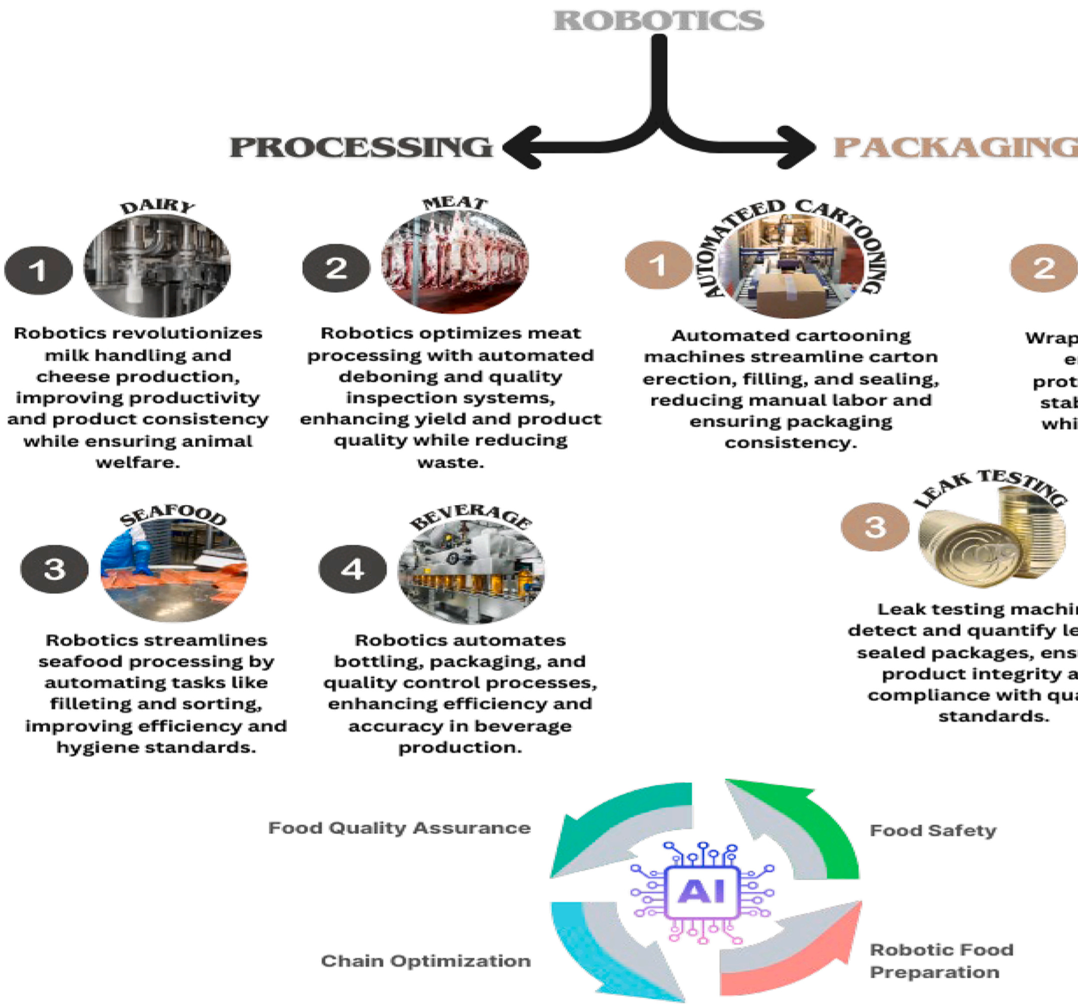

Fig. 2. Sector-wise applications of robotics and artificial intelligence (AI) in the processing and packaging segments of the food industry. This illustration categorizes key roles played by automation and AI in various food domains such as dairy, meat, seafood, bakery, and beverages. In processing, robotics enhances precision, speed, and hygiene by streamlining repetitive tasks such as cutting, sorting, and quality inspection, thereby ensuring food safety and consistency. In packaging, intelligent systems assist with wrapping, sealing, labeling, leak detection, and contamination control, significantly reducing material waste and increasing operational throughput. At the center, AI's integration supports overarching functions such as food safety monitoring, quality assurance, robotic food preparation, and supply chain optimization. By harnessing data-driven technologies and predictive analytics, robotics and AI collectively enable personalized, scalable, and resilient food production and distribution systems tailored to meet modern market demands.

analysis.

2.1. Data sources and search strategy

A comprehensive literature search was conducted across major academic databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. To ensure relevance and breadth, the following search terms were used in various combinations:

- Robotics in the food industry
- Artificial intelligence in food processing
- Automation in the dairy/meat/seafood/beverage/packaging sectors
- Collaborative robots (co-bots) in food manufacturing
- Smart sensors in food systems
- AI and food safety
- Food industry 4.0
- Machine learning in food production

2.2. Inclusion and exclusion criteria

To maintain the quality and relevance of the review, the following criteria were used:

- Inclusion Criteria:
  - Studies reporting real-world applications of robotics or AI in food production and processing.
  - Research focusing on system integration, safety, or performance evaluation of robotic technologies in food environments.
  - Reviews, technical papers, and case studies from recognized journals or conferences.
- Exclusion Criteria:
  - Articles with only theoretical modeling or without practical food industry relevance.
  - Non-English publications or those without accessible full texts.
  - Duplicated entries and outdated technologies superseded by newer systems.

2.3. Screening and data extraction

All identified studies were initially screened based on title and abstract. Full texts were then reviewed for those meeting the inclusion criteria. Key data were extracted and organized thematically under sectors such as dairy, meat, seafood, beverages, packaging, and quality/safety systems. Information was compiled on:

- Type of robotic or AI system used
- Function or application area
- Performance outcomes
- Challenges and limitations
- Future research or implementation potential

Thematic analysis was used to identify cross-sectoral patterns, technological enablers, and bottlenecks.

2.4. Justification for review approach

A narrative thematic review was selected over other methodologies (e.g., systematic reviews, meta-analyses, or bibliometric studies) because:

- The topic covers a rapidly evolving and technologically heterogeneous field where quantitative comparisons are often not feasible.
- Many valuable insights are available in industry white papers, case reports, and technical communications that fall outside the scope of strict systematic reviews.
- The goal of this paper is not only to summarize past findings but also to identify emerging trends, practical challenges, and future directions, which are better served by a thematic synthesis.

This methodology provides the flexibility to integrate scientific literature with practical industrial applications while preserving academic rigor and comprehensive coverage.

3. Utilization of robotics in different food industries

3.1. Food industry

3.1.1. Dairy industry

The upkeep of dairy farms depended only on proficient labour to execute various activities, such as milking, feeding, and visually recognising oestrus detection, among others. DeLaval, a Swedish dairy equipment firm, has launched the first commercial robotic milking rotary system at a test farm in Quamby Brook, Tasmania, Australia. This innovative setup consists of five robots and is capable of milking as many as 90 cows in a single hour (Prasad, 2017). Automatic milking systems can perform milking three times a day and, in addition, can lead to an approximate 12% increase in milk production (Brady, 2017) (Fig. 3) (Table 2).

The introduction of an automation system to handle these operations reduces manual labor costs and helps in preventing the loss of dairy cattle (Sarangi et al, 2016). The production of food products encompasses a range of operations, each varying depending on the specific product. To ensure the production of high-quality goods, it is essential to have a control system in place for all these operational parameters. Automation is considered a versatile tool in dairy plants, offering solutions to various critical challenges (Grimsen et al, 1987). Automation incorporates multiple skills to efficiently carry out planned processing steps. In contrast to the wider food business, the dairy sector has profited from automation technology, which can manage large volumes of raw milk without constraints imposed by biological differences in size, shape, or uniformity of the raw materials (Judal and Bhadania, 2015).

