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Sensor technologies in the food industry under industry 4.0: A systematic review

Mattia Braggio [a,*], Tsega Y. Melesse [a], Simone Arena [a], Pier Francesco Orrù [a], Federico Briatore [b]

[a] Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo 2, Cagliari, 09123, Italy
[b] Department of Mechanical, Industrial and Transport Engineering, University of Genoa, 16126, Genoa, Italy

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ABSTRACT

The food industry is undergoing a rapid transformation driven by the integration of advanced sensor technologies and Industry 4.0 digital enablers. Ensuring food quality, safety, sustainability, and traceability across increasingly complex supply chains requires real-time, scalable, data-driven monitoring solutions. This paper presents a comprehensive analysis of the scientific literature on sensor technologies applied to the food industry within the Industry 4.0 framework, using both bibliometric and content-based analyses. The former aims to examine publication trends, geographical distribution, and keyword co-occurrence patterns, identifying dominant research themes and technological directions. The latter concentrates on the principal sensor classifications employed in food systems, including chemical, biological, optical, physical, and nano-enabled sensors. The study further investigates how these sensing technologies are integrated with key digital enablers such as the Internet of Things, artificial intelligence, machine learning, cloud computing, blockchain, and additive manufacturing. The focus is on the role of sensors at each step of the food supply chain, from growing and processing to storage, transport, sales, and consumption. The results indicate that sensor-based solutions are becoming more mature and have the potential to improve food safety, operational efficiency, sustainability, and traceability. At the same time, the paper identifies the main challenges that still limit their large-scale adoption and outlines future research directions toward fully integrated smart food systems.

1. Introduction

The food industry is undergoing an important transformation driven by the pressing need to meet increasing global demand while ensuring safety and sustainability. The world population is projected to double by 2050. The issue is not only to increase production but also to ensure the nutritional quality of the products while minimizing environmental impacts (Apetrei et al., 2023; Rojas et al., 2022).

To ensure product safety, food production involves key activities. These activities include sourcing safe, high-quality raw materials, transforming them into consumable products, packaging products under controlled conditions, storing them under controlled conditions, and making them available to consumers. To ensure the safety of the products, we must perform all activities while ensuring risk management (Konfo et al., 2024).

Food hazards are of different natures. Some of the common hazards include microbiological contamination, which is the presence of harmful microorganisms; chemical contamination; adulteration (the act of adding inferior substances to products); misbranding (labeling products inaccurately); improper use of additives; GMOs (genetically modified organisms); and expiration dates. Among the common microbiological hazards is contamination caused by unsanitary practices during processing or poor-quality raw materials (Paliwal et al., 2025; Veerapandi et al., 2025). Chemical hazards (such as pesticide residues, disinfectants, and packaging-related substances) often arise from weak control systems, particularly in poorly regulated contexts (Amalraj et al., 2025; Wahid et al., 2025). Adulteration, the intentional modification of food for economic gain, threatens public health and market integrity (Apetrei et al., 2018; Ragavan & Neethirajan, 2018). Mislabeling, whether intentional or not, can mislead consumers and hinder traceability (Hussain et al., 2016; Sachchan & Sabharwal, 2024). Food additives play a central role in preservation and fortification; misuse or excessive application can cause adverse health effects, including long-term complications (Scognamiglio et al., 2016; Wei et al., 2024). GMOs raise

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* Corresponding author.
E-mail address: mattia.braggio@unica.it (M. Braggio).

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concerns related to allergenicity and traceability, and their health implications remain under scientific examination (Patel et al., 2020, pp. 355–368; Wang et al., 2022). Consumption of expired products, often linked to poor inventory and storage practices, contributes significantly to foodborne illness and waste (Cai et al., 2021; Melesse et al., 2022; Pandey et al., 2024).

While regulatory schemes and assurances of quality rules are in place to mitigate such risks, traditional methods of ascertaining food quality, e.g., laboratory analyses of chemical and microbiological attributes, are usually destructive, time-consuming, and resource-intensive, which can delay the availability of safe food products to consumers. As a result, there is a significant need for more efficient, accurate, and scalable methods. Conventional techniques, such as HPLC, GC-MS, ELISA, and PCR, are mainstays of food safety analysis owing to their high precision, which is coupled with the availability of validated procedures. However, most labs restrict these techniques due to their complex sampling procedures, sophisticated instrumentation, and longer analysis times. On the other hand, sensor-based methods are renowned for their portability and speed. These characteristics enable real-time, on-site food analysis and continuous monitoring across the food chain. The merging of different digital technologies, like the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, Blockchain, and Digital Twin (DT) technologies, has led to a shift towards predictive, real-time, and decentralized systems for monitoring food quality (Ador et al., 2024). This phenomenon has led to the development of Food Quality 4.0, which is a term that encapsulates the way Industry 4.0 technologies can be utilized for the rapid, objective, and automated analysis of food products (Garcia-Hernandez et al., 2025; König, 2022). The German Federal Government introduced Industry 4.0 in 2011 as a strategic initiative to usher in the fourth industrial revolution. Industry 4.0 is about "integrating digital technologies into smart, connected, and flexible value chains along the entire product lifecycle" (Oztemel & Gursev, 2020). Industry 4.0 is not only about technology but also about the broader transformation of the way value is created in industries, including changes to the way we organize, the business models we adopt, the way we are competitive, or our environment (Alcácer & Cruz-Machado, 2019). Through improved traceability and encouraging proactive quality control and process optimization, Food Quality 4.0 may offer a competitive advantage to food manufacturers in pursuing efficiency, resilience, and compliance with regulations in increasingly complex markets (Ador et al., 2024; Flores-Rangel et al., 2024).

The core of this evolution is the integration of three interrelated elements: food science, quality assurance, and digital technologies. Food science involves basic elements of safety, processing, and sensory analysis. Quality assurance involves the application of monitoring and control measures in both traditional environments and digitally augmented environments. Technologies typical of Industry 4.0 provide the basis for intelligent automation, data integration, and real-time decision-making (Bhatt et al., 2023). Their combined application supports holistic, flexible systems better equipped to manage the complexity of contemporary food systems with greater accuracy and reliability.

This paper examines the recent adoption of sensor technologies, combined with digital enablers, to enhance quality and safety standards in the food industry. It systematically discusses the limitations of conventional monitoring practices and the growing need for real-time data. It explores the classification and working principles of the various sensors deployed in food systems. It provides a thorough examination of the surrounding digital technologies and their interfacing with sensing platforms. The study further examines the contribution of smart sensors across the key stages of the food supply chain, outlining their implications for safety, operational performance, sustainability, and traceability. These insights lead to a discussion of research avenues and implementation models applicable worldwide The paper is structured as follows: Section 1 (this section) serves as an introduction to the paper by presenting the general topic and outlining its structure. Section 2 describes the bibliometric methodology and presents the results of the literature review, including publication trends, geographical distribution, and keyword co-occurrence. Section 3 provides a content-based analysis of sensor technologies and Industry 4.0 enablers, discussing sensor typologies, stand-alone and integrated approaches, and representative applications. Section 4 examines the role of smart sensors across the main stages of the food supply chain, while Section 5 discusses challenges, limitations, and future research directions. Finally, the conclusions are presented in Section 6.

2. Bibliometric analysis

2.1. Methodology

The methodology adopted in this study follows the Systematic Literature Network Analysis (SLNA) approach, a quantitative method that combines the Systematic Literature Review (SLR) structured approach with bibliographic network analysis to identify research advancements, current trends, and the evolution of knowledge within a research domain (Tranfield et al., 2003). Our study aims to investigate the latest advancements in Industry 4.0 technologies and sensors, which, when combined, significantly influence the modern food industry. We conducted a bibliometric analysis (in November 2025) by examining the trend of publications over time, the countries in which they were produced, and the co-occurrence clusters of keywords. The analysis of the latter served as the basis for narrowing the scope and focusing the study exclusively on sensors and Industry 4.0 technologies of current relevance. We selected the Scopus database since it provides extensive coverage of scientific, technical, and social science literature (Marty & Ruel, 2024). Therefore, Fig. 1 illustrates the methodological approach that guided our literature analysis, specifically focusing on the following research question: What sensors and Industry 4.0 technologies impact the modern food industry?

To address this question, an initial search was conducted in the Title, Abstract, and Keyword fields using the following strings: "Sensor*" and "food" and "industry*" and ("quality" or "detection" or "safety" or "contaminant*"), which yielded 10,863 documents.

Subsequently, the collected documents were screened in accordance with the following inclusion criteria:

- Publication year: only documents published between 2016 and 2026 were considered (8330 results).
- Subject area: only documents in Agricultural and Biological Sciences, Engineering, Chemistry, Biochemistry, Genetics and Molecular Biology, Chemical Engineering, Materials Science, Environmental Science, Computer Science, Multidisciplinary, Energy, Mathematics, and Decision Sciences were included (7937 results).
- Document type: only journal articles (original research or review articles), book chapters, and books were considered (7283 results), while conference papers, technical reports, etc., were excluded.
- Language: only documents written in English were considered (6923 results).

Based on this dataset, bibliometric analyses were conducted to examine the temporal evolution of the research field and to map the geographical distribution of countries showing significant interest in the topic. A keyword co-occurrence analysis was then performed using VOSviewer to identify the main current and emerging research streams. Drawing on the results of the cluster analysis, the relevant types of sensors in the modern food industry were identified. Using these sensors as a new search string, 852 papers were retrieved. This technique resulted in a broad set of publications. However, reporting the complete list of retrieved records was neither practical nor meaningful for this study. Therefore, a structured screening process based on relevance, quality, and scope alignment was applied, and only the studies selected for the final analysis (177 papers) are presented. The full list of retrieved records is available upon request.