Numerous food and dairy companies have achieved significant advantages through the successful implementation of industrial robots for tasks like palletizing, inspection, and quality assurance. Vision-assisted robots, in particular, can recognize product arrays or stacks as part of standard operations, allowing them to efficiently place finished goods or products into packaging materials, facilitating the feed into a flow wrapper (Prasad, 2017). The IC AD5933 has been instrumental in the development of an electronic impedance system, offering high-precision

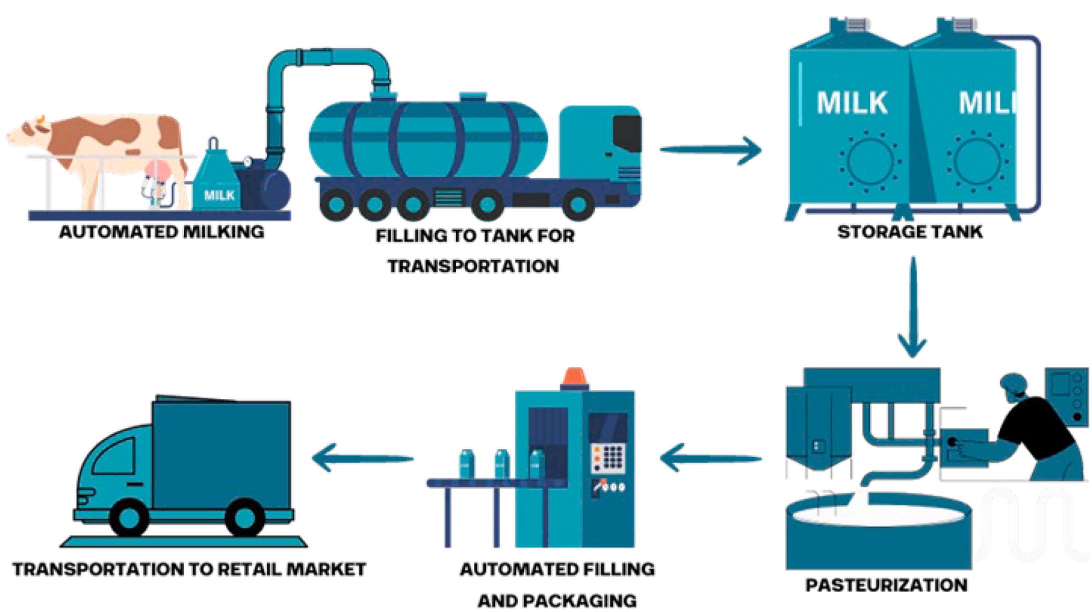

Fig. 3. Automation across various stages of the dairy value chain. This illustration highlights the integration of automated technologies throughout the milk production and distribution process—from initial milking to final retail delivery. It begins with automated milking systems, which enhance efficiency and animal welfare by enabling precision milking and real-time monitoring. The milk is then transferred to transportation tanks using automated filling systems, followed by storage in temperature-controlled tanks to ensure safety and quality preservation. Subsequent stages involve pasteurization, automated filling and packaging, and logistics systems that streamline distribution to retail markets. The use of robotic and AI-enabled systems improves process accuracy, enhances hygiene standards, reduces reliance on manual labour, ensures traceability, and maintains consistent product quality across the dairy supply chain. These smart technologies play a crucial role in modernizing dairy operations, meeting consumer demands, and ensuring compliance with food safety regulations.

Table 2
Commercialized robots' usage in different dairy sectors and their impact on different asepcts in Mankind.

Robot's Name	Sector	Use	Impact	Company
BouMatic Milking Robot	Milking	Automated milking of cows	Increase efficiency, reduce labour	BouMatic (Madison, Wisconsin), USA
DeLaval VMS (Voluntary Milking System)	Milking	Automated milking of cows	Improve milk quality, labor savings	DeLaval (Tumba), Sweden
DeLaval AMR (Automatic Milking Rotary)	Feeding	Automated feeding of cows	Precision nutrition, labor efficiency	DeLaval (Tumba), Sweden
DeLaval Optimat	Cleaning	Barn cleaning and maintenance	Enhance barn cleanliness, labor savings	DeLaval (Tumba), Sweden
Fanuc M-20iD/25	Feeding	Feeding and management of cattle	Consistent feeding, reduced waste	Fanuc Corporation (Oshino, Yamanashi), Japan
Fullwood Merlin	Milking	Automated milking of cows	Increase productivity, data insights	Fullwood (Ellesmere), United Kingdom
Lely Astronaut	Milking	Automated milking of cows	Augment milk yield, labor savings	Lely, Netherlands
Lely Juno	Feeding	Automatic feed pushing for cows	Upgrade feed distribution, labor savings	Lely, Netherlands
Lely Luna	Cleaning	Robotic barn cleaning	Improve hygiene, reduce labour	Lely, Netherlands
SCR Allflex SenseTime	Health Monitoring	Cow health monitoring	Early disease detection, improve animal welfare	SCR Allflex (St. Neots), United Kingdom

impedance conversion capabilities along with advanced control systems. This portable sensor-type analyzer holds a distinct advantage over chemical laboratory methods, as it enables real-time milk testing and enhances the accuracy of milk analysis, addressing the challenges associated with traditional methods (Ruiz-Garcia et al, 2009).

Supervisory Control and Data Acquisition (SCADA), a system that has developed over several decades, is currently widely deployed in the dairy products and other food sectors to monitor complex processes, especially in the dairy industry with its high productivity requirements (Sverko et al, 2022). These processes are monitored by a master terminal unit (MTU), sometimes known as a remote terminal unit (RTU). Despite facing multiple hurdles, many food companies have adopted the SCADA system to guarantee excellent manufacturing (Holmes et al, 2013). The SCADA system involves data collection, transfer to a central hub, execution of critical analytical and control operations, and the eventual presentation of this data on various operators' screens or displays. Subsequent to the analysis, requisite control measures are relayed to the procedure (Boyer, 2004). SCADA systems need the implementation of sophisticated automation frameworks that provide the ability to retrieve manufacturing data and dispersed variables over extensive distances and from several tiers of automated manufacturing (which incorporates field, control, and supervisory levels) (Adamo et al, 2007).

The automation of the technical process for generating liquid starter cultures (LSC) and microbial concentrates is essential in dairy production (Bintsis and Athanasoulas, 2015). The manufacture of LSC and microbial concentrates comprises a continuous cultivation procedure. This procedure involves introducing milk or whey, supplemented with bacterial concentrates, into a cultivator for microorganism proliferation (Gonzalez-Gonzalez et al, 2022). The fermented product exiting the cultivator possesses distinct features, including microbe quantity, metabolic by-products, and numerous physicochemical parameters like as pH and temperature. The ambient temperature of the culture fluid serves as a control parameter, allowing for pH stabilisation during continuous cultivation by modulating the movement rate of fresh or fermented milk. These concepts establish the basis for creating automation strategies to enhance and regulate the manufacturing process effectively (Kozub et al, 2020).

Robots play an important role in various aspects of cheese production, including packaging, slicing, and curd handling. Within cheese production, robots perform tasks such as stirring curds, transferring cheese moulds, turning, cutting, portioning, packaging, and palletizing cheeses. They make use of integrated sensors and measurement systems, making it straightforward to execute intricate processes. Upon arrival of cheese blocks on wooden planks to the robot's specified location, a specialised gripper is utilised to lift the cheese blocks and transfer them onto a conveyor for further processing (Kempthorne, 1995). One of the latest innovations in the dairy industry involving robotics is the process of cheese portion multiplexing. With this technology, a robot can create as many as 12,000 portions per hour. Notably, these robotic operations are found to be more hygienic when compared to manual processes, and they exhibit high levels of productivity. Moreover, the investment in this robotic system typically yields a return on investment in less than six months (Suganya et al, 2011).

Soft serve ice cream, a variety of ice cream that is served directly from the freezer without undergoing hardening, was traditionally dispensed manually. However, the advent of robotic technology has revolutionized the dispensing process, leading to substantial material savings and cost efficiency. In the highly competitive food industry, where product attributes such as size, shape, and consistency are closely scrutinized by consumers, robots have found significant application primarily at the end of the processing line, particularly in tasks like packaging and palletizing (Iqbal et al, 2017). The portion of the ice cream is determined by the ice cream flow rate instead of being predicted by measurable variables (Friedrich and Lim, 2001). Palletising robots are placed in the freezer to prevent frosty condensation from forming on ice cream packets (Prasad, 2017).