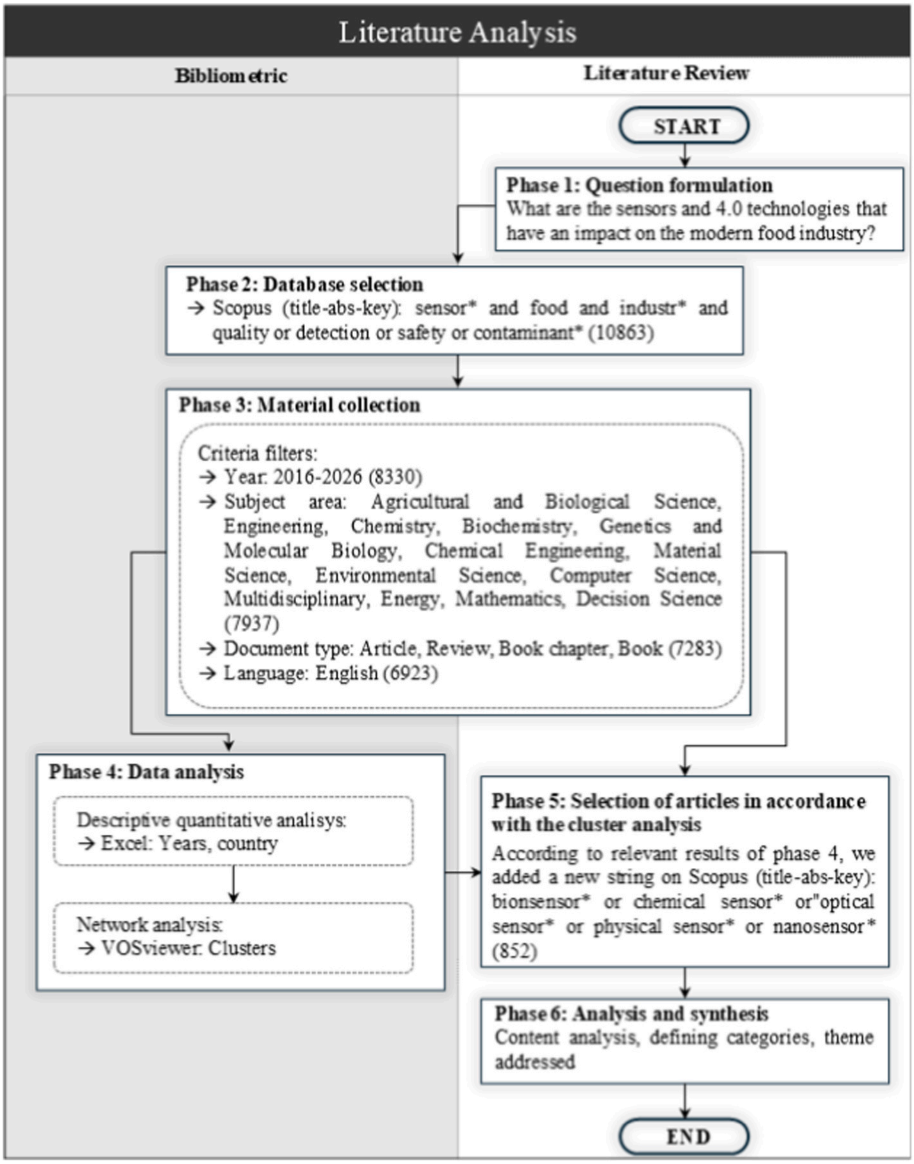

Fig. 1. Methodological approach: flow diagram illustrating the study selection process across the different phases of the systematic review.

2.2. Publication trends

Fig. 2 shows the evolution of the percentage of articles published on the topic each year since 2016. It is evident that up to 2020, the number of publications remained stable, showing no significant growth, although it was already being recognized that there is a need for more sensors in the food sector (Mustafa & Andreescu, 2018). A clear shift occurred in 2021, after which the number of published papers increased each year, as supported by the development of new kinds of sensors and an increased interest (Ador et al., 2024; Mukherjee et al., 2021). By 2024, the number of publications was three times higher than in 2020, following and anticipating the market growth (Franca & Oliveira, 2021). This marked increase in scientific interest can be interpreted considering the growing consumer awareness of food quality, safety, and sustainability, which has progressively influenced both market dynamics and policy agendas. At the European level, this attention has been formalized through initiatives such as the Farm to Fork (F2F) strategy (European Commission Farm to fork strategy), a key pillar of the European Green Deal. The F2F strategy's goal is to “ensure that everyone has access to sufficient, safe, nutritious, and sustainable food” (European Commission) and to promote public health. In this context, the adoption of

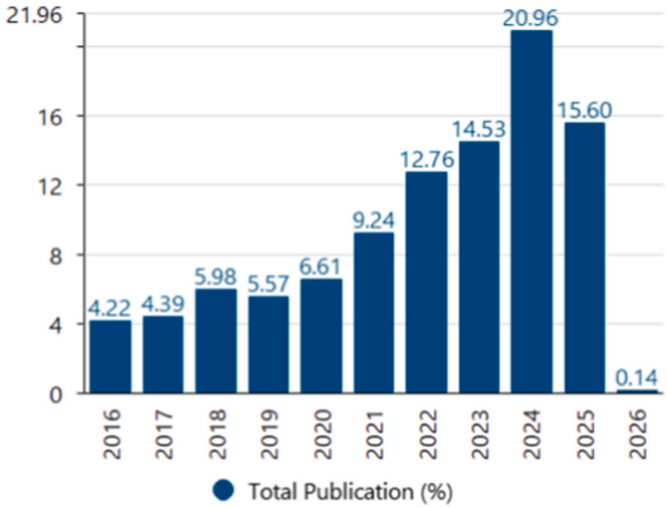

Fig. 2. Number of papers published per year.

advanced sensing technologies and Industry 4.0 solutions plays a crucial role in enhancing transparency, traceability, and process control across the food supply chain, thereby supporting the observed growth in research outputs.

Furthermore, food industries are facing growing global competition driven by rising consumption, population growth, and changing lifestyles, which heighten consumer demands for both food quantity and quality. To address this, researchers have developed advanced tools such as thermometers, pH meters, microscopes, spectrophotometers, and biosensors, which are gaining increasing scientific attention (Dirpan et al., 2023). Gas and colorimetric sensors (Xiao-Wei et al., 2016), nanozymes (Lou-Franco et al., 2023), 3D printing (Skowronková et al., 2024), and nanotechnologies (Fathima et al., 2022) applied to sensors are gaining a lot of interest and showing promising results in monitoring food safety and spoilage (Veerapandi et al., 2025). Recently, the food industry has been using new technologies to improve quality control and safety monitoring. These technologies include integrated data-driven modelling and computational techniques, encompassing kinetic modeling, modeling, artificial neural networks (ANNs), hyperspectral imaging, modeling, artificial neural networks (ANNs), hyperspectral imaging, delling, artificial neural networks (ANNs), hyperspectral imaging, and computer vision (Ghaffari, 2024; Patil & Meshram, 2023). At the same time, the COVID-19 pandemic has exposed vulnerabilities in food production and packaging chains, especially in cold-chain environments, where low temperatures can prolong viral persistence on surfaces and packaging materials. Such an event has emphasized the importance of implementing stricter hygiene measures and sanitation protocols, as well as the need to develop more efficient and sustainable decontamination technologies (Ghaffari, 2024; Patil & Meshram, 2023). In this scenario, advanced sensing and digital monitoring systems play a crucial role in ensuring food safety, real-time traceability, and process resilience across the entire food supply chain.

2.3. Global patterns

Fig. 3 shows the most influential countries based on the distribution of published articles. Asia (4529) and Europe (2939) clearly dominate global publications. Several national and international initiatives have been proposed and developed recently to improve various aspects of the agri-food sector through the digitalization of distinct stages of the supply chain. In Europe, as said, the F2F strategy (European Commission) provides a common policy framework that supports research and innovation in the agri-food sector, indirectly fostering the adoption of digital and sensing technologies along the food supply chain. This policy-driven environment has contributed to the prominent role of European countries in advancing sensor-based, data-driven, and traceability-oriented solutions for food quality and safety.

This process resulted in the development and adoption of sensors like CoolVu in Freshpoint-Switzerland, which changes, and the Swiss sensor FOOD sniffer for fish freshness assessment (Mustafa & Andreescu, 2018). These innovations align with the F2F objectives by promoting responsible consumption, reducing food waste, and supporting the transition toward smarter and more resilient food systems.

In China (1499 articles), India (1182 articles), and Brazil (429 articles), research is largely driven by high population demand for enhanced food security (Zhu et al., 2022). In contrast, in the USA (549 articles), the focus is primarily on treatment and food safety. The country's significant agricultural production underpins this emphasis, particularly because the Environmental Protection Agency (EPA) regulates pesticide use (Akhavan-Mahdavi et al., 2024) and the Food and Drug Administration (FDA) sets maximum allowable levels for various compounds in food (Mustafa & Andreescu, 2018), which points to the need for greater control through proper sensor-based technologies. Annually, 40% of food is wasted, resulting in a $165 billion loss, and 48 million people are infected every year, pushing the USA to innovate in this direction (Mustafa & Andreescu, 2018). It is worth mentioning that the USA is a major producer of sensors, such as MonitorMark™ by 3M™, which monitors the thermal exposure of food during transport; a Radio Frequency Identification (RFID) sensor by Flex Alert to detect *Escherichia coli* and Salmonella in packaged food; and a gluten detection sensor developed within the American Chemical Society. The WHO and the outbreaks of foodborne diseases further reinforce this need (Kaur et al., 2025).

Zhu et al. (Zhu et al., 2022) reported that the implementation of IoT-based sensors has contributed to a significant reduction in food loss across several regions, including China, the Nordic European countries (particularly Sweden and Finland), and Australia, especially related to animal products, as well as commodities such as honey, coffee beans, and cocoa. In the Asia-Pacific, beyond China and India, an example worth mentioning is RipeSense®, developed in New Zealand, which functions as a smart ripeness-indicator label designed to assess fruit freshness (Mustafa & Andreescu, 2018). The reported geographical distribution is influenced by another key factor: in recent decades, there has been increasing attention to the growing concern over food allergies.

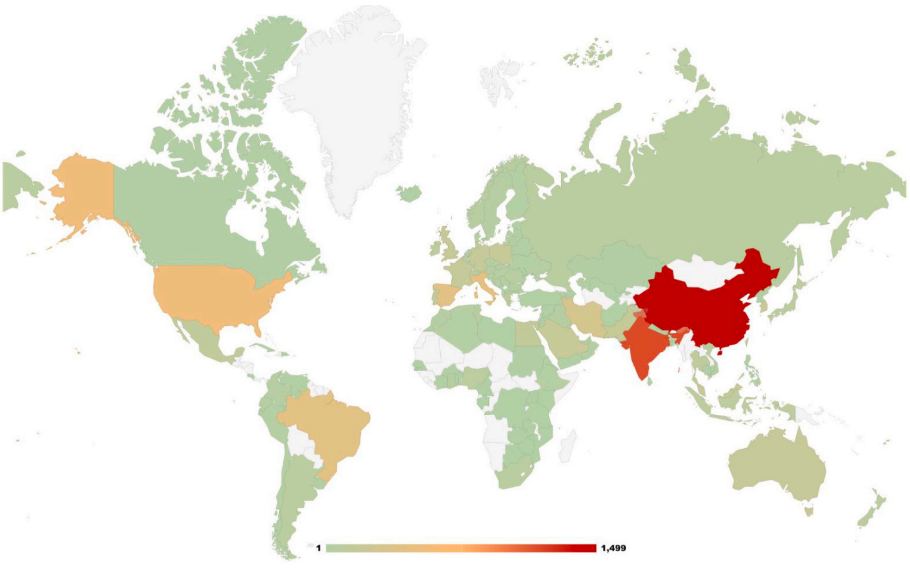

Fig. 3. Distribution of articles by country.

Although the issue is widespread globally, Western countries have driven the development of specialized detection tools, such as the peanut allergen detector by NIMA (USA) and the LactoSens® by Directsens (Austria) (Mustafa & Andreescu, 2018). specialized detection tools, such as the peanut allergen detector by NIMA (USA) and the LactoSens® of Directsens (Austria) (Mustafa & Andreescu, 2018).

It is important to emphasize how crucial it is to ensure that developing countries have access to these types of technological solutions, as otherwise existing inequalities in food systems and supply chain efficiency could be exacerbated. To achieve this goal, policymakers, educators, investors, and developers of sustainable technologies must coordinate their efforts. Thus, by fostering collaboration across these sectors, it becomes possible to support technology transfer, capacity building, and the adoption of green and smart solutions in regions where resources and infrastructure may be limited to promote a more equitable and resilient global food system.

2.4. *Keyword co-occurrence analysis*

To improve the completeness of the bibliometric analysis, the co-occurrence keywords analysis has been conducted using VOSViewer (Version 1.6.20). Keywords capture the main themes of research articles, and analyzing co-occurrence helps identify key research hotspots and trends within a field. This approach not only provides a clear overview of the knowledge structure but also helps uncover potential connections between topics and identify thematic clusters within the research domain. All keywords have been analyzed with a full count (Aisa et al., 2023). Aiming to consider only the most relevant ones, the minimum number of occurrences was set to 10, considering only the 1000 items with the greatest total link strength. The keyword co-occurrence network map revealed five clusters. Grouped keywords are represented by distinct colors, and centered keywords are each represented by a distinct color and centered around specific leading keywords, as shown in Fig. 4. Although the red cluster appears to be the most extensive in terms of the number of interconnected terms (370 elements), the keyword "chemistry" emerged as the most frequently used across the entire dataset. This prevalence reflects the nature of sensor-based research in the food sector, which largely focuses on detecting chemical phenomena related to food quality, safety, and contamination. Such applications typically involve the measurement of volatile compounds, pH variations, chemical contaminants, or biochemical reactions. Many sensing technologies in this domain originate from analytical and food chemistry disciplines, which explains the central role of "chemistry" in the keyword co-occurrence analysis.