3.1.2. Meat industry

Historically, the automation of meat processing facilities has posed significant obstacles due to the substantial upfront investments required and the variability in carcass sizes, which presents difficulties in ensuring consistent cutting processes with robotic systems (Duong et al, 2020). However, with the emergence of the COVID-19 pandemic, several meat processing facilities were forced to suspend operations temporarily owing to security considerations for their employees. Interestingly, this crisis also accelerated their intentions to implement factory automation (Weersink et al, 2021). The manual tasks of cutting, deboning, and shredding meats like beef, lamb, pork, and poultry, once heavily reliant on the manual dexterity of human workers, have now transitioned to being executed by robotic systems and automation. This transition has produced significant benefits for manufacturers, such as decreased cycle times and increased production efficiency. As a result, meat products may be dispatched to clients more rapidly, reducing spoilage and prolonging product shelf life. The reduction of human participation in these processes has resulted in fewer staff injuries and a lowered danger of product contamination (Echegaray et al, 2022) (Table 3).

The conventional automated slaughter line can handle over 1000 pigs per hour, achieving a productivity rate about tenfold that of the average production reported in Norwegian slaughter plants (Alvseike et al, 2018). A major concern with conventional abattoir operations is the perilous working conditions for staff. This environment often includes conditions characterized by cold temperatures, moisture, slippery surfaces, and high levels of noise. Coupled with the frequent use of sharp

Table 3
Commercialized robots' usage in different meat sectors and their impact on different aspects in Mankind.

Robot's Name	Sector	Use	Impact	Company
ABB FlexPicker	Packaging	Robotic Pick and Place	Increase packaging speed and precision	ABB (Zurich), Switzerland
Fanuc M-710iC/70T	Processing	Meat Handling and Sorting	Enhance production line efficiency	Fanuc (Oshino, Yamanashi), Japan
JBT CoreGard™	Packaging	Automated Tray Handling	Augment productivity and safety	JBT Corporation (Chicago, Illinois), USA
Marel AMF-BX	Processing	Automated Deboning and Filleting	Improve yield and efficiency	Marel (Garda Baer), Iceland
Scott X-Ray Robot	Inspection	X-Ray Inspection	Upsurge quality control	Scott Technology (Dunedin), New Zealand
Yaskawa Motoman	Processing	Meat Cutting and Slicing	Precision cuts and labor savings	Yaskawa (Kitakyushu, Fukuoka), Japan

tools such as knives and saws, as well as the repetitive, high-speed nature of operations, these conditions contributed to a substantial number of injuries and illnesses among workers (Ursachi et al, 2021) (Fig. 4).

Evisceration, the removal of organs from a slain animal's body cavity, presents a contamination risk due to the delicate nature of the visceral layer encasing the carcass. Recent improvements have facilitated the automated execution of the evisceration process, particularly for chicken (Chen and Yu, 2022), although total automation for pork and beef evisceration is still unachieved (de Medeiros et al, 2021). Recent advancements include semi-automated robots engineered for activities such as rectum excision, H-bone cutting, leaf fat extraction, and carcass division (Khodabandehloo, 2022). The robotic systems engineered for evisceration generally have three primary components: a measuring location and an operating unit (Purnell and Loeffen, 2006). In a combined process line, the system must initially detect and monitor the carcass while meticulously regulating the incision trajectory via sensors. Thereafter, the end-effector, such as the cutting edge of the processing unit, must manoeuvre with accuracy to arrive at the initial position and thereafter execute the incision. The robot must possess extensive mobility and a versatile trajectory for the evisceration of beef, hog, and sheep carcasses, especially during the extraction of the intestines (Ming ET AL. 2019).

3.1.3. *Seafood industry*

In recent decades, automation has gained significant traction in food production due to limited access to manual labor. Among the protein industry sectors, fish production, along with poultry, stands out as one of the most technologically advanced and automated. (Komlatsky et al, 2019). In the realm of seafood harvesting, autonomous underwater vehicles (AUVs) have developed as powerful implements for assessing and tracking fish populations, addressing issues of overfishing, and protecting endangered species (Aguzzi et al, 2022). Concurrently, robotic

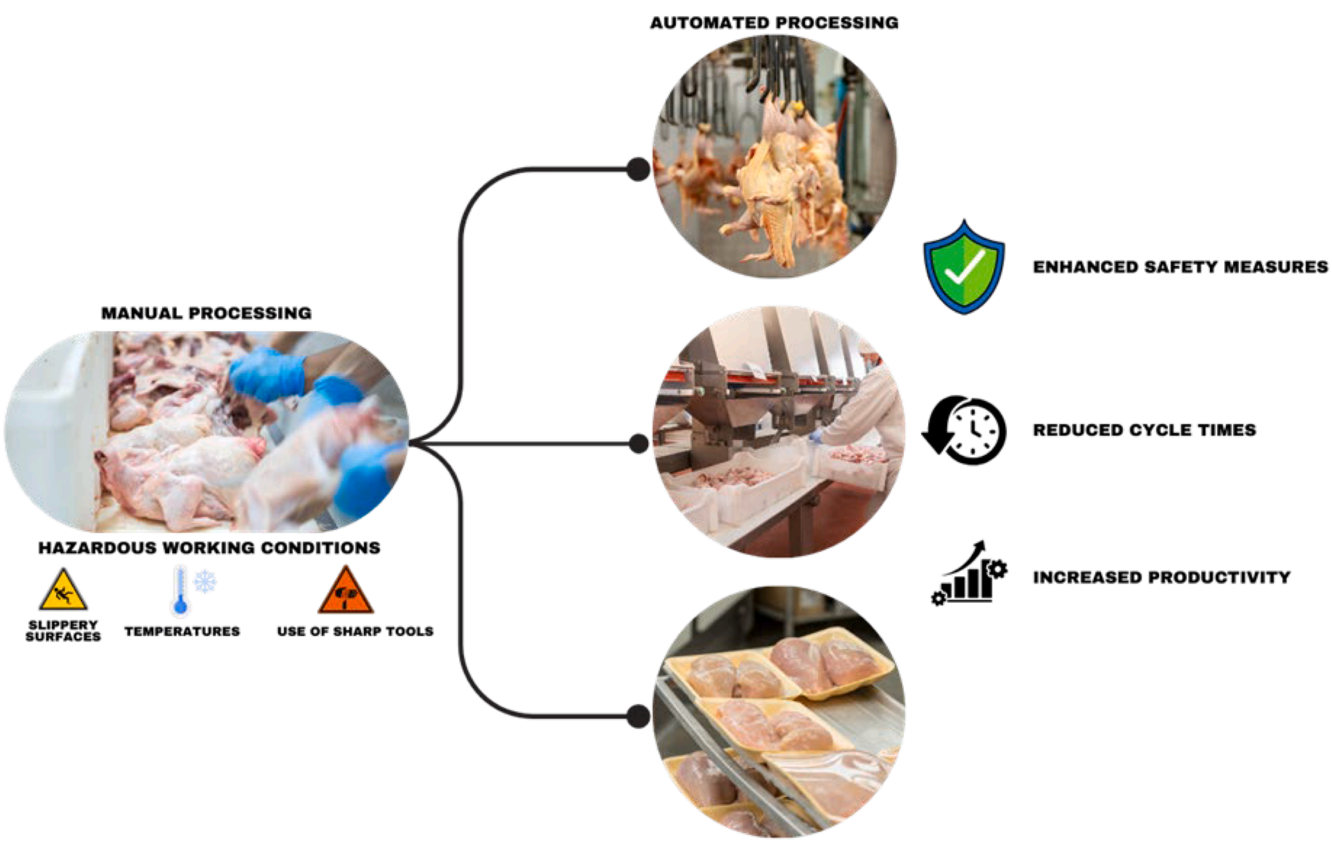

Fig. 4. Comparison of manual versus automated meat processing: safety, efficiency, and productivity implications. This figure presents a visual contrast between traditional manual meat processing and modern automated systems, emphasizing key differences in operational safety, hygiene standards, efficiency, and labour requirements. Manual processing is often associated with hazardous working conditions, including exposure to sharp tools, biohazardous materials, fluctuating temperatures, and surface contamination risks, posing health and safety challenges to workers. In contrast, automated meat processing incorporates advanced robotics, vision systems, and intelligent controls to ensure enhanced safety, reduced cycle times, and higher throughput. Automation minimizes human contact, thereby reducing the risk of cross-contamination and improving overall sanitation. Additionally, automated systems support consistent portioning, faster line speeds, and better traceability, while reducing the dependency on physical labor. This comparative overview highlights how the transition to automation improves both food quality and worker well-being in the meat industry through smart engineering solutions.

fish and drones have revolutionized precision fishing and underwater inspections. Despite the promise of these advancements, challenges such as initial investment costs and regulatory complexities remain focal points (Wang et al, 2021). The integration of computer vision and machine learning technologies in quality assessment is becoming increasingly prevalent. These advancements have aided in identifying defects, monitoring product quality, and reducing reliance on manual inspection (Kaur et al, 2023). Moreover, robotics equipped with sensors play a pivotal role in detecting contaminants and pathogens, ensuring the safety of seafood. Advanced systems even assist in flavor profiling and maintaining product consistency (Djekic et al, 2023) (Fig. 5) (Table 4).