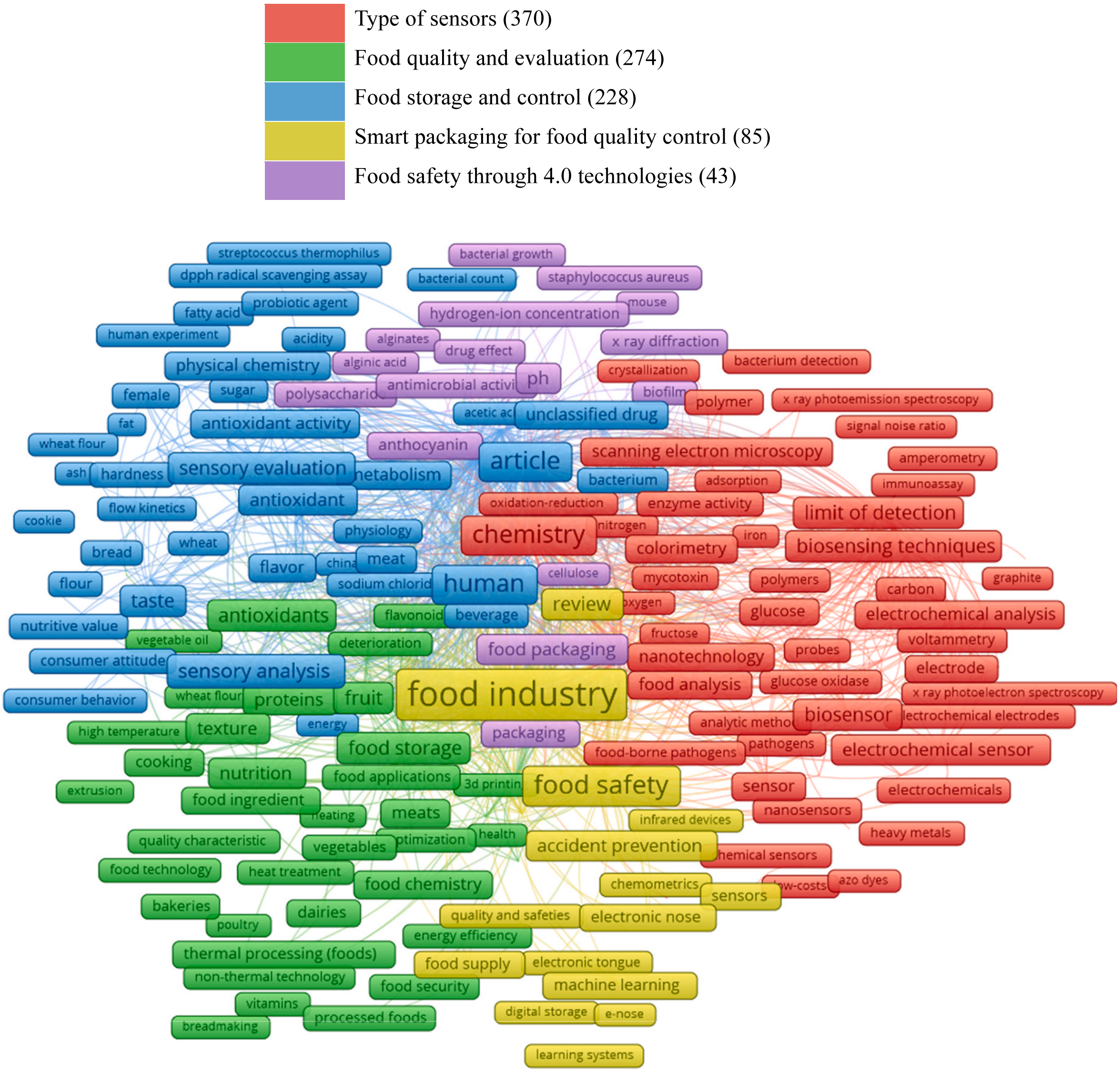

Fig. 4. Keyword co-occurrence analysis.

2.4.1. Cluster 1. Type of sensors (red)

The first cluster, which is the largest, is primarily associated with several types of sensors and their underlying technological principles. It encompasses research on chemical sensors (R. Ali and Saleh, 2024; Saputra et al., 2025; Singh, Maurya, & Malviya, 2025), Singh, Pandey, et al., 2025iosensors (Fdez-Sanromán et al., 2025; Ma et al., 2025; Nanda Kumar et al., 2025), optical sensors (Guliy et al., 2025; Selva Sharma et al., 2024; Zhang, He, et al., 2025), physical sensors (Raheel et al., 2021; Sanni et al., 2023), and nanosensors (Dos Santos et al., 2025; Kulkarni et al., 2025; Paliwal et al., 2025), which represent the core technologies driving research and applications in this field. Studies within this cluster mainly aim to enhance sensor performance in terms of sensitivity (Alam et al., 2025; Nasiri et al., 2026), selectivity (Arana & Tao, 2025; Wang, Liu, et al., 2025), Wang, Lan, et al., 2025nd portability (Dos Santos et al., 2025; Huang et al., 2024) for detecting contaminants (Rawat et al., 2024; Zhou et al., 2023), pathogens (Bonyadi et al., 2024; Kızılkurtlu et al., 2023), and adulterants (Anweshan et al., 2023; Garg et al., 2022) in food. The frequent occurrence of the keyword “limit of detection” (Alagumuthu et al., 2025; Hong et al., 2024; Wang et al., 2024) highlights a central technical priority in sensor development for food quality and safety monitoring. Achieving low detection limits is essential, as many hazardous substances, such as pesticide residues, mycotoxins, heavy metals, and microbial metabolites, are present at trace levels and regulated by stringent legal thresholds. Consequently, enhancing analytical performance is critical to ensure regulatory compliance, early risk identification, and consumer protection. At the same time, the bibliometric evidence reveals a persistent gap between laboratory-scale results and real-world implementation. Although increasingly low detection limits are reported under controlled experimental conditions, translating these advances into robust, cost-effective, and scalable solutions suitable for complex and variable food matrices remains challenging. In practice, detection performance is strongly influenced by matrix interference, sensor stability, reproducibility, and integration into packaging and supply chain systems. While the integration of Industry 4.0 technologies has accelerated progress through real-time monitoring and enhanced analytics, significant barriers to full implementation persist. These include challenges in achieving standardization, high accuracy, and economic viability, as well as the lack of interoperability between different systems and the high costs of upgrading legacy equipment. These elements collectively highlight both the rapid technological advancement of the field and the multidisciplinary effort still required to transform promising laboratory innovations into reliable and scalable solutions for the food industry.