The cold chain is essential in seafood preservation, and robotics shows a vital role in its management. These systems monitor and regulate temperature and humidity, decreasing the risk of spoilage and ensuring seafood reaches consumers in optimal condition. As a result, food waste in the seafood supply chain is significantly reduced (Hassoun et al, 2022). Robotic filleting systems are at the forefront of automating the often delicate and precise task of filleting fish. These systems are prepared with cutting-edge sensors, vision systems, and end-effectors capable of identifying the fish's anatomy and executing precise cuts. The benefits are manifold, including increased efficiency, consistent fillet quality, and a significant reduction in labor costs (Mubango et al, 2023). Scaling and gutting fish is another labour-intensive process that has been streamlined with the introduction of robotics. Robots equipped with specialized tools can accurately remove scales and entrails, reduce the risk of contamination and improve hygiene standards. These automated systems are proficient of handling a huge diversity of fish species, adapting to their shape dimensions (Einarsdottir et al, 2022). In the quest for sustainability, robotics is being employed to reduce bycatch and minimize environmental damage. They enable more selective harvesting and environmentally sustainable fish farming in aquaculture (Cooke et al, 2021).

3.1.4. Beverage industry

The beverage industry, characterized by its dynamic nature and consumer-driven trends, continually seeks innovative solutions to enhance production efficiency, maintain product quality, and streamline supply chain operations (Hutt and Speh, 2021). Robotics has emerged as a transformative force within this sector, offering advanced automation capabilities that revolutionize traditional manufacturing processes and logistics (Javaid et al, 2021). Robotic systems have been extensively integrated into beverage manufacturing processes, optimizing efficiency and precision across diverse tasks such as bottle handling, filling, capping, labeling, and packaging. Automated production lines equipped with robotic arms enable high-speed, consistent operations while maintaining stringent quality standards (Otles and Sakalli, 2019) (Fig. 6). Robotics plays a pivotal role in quality control and inspection processes, ensuring product integrity through efficient defect detection and contaminant identification (Chen and Yu, 2022). In warehousing and logistics, robots optimize material handling, inventory management, and order fulfillment, facilitating faster and more accurate distribution (Custodio and Machado, 2020). Additionally, robotics contributes to workplace safety by automating hazardous tasks and implementing predictive maintenance strategies to prevent equipment failures (Javaid et al, 2021) (Table 5).

Notwithstanding the many advantages, the use of robots in the beverage sector entails problems including early capital expenditures, integration difficulties, and workforce training necessities (Duong et al, 2020). Addressing these challenges necessitates cooperation among stakeholders to design scalable and economical solutions. The foreseeable future of robotics in the beverage sector is characterised by developments in cooperative robotics, AI, and autonomous systems (Grau et al, 2020).

2.2. Food packaging

Packaging, as defined by experts in the field, denotes to the

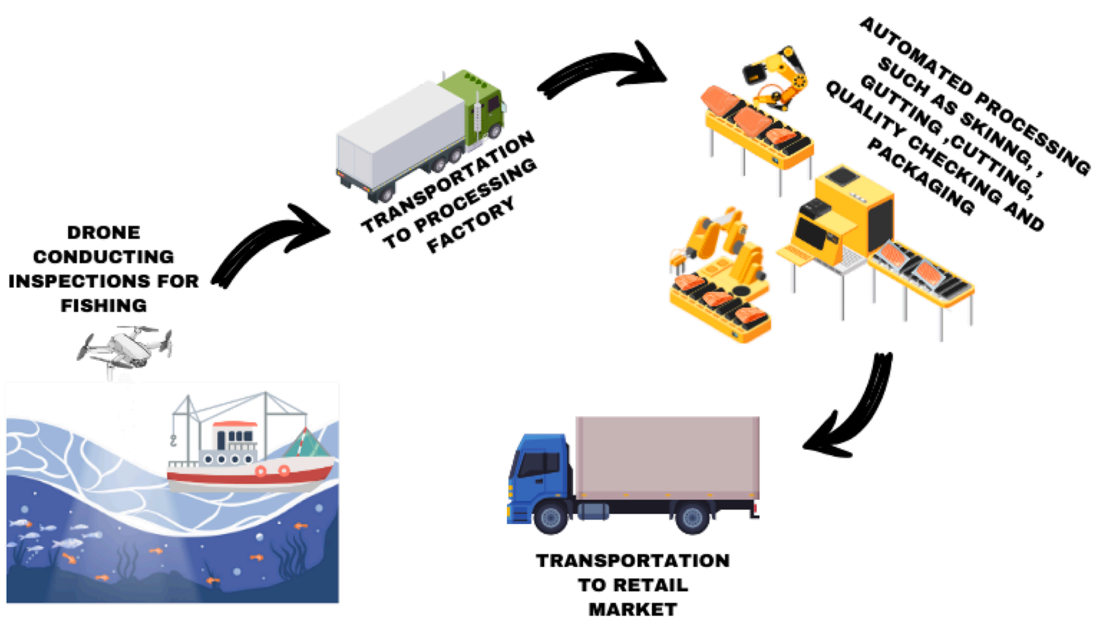

Fig. 5. Automation in seafood processing and inspection: enhancing precision, hygiene, and traceability. This figure illustrates the application of advanced automation technologies across various stages of the seafood supply chain, starting from drone-assisted fishing surveillance and continuing through transportation, processing, packaging, and distribution. The use of drones and remote sensing technologies allows for real-time monitoring of fishing activities, helping ensure sustainability and traceability at sea. Post-harvest, seafood is transported to processing plants where automated systems handle sorting, filleting, portioning, cleaning, and packaging using robotics, machine vision, and AI-driven inspection tools. These innovations enhance food safety compliance, reduce microbial risks, and ensure product uniformity. Finally, the products are distributed to retail markets using optimized logistics networks. By reducing manual intervention, these technologies minimize labor-intensive tasks, reduce contamination risks, and improve operational efficiency—ultimately leading to higher throughput, better product quality, and lower overall waste within the seafood industry.

Table 4
Commercialized robots' usage in different seafood industry and their impact on different aspects in Mankind.

Robot's Name	Sector	Use	Impact	Company
Aquabot	Aquaculture	Automated fish feeding	Increase efficiency and reduce waste in fish farming	Aqua Robotics In corporation (San Diego) California, USA
LobsterBot	Lobster Fishing	Lobster harvesting	Increase lobster yield and reduce the need for manual labour	Canadian Centre for Fisheries Innovation (CCFI) (Newfoundland and Labrador), Canada
CrabMaster	Seafood Processing	Crab meat extraction	Speeds up crab meat extraction and minimizes manual labour	Dungeness Development Company (Washington State), USA
RoboFish	Fisheries	Fish sorting and quality control	Improve the accuracy of fish sorting and grading	Marel (Reykjavik), Iceland
SeaScanner	Inspection	Seafood quality inspection	Enhance quality control and minimize the risk of contaminants in seafood	OptoSort, Germany
ScallopScanner	Aquaculture	Scallop grading and quality control	Augment accuracy of scallop grading and improves product quality	ScanTech Sciences (Georgia), USA
SushiBot	Foodservice	Sushi rolling and assembly	Automates sushi preparation, leading to consistency and faster service	Suzumo Machinery Co, Ltd. (Tokyo), Japan
OctoPicker	Processing	Octopus handling and processing	Speeds up the processing of octopus and minimizes labor-intensive work	Universal Robots (Odense), Denmark

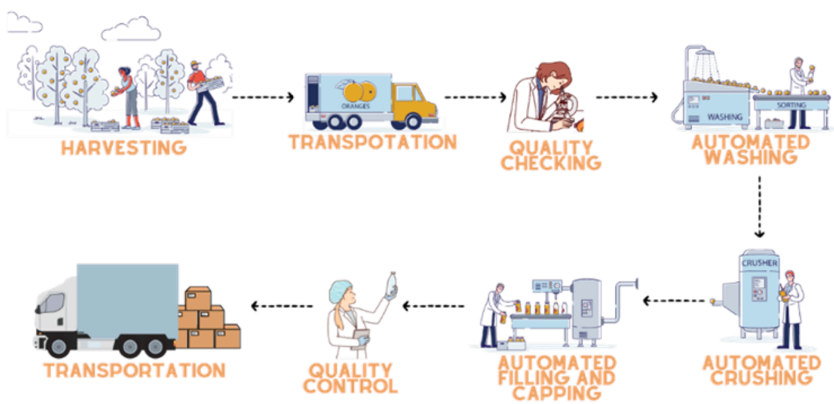

Fig. 6. Integration of automated systems in the beverage sector: enhancing efficiency, hygiene, and production consistency. This illustration outlines the application of automation across various stages of beverage manufacturing—from harvesting and transportation of raw materials to quality inspection, washing, crushing, filling, capping, labelling, packaging, and final distribution. Each step employs specialized robotics and programmable logic controllers (PLCs) to reduce manual handling, ensuring minimal contamination and uniform output. Automated washing ensures sanitation of containers, while automated crushing, filling, and capping improve speed and precision in processing liquid beverages. Labelling and quality control systems verify compliance with food safety standards and branding accuracy. The deployment of such technologies not only reduces dependency on human labour but also enables real-time monitoring, traceability, and error minimization. Ultimately, automation helps maintain product quality, enhances regulatory compliance, and scales up production capacity to meet growing consumer demand in the beverage industry.

Table 5
Commercialized robots usage in different beverage industry and their impact on different aspects in Mankind industry.

Robot's Name	Sector	Use	Impact	Company
ABB IRB 4600	Manufacturing	Case packing and palletizing	Increases productivity and accuracy	ABB Robotics (Zurich), Switzerland
Aethos DrinkBot	Service	Bartending and drink preparation	Improves customer experience	Aethos Technologies (Pittsburgh) Pennsylvania, USA
Briggo Coffee Haus	Service	Automated coffee kiosk	24/7 availability and consistency	Briggo (Austin) Texas, USA
Clearpath Robotics Grizzly	Material Handling	Material transport	Increases efficiency and safety	Clearpath Robotics (Waterloo, Ontario), Canada
Fanuc M-710iC/70	Manufacturing	Automated palletizing	Improve precision and speed	FANUC Corporation (Yamanashi), Japan
Kuka KR AGILUS	Manufacturing	Bottling and packaging	Increase production efficiency	KUKA Robotics (Augsburg), Germany
Makr Shakr	Service	Cocktail mixing and bartending	Novel customer engagement	Makr Shakr (Milan), Italy
Soft Robotics mGrip	Picking and Packing	Picking and handling of soft objects	Reduce damage and product waste	Soft Robotics (Bedford) Massachusetts, USA
Universal Robots UR10	Manufacturing	Conveyor handling and quality control	Enhance flexibility and safety	Universal Robots (Odense), Denmark

equipment and materials used for encompassing or safeguarding foodstuffs to ensure their safe distribution, storage, sale, and use (Amewu and Amuzu, 2019). The primary objective of food packaging is multifaceted. Firstly, it serves as a protective barrier, shielding food products from external contaminants and safeguarding them against physical damage. Simultaneously, food packaging offers invaluable information to consumers, presenting details about ingredients and nutritional content (Coles et al, 2003). The paramount role of food packaging includes the preservation of the product's quality, extending its shelf life, and ensuring its safety. This is achieved by safeguarding the packaged food against various environmental factors, encompassing heat, light, moisture, oxygen, pressure, unwanted odors, microbial threats, insects, and foreign particles such as dirt and dust. Furthermore, packaging also acts as a shield against gaseous emissions that could compromise the product's integrity (Jiang et al, 2023) (Fig. 7). Beyond these primary functions, modern packaging has evolved to encompass secondary functions that are of growing importance in the industry. These include traceability, which allows for the tracking of a product's journey through the supply chain, tamper indication to ensure the safety and authenticity of the product, and portion control, which aids consumers in managing their consumption more effectively (Marsh and Bugusu, 2007).

In the assessment of the Food Processing and Packaging Machinery Industry, current innovations in food packaging transcend basic enhancements in efficiency and increasingly include advanced robotics, control, and monitoring methodologies. Computer vision systems can not only substitute inspections by hands but also augment their functionalities. Computer vision systems are effective instruments for automating the examination of fruits and vegetables (Mahalik, 2014). Current trends in beverage packaging focus on altering the structural properties of packaging supplies and creating innovative proactive and smart systems. These systems can engage both the product or its surroundings, so improving the preservation of liquids such as wine, juice, or beer. Additionally, they enhance customer acceptance and strengthen food security initiatives (Ramos et al, 2015). In contemporary packaging operations, electronic instrumentation and computerised controls are essential for performing numerous operational, quality, and safety evaluations at several stages of the packaging line. Modern instrumentation has reached a level of speed and precision that enables the inspection of each package as it moves down the line, even when the line is operating at high speeds. Packages that fail any of these tests are automatically removed from the line, resulting in a more meticulous and dependable inspection process that requires minimal manual intervention (Srivastava et al, 2018).

The data collected from these sensors can be seamlessly integrated into statistical process control (SPC) charts, facilitating the determination of whether the system is operating within established parameters. Moreover, this information may be utilised within a MIS (management information system) for thorough examination. Sensor data can be directed into programmed logic controllers (PLCs), enabling real-time decision-making and the issuance of instructions to modify the operations of packing machines. Significantly, sensors like metal detectors are now available for assessments that were before unfeasible for human operators to do (Kanimozhi et al, 2015).

Rising labour costs and escalating health and safety concerns have facilitated the incorporation of robotics and automation in the processing of food and packaging. The necessity to automate processes in these areas is supported by numerous essential conditions, crucial for achieving competitive advantage and, in certain sectors, the viability of production facilities (Sani and Aziz, 2013). The implementation of sophisticated equipment, robotics, and automation technologies has significantly decreased the total expense of processed food relative to the expenses of raw food items (Mahalik, 2014). An automated system integrates many machine types into a cohesive packing line. These machine types include a diverse range of functions, such as cartooning, wrapping, labelling, shrink-wrapping, sealing, tray forming, capping, drying, cooling, feeding, palletising, depalletizing, robotic pickers and