2.4.2. Cluster 2. Food quality and evaluation (green)

This cluster relates to the evaluation of food quality, addressing the role of sensors in detecting microbiological and chemical contamination, allergens, and other food safety risks. The focus is to safeguard consumer health and prevent foodborne illnesses through early detection and continuous monitoring. Biosensing technologies, immunoassays, and lab-on-chip systems strongly connect to the subject, enabling rapid, on-site detection of hazardous substances. Zhang et al. (Zhang et al., 2024) proposed the use of sensors for glucose concentration detection to support advancements in the food industry related to diabetes management. Furthermore, Ahuactzi et al. (Saldaña-Ahuactzi et al., 2025) investigated recent advancements in electrochemical (EC) and optical biosensing techniques for detecting bacteria and viruses. In fact, an elevated risk comes from bacteria, which can grow in food in both aerobic and anaerobic environments (Mehrzad & Verdian-Doghaei, 2024).

2.4.3. Cluster 3. “Food storage and control” (blue)

This cluster focuses on food storage and control, emphasizing how sensors are employed within supply chain and cold-chain environments. This is especially important for foods that go sour quickly, like meat, dairy, fruit, and vegetables. This kind of product, because of its characteristics, requires regular control to avoid the generation of harmful substances, especially when heat is involved. Here, the use of IoT-enabled devices, RFID tags, and real-time monitoring systems is applied to control and optimize temperature and humidity conditions, extending product shelf life and ensuring quality (Ramezanzadeh et al., 2019) and during transport (Matindoust et al., 2016). Research in this area moves beyond laboratory studies, highlighting the practical integration of sensors in logistics (Annanouch et al., 2021) and preservation systems (Soltani Firouz et al., 2021). In this context, Pant et al. (Pant et al., 2024) and Zhang et al. (Zhang et al., 2023) reported that checking food texture and gas production represent effective strategies to reduce hazards and improve food security.

2.4.4. Cluster 4. Smart packaging for food quality control (yellow)

This cluster deals with smart packaging for food quality control, integrating active and intelligent materials that can detect changes in product freshness, temperature, or gas composition. Technologies such as colorimetric indicators (Weston et al., 2020) and time-temperature sensors (Full et al., 2021; Upadhyay et al., 2024) are employed to monitor the condition of food since they can give information to both producers and consumers regarding the quality and the safety of the packaged food during transportation and storage (Mistewicz & Nowak, 2016; Paliwal et al., 2025).

2.4.5. Cluster 5. Food safety through 4.0 technologies (violet)

This group looks at the digital and technological side of food safety, focusing on how sensors work with advanced I4.0 technologies. Research in this area focuses on transforming traditional monitoring systems into intelligent, data-driven infrastructures capable of predictive control, real-time decision-making, and improved traceability throughout the supply chain. In this context, keywords such as “deep learning” (He et al., 2024), “artificial neural network” (Al-Hilphy et al., 2022), and “machine learning” (Guo et al., 2025) appear as effective tools applied to pursue the food safety goal. Instruments to detect smells and tastes are especially useful, as they mimic human senses and enable a quick detection of spoiled food (Gabrieli et al., 2023). AI forecasting capabilities can be exploited to find patterns and schemes, associating certain parameter values with risk of spoilage and hazards. For instance, He et al. (He et al., 2024) reported that machine learning (ML) can be employed to predict the quality of gypsum tofu, assess the quality and geographical origin of ginger powder, rapidly identify adulteration in sour jujube products, evaluate the edibility of wild porcini mushrooms, and forecast the shelf life of catfish fillets. Deng et al. (Deng et al., 2025) analyzed the integration of AI algorithms, ML, and deep learning (DL) techniques to overcome challenges in sensitivity, accuracy, and adaptability related to biosensing technologies.

The five clusters together show the research area focused on sensors and detection methods used in the food industry. They also provide a full picture of how sensor technologies, which are being driven by digital transformation, are making food systems smarter, safer, and more resilient. The analysis of these clusters has been instrumental in identifying and classifying the main categories of sensors currently used in the food industry. Therefore, the following section presents a detailed examination of these sensor typologies, discussing their working principles, advantages, limitations, and the application domains in which they are most effective. This categorization provides a structured understanding of the research advancements, emerging methodologies, current trends, and perspectives. From Fig. 4, it emerges that the integration of 4.0 technologies in the food sector is still a new field, although some papers already discuss potential applications. For instance, Koenig (König, 2022) suggests employing ML to create soft sensors for ongoing, non-intrusive surveillance of hive infestation and health status. Similarly, Niyigaba et al. (Niyigaba et al., 2025) propose using blockchain technology to enhance traceability, transparency, and consumer trust in the fermented food supply chain through decentralized applications and smart contracts that ensure secure, real-time, and tamper-proof tracking of products. For this reason, in the following sections of the paper, we will include a paragraph that examines this topic in detail. Through this approach, the study aims to provide a deeper and more systematic insight into the technological diversity and practical relevance of sensor-based solutions in modern food systems.

3. Sensor and digital technologies in the food industry

This section deals with the interpretation of the results emerging from the cluster analysis, with the aim of providing an overall picture of the sensors and digital technologies that are most widely applied today in the food industry. It presents an extensive description of the main sensor technologies used in food applications and of the digital platforms enabling their integration into the Food Industry 4.0 strategy.

Generally, conventional techniques adopted to monitor food freshness and quality are mainly based on manual inspection and laboratory-based analyses, including sensory evaluation, microbial testing, high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and hyperspectral imaging (Kumar, Karthika, et al., 2024). Although accurate, these approaches are often time-consuming and costly and require dedicated instruments and trained personnel, with limited on-site applicability (Mani et al., 2025). This disadvantage makes them unsuitable for rapid or real-time analysis, particularly within industrial food quality monitoring (Li et al., 2020). However, current technological and industrial advances have driven the development of intelligent sensors capable of overcoming these limitations. These smart sensing systems have many benefits over traditional methods, such as high accuracy and precision, the ability to process data in real time, and advanced analytical capabilities. Their effectiveness depends on how well advanced sensor technologies work with digital platforms (Ador et al., 2024). The sensors continuously generate real-time data on the physical, chemical, and biological parameters that determine food quality and safety, while the digital platforms enable the processing, transmission, and consolidation of this information across the entire value chain (Kumar, Kannampilly, & Joy, 2024). Together, they enable a transition to data-driven and automated monitoring systems that enhance efficiency and sustainability in food production.

The cluster analysis in the previous section showed that the food industry uses various sensors to meet its different monitoring needs. Every sensor is based on different detection principles and designed for a specific target and operating environment. However, five main categories can be identified: chemical sensors, optical sensors, physical sensors, nano-enabled sensors, and biosensors. The effective optimization of these sensor systems requires their integration into a proper digital ecosystem supporting data generation, processing, and application. To achieve this, the IoT may provide the functional foundation of such an ecosystem by interconnecting sensor nodes with decentralized as well as centralized data storage systems (Kaushal et al., 2023). In this respect, it is worth mentioning that IoT technology is being applied in food systems at all tiers of production, processing, distribution, and retailing for real-time monitoring of both product conditions and environmental parameters (Rafi et al., 2025). This procedure facilitates real-time alerting, process optimization, and timely response to events, thereby enhancing overall efficiency and safety within the food system (Bhuiyan et al., 2024).

3.1. Sensor technologies

A sensor can be broadly defined as a device or system that detects and quantifies the chemical or physical characteristics of a substance or its environment, aiming to provide essential data for the monitoring of food quality and safety (Kress-Rogers and Brimelow, 2010). These devices can either directly measure specific key food attributes (e.g., freshness indicators), such as gases or pH variations, or indirectly monitor environmental and temporal changes that reflect product condition and integrity. Depending on their design, sensors may operate through direct contact, like gas or pH sensors, or through non-contact mechanisms, including time-temperature indicators (TTI), humidity sensors, and RFID-based systems (Mustafa & Andreescu, 2018).

3.1.1. Physical sensors

Physical sensors are commonly used to measure various mechanical and environmental parameters, such as temperature, humidity, vibration, pressure, and mechanical stress, which are essential for maintaining optimal conditions in food storage and transportation operations (Satpati et al., 2017). They represent the backbone of cold chain logistics, ensuring effective environmental control to prevent spoilage and to meet regulatory compliance (Flores-Rangel et al., 2024; Pandey et al., 2024). Image-based physical sensors like X-ray technology (as shown in the cluster analysis) permit foreign object detection and non-destructive assessment of internal product quality (Popov et al., 2021). These systems play a key role in detecting contamination by foreign bodies, such as glass, metal, or plastic fragments, that may result from mechanical failures or improper handling during the food processing process (Raheel et al., 2021). Other innovations include flexible sensors developed for real-time monitoring and smart packaging solutions incorporating built-in physical sensors (Konfo et al., 2024; Rafi et al., 2025). These technologies allow for constant monitoring during production, storage, and distribution, which helps track products better, ensures safety, and greatly lowers the chances of contamination.

3.1.2. Chemical sensors

Chemical sensors are designed to detect poisonous or unwanted chemicals, such as pesticide residues, toxins, and heavy metals. These analytical devices convert chemical information, ranging from the concentration of individual analytes to the overall composition of samples, into measurable signals (Dodevska, 2025; Lenik, 2017). The sensors typically consist of two key components: a receptor that selectively interacts with the analyte and a transducer that converts this interaction into a measurable output. The significant selectivity is attributed to the receptor, while the transducer ensures reliable and reproducible signal generation. Such sensors often adopt EC, colorimetric, or fluorometric principles to generate quantitative signals (Beladona et al., 2025; Yang et al., 2025).

Fluorometric chemical sensors that are overly sensitive can detect changes in wavelength, intensity, or fluorescence lifetime caused by the presence of compounds (Yang et al., 2025). Among practical applications, pH sensors are widely employed in packaged food systems to evaluate the freshness of protein-rich foods like meat and fish because spoilage processes are related to rising pH values (Kadian et al., 2024). In the same way, molecularly and ionically imprinted polymers (MIPs and IIPs) mimic the recognition process of nature through the creation of binding sites that are specific to target molecules. This approach improves the selective rebinding of the target molecules (Arana & Tao, 2025; Sun et al., 2025). When it comes to the monitoring of foods, MIPs/IIPs have been used to identify contaminants such as pesticides, antibiotics, heavy metals, and mycotoxins. This approach provides high selectivity along with improved chemical stability. Gas-phase chemical sensors are used to detect volatile spoilage markers, such as ammonia (NH_3) and hydrogen sulfide (H_2S), generated by microbial breakdown (Bhuiyan et al., 2024). Materials such as polyaniline, metal oxides, graphene, and carbon nanotubes (CTNs) are often used due to their excellent sensitivity, stability, and flexibility (Popov et al., 2021; Srivastava et al., 2018). Chemical sensors are used to detect hydrogen peroxide (H_2O_2), an important disinfectant widely adopted in food processing, due to the possible health risks posed by residual concentration on food surfaces (Karimi et al., 2025). Recently, there has been growing interest in the development of intelligent packaging systems that integrate sensors for real-time freshness monitoring. (Rafi et al., 2025). Advancements have extended to robotic systems equipped with artificial sensory capabilities, such as humanoid fingers combined with EC sensors capable of distinguishing taste attributes like sourness, sweetness, and spiciness, effectively mimicking human sensory perception (Ali et al., 2022; Mustafa & Andreescu, 2020).