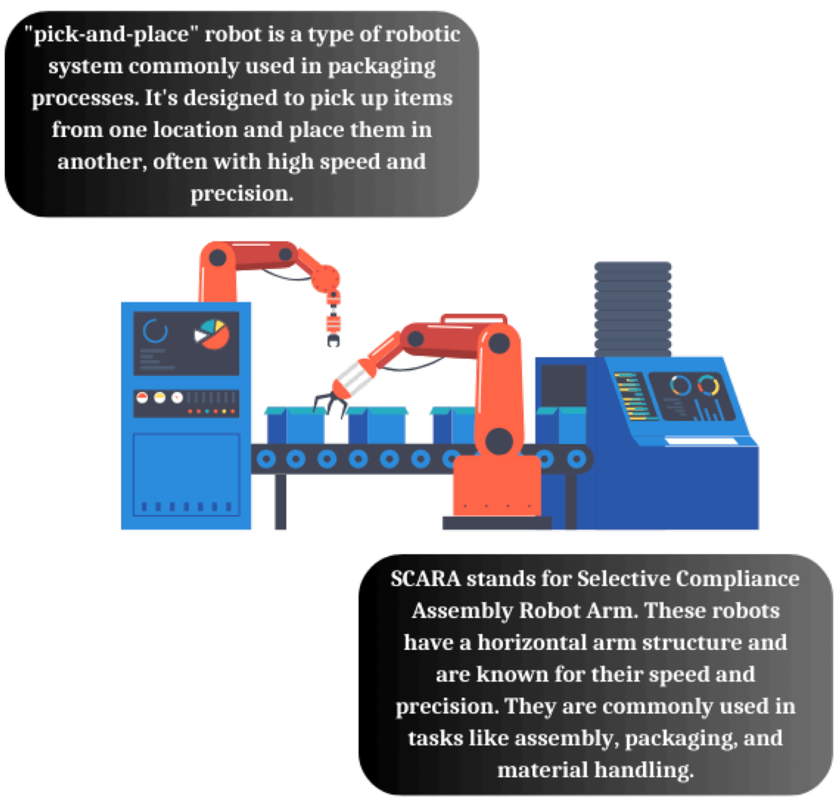

Fig. 7. Integration of Pick-and-Place and SCARA (Selective Compliance Articulated Robot Arm) systems in food industry automation. This figure highlights the deployment of two widely used robotic technologies—pick-and-place robots and SCARA arms—in packaging and material handling operations within modern food processing environments. Pick-and-place robots are designed for rapid, precise movement of items from one point to another, making them ideal for handling lightweight, uniform food items or packages. SCARA robots, with their horizontal articulated arm structure, offer high-speed, repeatable motion and are commonly utilized in tasks requiring lateral movement such as sorting, assembling, packaging, and transferring products along conveyor systems. These systems are particularly advantageous in high-throughput production lines where accuracy, speed, and hygienic handling are critical. Their integration not only reduces reliance on manual labor but also enhances operational efficiency, improves food safety, and ensures consistent product quality through uniform motion control and reduced contamination risk.

placers, cleaning, sterilising, and inspection and detection equipment. (Mahalik and Nambiar, 2010) (Table 6).

3.2.1. Automatic cartooning machine

Cartooning machines are frequently used in the food and beverage products sector for various packaging purposes. A carton is an advanced packaging machinery system engineered to execute a series of operations. which include the assembly of individual products, the creation of a fibreboard carton, the collation of products, their placement into the carton, and ultimately sealing the carton's flaps, achieved through folding, locking, taping, or gluing (Ghaani et al, 2016). This versatile machinery is well-suited for various food products and is adaptable to different packaging formats, including blisters, tubes, bottles, and square boxes. It boasts configurability to accommodate different box sizes and may exhibit multiple functions within a vertical-type configuration. Notably, it can swiftly change moulds when needed (Krochta, 2018). Moreover, cartooning machines can also be configured as intermittent horizontal cartoners, offering automatic carton opening and folding capabilities. These machines are characterized by their ability to receive in-feed products and additional informational leaflets on the cartons (Cheruvu et al, 2008). Pushers are equipped with safety devices for inserting the product; the safety device is controlled by sensors (Kustiyawan et al, 2023).

3.2.2. Wrapping and sealing machines

Presently, state-of-the-art fully automated stretch wrapping equipment offers a host of compelling advantages, emphasizing structural integrity, flexibility, reliability, and performance (Cheruvu et al, 2008). These complex machineries proficiently bundle several bottles and shrink-wrap them with efficiency. They employ solid-state relays to enable immediate switching of heaters, thus ensuring accurate temperature control and consistent shrinking of the plastic wrap. Significantly, solid-state systems enable frequent switching without inducing wear, setting them above physical contactors (Kirwan, 2005). A transparent material sensor is carefully placed at the bottle necks to verify the actual existence of the shrink-wrap. Upon detection of the shrink-wrap, the transparent object sensor produces a continuous output while the package traverses the diffuse reflecting photoelectric sensors. These sensors have a diverse range of applications, including the automation of continuous processes such as thermoforming, filling, and sealing (Anderson et al, 2020). The solutions available encompass a wide spectrum, ranging from basic solid-state switching of heaters to more sophisticated systems that integrate monitoring features. These integrated features are capable of detecting load and system malfunctions, thus ensuring the reliability of the thermal processing (Srivastava et al, 2018).

3.2.3. Leak testing

The prevalence of leaks in packaging is a topic that extends across several package types. It has been observed that flexible packaging is more susceptible to leaks than its stiff, sealed equivalents. Leaks arise from several sources, such as pinholes, fissures, punctures, inadequate seals, and additional manufacturing defects. Any of these imperfections may permit the infiltration of external elements such as moisture, oxygen, or contaminants into either the package or the enclosed product (Guazzo, 2016). In cases where the product relies on a specific level of moisture, the loss of moisture due to leaks can lead to the product drying out, while, conversely, excessive moisture can trigger quality issues. Ultimately, these factors contribute to a deterioration in product quality and a reduction in its shelf life. As a proactive measure to safeguard product quality, manufacturers are increasingly adopting leak testing procedures to prevent the release of packages with leaks into the market (Haider et al, 2024).

These leak testing systems are engineered to meet various container standards, line velocities, handling criteria, and testing sensitivity requirements. They are offered in many configurations, encompassing linear and continuous movement leak testing, suitable for both empty and loaded containers (Srivastava et al, 2018). Changes in the packaging's mechanics can result in the pressurized product becoming unsealed and malfunctioning due to depressurization. This can lead to a decrease in product effectiveness due to contamination from metal ions or valve blockage caused by loose fragments of coating or laminate film (Piotrowski, 2024). The objective of the compatibility test is to assess the possible transfer of substances between the product and its principal packaging. The packaging can substantially affect the stability and safety of the product due to potential physical and chemical interactions involving the product, the packaging, and the surrounding environment (Rojek et al, 2019).

4. Artificial intelligence in the food industry

The use of artificial intelligence (AI) in the food and beverage sector has transformed several facets of the production, processing, distribution, and customer experience. By integrating machine learning, computer vision, and data analytics, AI complements robotic systems and enhances decision-making, adaptability, and efficiency in food-related operations. The specifics have been presented below:

Food Quality Assurance: Artificial intelligence-driven solutions are utilised for automated inspection and quality assurance. Artificial intelligence algorithms can detect faults, classify products, and maintain uniform quality in food items, minimizing waste and improving consumer happiness (Chhetri, 2023). For example, convolutional neural networks (CNNs) can identify surface anomalies on fruits or bakery items and sort them accordingly. This reduces human error, minimizes waste, and increases throughput.

***Food Safety Monitoring*:** AI systems equipped with real-time sensors and predictive analytics monitor critical safety parameters such as temperature, humidity, gas emissions, and microbial contamination. Machine learning models trained on historical food safety data can identify early signs of spoilage or contamination, enabling timely interventions. These systems help meet HACCP and ISO 22000 standards more efficiently (Chhetri, 2023).

Table 6
Commercialized robots' usage in different packaging industry and their impact on different aspects in Mankind.

Robot's Name	Industry Sector	Use	Impact	Company
ABB FlexPicker	Food and Beverage	Pick and place packaging	Increases production efficiency and precision in packaging processes	ABB (Zurich), Switzerland
FANUC M-410iC/185	Food Processing	Palletizing	Reduces labour costs and minimizes product damage during palletization	FANUC Corporation (Yamanashi), Japan
KUKA LBR iiwa	Food Manufacturing	Machine tending	Improves consistency and precision when loading and unloading machines	KUKA AG (Augsburg), Germany
Omron Adept Quattro	Dairy Processing	Carton and case handling	Reduces product damage and downtime in cartooning and case packing	Omron Corporation (Kyoto), Japan
Universal Robots UR10	Food Packaging	Collaborative packaging	Enhances flexibility and safety in packaging lines by working alongside human workers	Universal Robots (Odense), Denmark
Yaskawa Motoman MPL100	Confectionery	Wrapping and labelling	Speeds up the wrapping and labelling process	Yaskawa Electric Corporation (Kitakyushu), Japan

Supply Chain Optimization: Artificial intelligence enhances the chain of logistics through demand forecasting, inventory management, and optimization of transportation routes. In warehouse robotics, AI guides automated picking, packing, and restocking operations. AI-powered robotic arms with 3D vision are used in real-time inventory sorting, improving fulfilment speed and reducing errors (Dash et al, 2019).

Food Safety: AI systems equipped with sensors and machine learning algorithms monitor food safety parameters like temperature, moisture, and contaminants. This ensures compliance with safety standards and minimizes risks. (Chhetri, 2023).

Smart Agriculture: AI and robotics are transforming agriculture through precision farming. Drones, autonomous vehicles, and sensors analyze crop health, optimize resource usage, and increase agricultural productivity (Javaid et al, 2021).

Personalized Nutrition: AI algorithms analyze consumer data to offer personalized nutrition recommendations and develop tailored food products, catering to specific dietary needs or preferences (Boland et al, 2019).

Consumer Insights and Experience: AI-driven analytics capture consumer preferences, behaviours, and trends. This data helps in creating new food products, designing marketing strategies, and improving the overall consumer experience (Yaiprasert and Hidayanto, 2023).

Robotic Food Preparation: Robotics equipped with AI capabilities are used in food preparation, such as chopping, mixing, and cooking. This aids in consistency, efficiency, and precision in food production. For example, AI-integrated robotic chefs use computer vision to monitor food consistency and adjust cooking parameters. Reinforcement learning algorithms allow these robots to improve over time through feedback from sensors (Kondaveeti et al, 2023) (Fig. 8) (Table 7).

Table 7
Application of AI along with its brief description and their impact on different food sectors.

AI Application	Description	Impact	References
Supply Chain Optimization	AI-driven tools for efficient supply chain management	Enhanced logistics, minimized disruptions	Lubag et al. (2023)
Precision Agriculture	Uses AI to optimize crop management and resource allocation	Increased crop yield, reduced resource wastage	Rahman et al. (2023)
Food Quality Control	AI-based systems for assessing and ensuring food quality	Improved food safety, reduced waste	Chen and Yu (2022)
Personalized Nutrition	AI analyses individual health data to suggest personalized diets	Improved health outcomes, reduced disease risk	Oh et al. (2021)
Smart Cooking Appliances	AI-powered kitchen devices for automated cooking processes	Simplified meal preparation, increased convenience	Berezina et al. (2019)

5. Integration of smart sensors and nanotechnology in the food industry

With the rising complexity and safety standards in food production and processing, the integration of smart sensors, quantum dots, and nanomaterial-based sensing platforms has become crucial in the evolution of intelligent food systems. These advanced tools enhance the functionality of robotic and AI-based systems by providing real-time monitoring, contamination detection, and data-driven process control (Table 8).

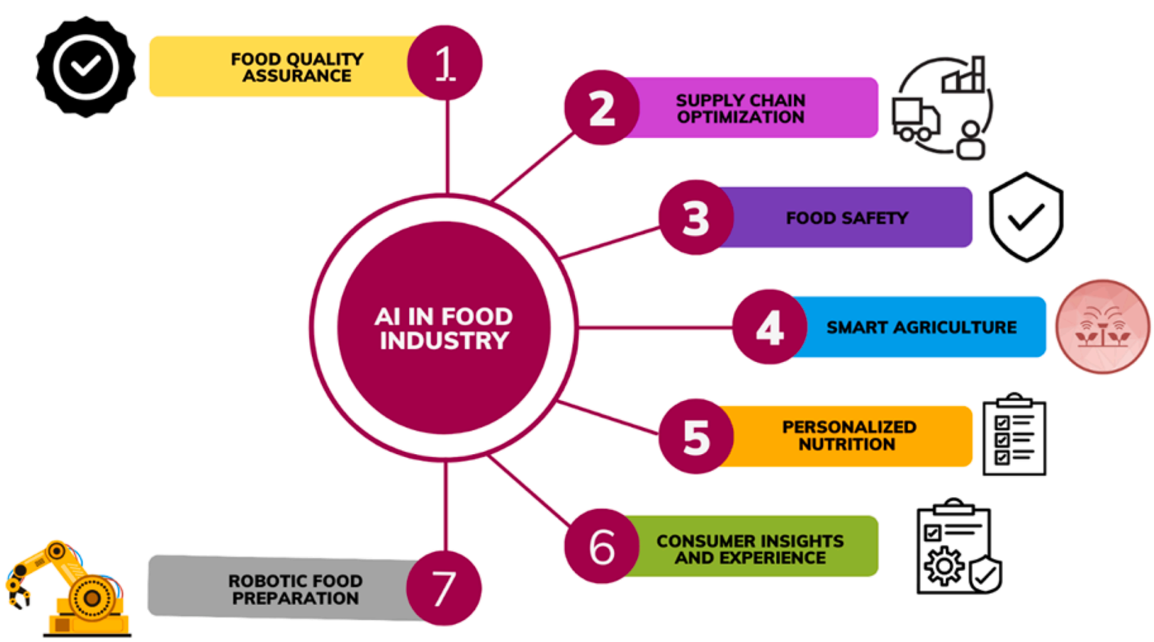

Fig. 8. Artificial Intelligence (AI) applications across the food industry: a sector-wide perspective. This diagram illustrates the diverse implementation of AI technologies throughout key domains of the food industry, including (1) food quality assurance, (2) supply chain optimization, (3) food safety, (4) smart agriculture, (5) personalized nutrition, (6) consumer insights and experience, and (7) robotic food preparation. AI enables real-time decision-making through technologies such as machine vision, predictive analytics, natural language processing, and reinforcement learning. In quality assurance, AI systems detect product inconsistencies, defects, and contaminants using computer vision and sensor fusion. For supply chain optimization, AI algorithms improve logistics, forecast demand, reduce waste, and enhance traceability. Food safety is bolstered through anomaly detection, microbial risk prediction, and compliance monitoring. In agriculture, AI-driven tools optimize resource use, crop yield, and environmental sustainability. Personalized nutrition benefits from AI-enabled analysis of consumer health data, dietary preferences, and metabolic needs. Consumer engagement is enhanced by AI-powered chatbots, taste profiling, and purchasing behaviour analytics. Finally, in robotic food preparation, AI integrates with automation to enable robotic chefs, precision cooking, and adaptive recipe adjustments—redefining traditional food handling processes for improved efficiency, hygiene, and customization.

Table 8
Comparative Overview of Robotics, Sensors, and Automation Technologies Across Food Sectors.

Food Sector	Technology Used	Sensors Employed	Robotic System	Key Functions
Dairy Industry	SCADA systems, electronic impedance analysers	Temperature, pH, flow sensors	Robotic milking arms, co-bots	Milking, quality inspection, cheese portioning
Meat Industry	Machine vision, AI-based deboning algorithms	Force sensors, optical encoders, 3D imaging	Cutting and deboning robots, carcass handlers	Deboning, slicing, evisceration, safety inspection
Seafood Industry	Autonomous Underwater Vehicles (AUVs), vision systems	Vision sensors, laser profiling, ultrasonic sensors	Robotic filleting arms, scaling robots	Sorting, filleting, decontamination, cold chain control
Beverage Industry	Automated bottling/capping lines, predictive analytics	Proximity sensors, flow meters, weight sensors	Robotic arms for filling, labeling	Filling, labeling, packing, stacking
Packaging	SCARA robots, intelligent PLCs, machine vision	Metal detectors, infrared, gas, and leak sensors	Pick-and-place, sealers, leak testing robots	Wrapping, sealing, leak detection, quality inspection
General AI Use	AI-driven analytics, ML-based decision tools	Integrated multi-modal sensors (vision, audio, thermal)	AI-powered collaborative robots (cobots)	Predictive maintenance, adaptive learning, traceability

5.1. Smart sensors for real-time food monitoring

Smart sensors embedded in food packaging or processing lines are designed to detect spoilage, contamination, and environmental changes such as pH, temperature, and gas composition. According to the review by (Yuce and Filippini, 2022), smart packaging sensors are increasingly being developed using fluorescence-based and electrochemical platforms to ensure real-time food safety and quality. These sensors, when connected to AI systems or robotic platforms, facilitate automated alerts and corrective actions, reducing the chances of human error and product recalls.

5.2. Amine-functionalized sulphur quantum dots for antibiotic detection

Recent advancements in quantum dot nanotechnology have enabled the development of sensitive probes for detecting chemical residues in food. One such example is the use of amine-functionalized sulphur quantum dots (NH_2-SQDs) for the detection of tetracycline, a widely used veterinary antibiotic. These SQDs exhibit strong fluorescence properties, high water solubility, and low toxicity, making them ideal for biosensing applications in food samples. They offer rapid and accurate quantification of tetracycline, thus serving as critical components in automated food safety assurance systems.

Significance: NH_2-SQDs can be integrated with AI systems to trigger real-time rejection of contaminated products on production lines using robotic arms or automated conveyors.

5.3. Fluorescent nanocomposites for pesticide detection

Another significant innovation involves the use of Sulfur Quantum Dots embedded in Graphitic Carbon Nitride (S-QDs@g-C_3N_4) nanocomposites for detecting malathion, a commonly used organophosphate pesticide. This fluorescence probe demonstrated exceptional selectivity, sensitivity, and stability in detecting trace levels of malathion even in complex food matrices. The system's high-performance response time makes it a powerful tool for real-time monitoring in AI-driven robotic inspection systems.

Application: This sensing platform can be employed on smart robotic inspection stations to scan for chemical residues before packaging or dispatch.

5.4. Metal–organic frameworks (MOFs) as multifunctional platforms

Metal–Organic Frameworks (MOFs) represent another class of advanced materials used in smart sensing. Their high porosity, tuneable surface area, and chemical versatility allow them to adsorb gases, volatile organic compounds (VOCs), and contaminants, which are key indicators of spoilage or tampering. MOFs have been integrated into sensors for detecting humidity, CO_2, ethylene, and microbial gases. These properties make MOFs highly suitable for AI-integrated packaging systems and environmental monitoring.

Industrial Potential: MOFs embedded in food packaging can be coupled with AI-based IoT systems to monitor freshness and send real-time alerts to supply chain operators.

5.5. Integrating sensing with process engineering

The review on emerging trends in food process engineering by Subramanian et al. (2024) emphasizes the fusion of sensor technology with automation and AI to optimize food processing. These technologies contribute to:

- Consumer-centric design (e.g., personalized nutrition through sensing-based formulation adjustments),
- Sustainability goals (e.g., energy and water efficiency),
- Data-driven quality control (e.g., machine learning models for process feedback from sensor data),
- Zero-defect manufacturing through real-time robotics-based correction mechanisms.

Example: Sensors measuring sugar concentration or pH in liquid foods can guide robotic mixers to adjust recipes dynamically, enhancing product consistency and reducing waste.

5.6. Outlook

These emerging sensor technologies not only reinforce the backbone of food safety and quality but also serve as key enablers for intelligent automation. When integrated with robotic platforms and AI-driven decision-making systems, they provide a closed-loop feedback mechanism that ensures precision, traceability, and compliance in real-time. Future advancements are expected to focus on miniaturization, multi-analyte detection, and wireless communication, making these tools indispensable for smart factories and Industry 4.0 in the food sector.

6. Challenges and safety measures

The integration of robotics into the food sector is challenged by the inherent diversity of raw materials, as standardised measures suitable for programming robots may be absent. Developing an automated system to peel apples presents significant challenges due to the many sizes and forms of apples, complicating the development of a universal algorithm (Chrisandina, 2018). In a dynamic food production setting, robots may unintentionally collide with personnel or other machinery, resulting in injury or damage. The use of technology such as proximity detectors along with secure zones can mitigate fatalities (Robla-Gomez et al, 2017). Another major concern associated with robots is software error. Faulty software or glitches can result in unintended actions by robots, causing injuries or product damage. Rigorous software testing, continuous monitoring, and redundancy in critical operations are crucial (Dhillon, 2012). Automation generates substantial data in the food industry, and a data breach can compromise sensitive information, including recipes, ingredient sources, and customer data. Robust cybersecurity measures should be implemented to protect data integrity (Munirathinam, 2020). Relying on robots makes the production process vulnerable to power outages. Establishing backup power systems, such as uninterruptible power sources (UPS), or contingency planning is crucial for ensuring operational continuity (Kuntke et al, 2022).

Maintaining optimum hygiene standards in food processing facilities is paramount for ensuring food safety and preventing contamination (Bogue, 2009). A critical aspect of hygiene is the choice of materials used in food processing equipment. To ensure safety, equipment must be fabricated of non-toxic, non-corrosive, and readily washable materials such as stainless steel. These materials exhibit corrosion resistance and withstand stringent cleaning protocols without affecting the nutritional value of food (Caldwell, 2012). Moreover, equipment design is essential in mitigating the accumulation of food residue, which might facilitate microbial contamination. Equipment must be devoid of fissures and holes that might harbour residue, hence jeopardising food safety. Innovative methods have been presented to address hygienic issues related to the integration of robots into food preparation. Coating robots with both persistent and removable protective coatings simplifies maintenance and safeguards from corrosion (Bader and Rahimifard, 2018). Notably, emerging food-grade industrial robots (IRs) are specifically designed for clean-in-place (CIP) operations. These robots withstand washdowns with soap and detergents, simplifying the cleaning process and ensuring compliance with hygiene standards. Clean-in-place operations reduce downtime and labor requirements while ensuring thorough cleaning and sanitation, crucial elements in maintaining hygiene standards in food processing facilities. (Godfrey and Tenuta, 2023) By employing appropriate materials, design considerations, and innovative solutions, the food industry can uphold stringent hygiene standards, safeguarding consumer health and well-being.

7. Conclusion and way forward

The use of robots in the food industry has catalysed a significant transformation across several sectors, including meat, dairy, fish and shellfish, beverage, and packaging. Robotics, powered by AI and automation technologies, has witnessed significant advancements in efficiency, precision, and safety. Companies like KUKA AG (Keller und Knappich Augsburg), ABB (Asea Brown Boveri), and Universal Robots have pioneered innovative robotic applications, leading to improved quality control, increased productivity, and minimized operational risks, while addressing challenges like labor shortages and stringent regulatory compliance. While initial investment costs, technological complexities, and the need for ongoing maintenance and workforce upskilling present hurdles, the overall benefits of robotic adoption outweigh these challenges. The risk analysis of this study indicates that these challenges can be alleviated via strategic planning and ongoing innovation. Anticipated advancements in AI, sensor technological advances, and deep learning are projected to augment the flexibility, flexibility, and portability of robotic systems, facilitating their smooth incorporation into current food production operations. Going forward, the collaboration of academics, businesses, and regulators will be essential in promoting innovation, establishing standards, and tackling significant issues related to the use of AI and robots in the food sector. The development of robots in the food industry remains nascent, offering several opportunities to improve productivity, sustainability, and safety in food production, yielding significant advantages for both enterprises and consumers.

The potential application of robots in the food and beverage sector is exceptionally exciting, set to transform the processes of manufacturing, processing, and transportation. Automation is progressively supplanting labour-intensive activities such as slicing and packing, enhancing effectiveness. Collaborative robots (co-bots) are set to become more common, working alongside human to streamline operations. Precision and quality control will see major advancement with AI-driven systems and sensors, ensuring higher product quality, safety, and uniformity. Personalized food products, tailored to individual dietary needs, may soon be prepared by robots, while advanced sanitation technologies like UV-C light and ozone will elevate hygiene standards. Moreover, robotics is also trasnforming sustainable farming farming through precision agriculture, with drone and autonomous systems optimizing crop monitoring, fertilization, and harvesting. Autonomous delivery robots and drones are set to optimize last-mile food delivery in response to growing e-commerce demand. Further, AI and machine learning will drive robot adaptability and decision-making while ensuring the resilience of global food supply chains, reducing dependency on manual labor, and mitigating vulnerabilities. Moreover, innovations will prioritize human-robot collaboration with advanced safety systems. As robot's advances, rules and regulations will be important for managing safety, quality, and ethical concerns, influencing the prospects of automation in the food sector.

Data availability

No new dataset associated with this MS.

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Ethical considerations statement

We confirm that this manuscript does not involve any studies with human participants, animals, or sensitive data, and therefore, no ethical approval was required

CRediT authorship contribution statement

Shweta: Writing – original draft, Software, Conceptualization. **Ashique Mohammed:** Writing – original draft, Software, Conceptualization. **Meisam Mohammadi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Sunny Sharma:** Writing – review & editing, Supervision. **Umesh Sharma:** Writing – review & editing, Writing – original draft. **Vishal Singh Rana:** Writing – review & editing. **Mohit Kumar:** Writing – review & editing. **Sonia Sood:** Writing – review & editing. **Ghasem Eghlima:** Writing – review & editing.

Declaration of competing interest

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

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