3.1.3. Optical sensors

Optical sensors exploit light-sensitive methods, such as absorbance, fluorescence, and surface plasmon resonance (SPR), to sense changes in the optical properties of food and the environment (Sourkouhi et al., 2025; Tarannum et al., 2023). They provide a label-free and contactless means of detecting spoilage, chemical alterations, and microbial contamination. The high-speed detection capability and easy integration into imaging systems are extremely attractive for making high-throughput quality measurements in food processing and packaging operations. These sensors typically operate by utilizing the basic principles of colorimetry, fluorescence, or spectroscopy to detect variations in analyte concentration or environmental conditions (Ibraheem Shelash Al-Hawary et al., 2023; Peveler, 2024; Sánchez et al., 2025). Among these mechanisms, colorimetric sensors are most widely used, especially for the detection of food spoilage since visible color changes often indicate variations in pH levels or gas emissions (Kadian et al., 2024). Fluorescence and SPR-based sensors exhibit exceptional detection sensitivities, rendering them effective for identifying pesticide residues and quantifying mycotoxin levels (Gopal et al., 2023; Santos et al., 2019). Sensors that incorporate optical techniques (fiber optics, Raman, fluorescence, and luminescence) into polymerase chain reaction (PCR) are used for detecting chemical and microbial contaminants (Balbinot et al., 2021). Recent advances have incorporated nanostructured materials into metal-organic frameworks (MOFs), aiming to enhance the sensitivity, specificity, and cost-effectiveness of optical sensing devices (Singh, Kumar, et al., 2024). The surface area of MOFs is also advantageous; the face area of MOFs is also advantageous since it improves adhesion to the surface. The area of MOFs is also advantageous since it improves adhesion to the surface. Also, being able to change the pore structure makes signals stronger. The structure also improves the amplification of signals. This improves the sensitivity of the sensors to detect contaminants such as volatile organic compounds, pesticide residues, and heavy metals in the food chain. The technology can also be used to develop smart packaging materials for tracking temperatures, gas levels, or the degree of ripeness of products. The materials can be designed to change color to indicate freshness or spoilage (Weston et al., 2020).

3.1.4. Biosensors

Biosensors achieve high selectivity through the incorporation of biological recognition components, such as enzymes, antibodies, or nucleic acid probes, that exhibit specific recognition of target analytes (Banerjee et al., 2021). These biosensing systems are employed for detecting various food constituents, from microbial pathogens and toxins to allergens, heavy metals, pesticide residues, and volatile organic compounds linked with food spoilage. Biosensing systems are especially appreciated for their ability to detect microbial pathogens, allergens, and toxins, thanks to their high levels of sensitivity and speed of response (Banerjee et al., 2021; Kushwaha et al., 2022). Portability and flexibility are characteristics that make them suitable for in-line measurement and mobile field testing, enabling timely risk assessment and effective quality control. Functionally, biosensors operate by coupling biological recognition with signal transduction. When the biological element interacts with a target analyte, a physicochemical transformation occurs, which is converted into an optical or electrical signal (B. Chen and Stephen Inbaraj, 2016).

EC biosensors are widely adopted since they are highly efficient and cost-effective, and they can provide fast and accurate results (Dodevska, 2025).

Recent advancements include biomimetic MIP-based and microelectromechanical systems (MEMS)-based biosensors, both of which can quantify molecular interactions through changes in mass or surface deformation (Dias et al., 2024; Rodriguez-Saona et al., 2020).

Biosensors have found broad applications across the food industry, including the detection of sweeteners and glutamate concentration, the identification of pathogenic microorganisms, and the measurement of the level of toxins, and they are integrated into intelligent packaging and environmental monitoring systems (Deng et al., 2025; Rainbow et al., 2025). Microbial enzymes, often immobilized on inorganic supports such as clay, are increasingly used in biosensing and waste treatment applications, offering advantages such as substrate binding specificity, biodegradability, and enhanced catalytic efficiency (Hong et al., 2024).

3.1.5. Nanotechnology-enabled sensors

Nanotechnology-enabled sensors can detect trace levels of contaminants and biochemical markers with high precision and are increasingly being applied in smart packaging, real-time quality monitoring, and multiplexed analytical systems (Jafarizadeh-Malmiri et al., 2019; Patel et al., 2020, pp. 355–368; Sharma et al., 2019). The adoption of nanomaterials has significantly enhanced the performance of food sensors, improving parameters such as sensitivity, selectivity, and miniaturization (Beladona et al., 2025; Gulia et al., 2025). A wide range of nanomaterials, such as gold and silver nanoparticles (AuNPs and AgNPs), CTNs, quantum dots (QDs), and MOFs, have been incorporated into sensing devices to enhance signal transduction, surface reactivity, and overall analytical performance (Benedetto & Mirica, 2024; Sukhavattanakul et al., 2025).

AuNPs and AgNPs are commonly employed to enhance both colorimetric and EC signals, whereas graphene and carbon nanotubes (CNTs) augment electrical conductivity, facilitating the expedited and precise detection of food contaminants (Fan et al., 2017; Rahman et al., 2025). Similarly, QDs and cerium oxide nanoparticles (nanoceria) improve optical sensors due to their remarkable photostability and luminescence properties (Sharma, Gupta, et al., 2025), while magnetic nanoparticles (MNPs) help in selective analyte isolation and provide simultaneous pathogen and toxin detection (Nasiri et al., 2024). Applications of these technologies include the measurement of heavy metal content, antibiotic residues, mycotoxins, and pesticide contaminants (Abedi-Firoozjah et al., 2024; Bhardwaj et al., 2023; Chen et al., 2023). Advances in electronic sensor technology, especially sensors called electronic noses and tongues that mimic human sensory responses (for instance, those associated with olfaction and gustation), are increasingly being employed for the quality analysis of most food commodities, such as olive oil and cereals (Cheli et al., 2018; Graboski et al., 2021).

3.2. Single-sensor and multi-sensor technological approaches

To identify potential gaps and prevailing trends in the current

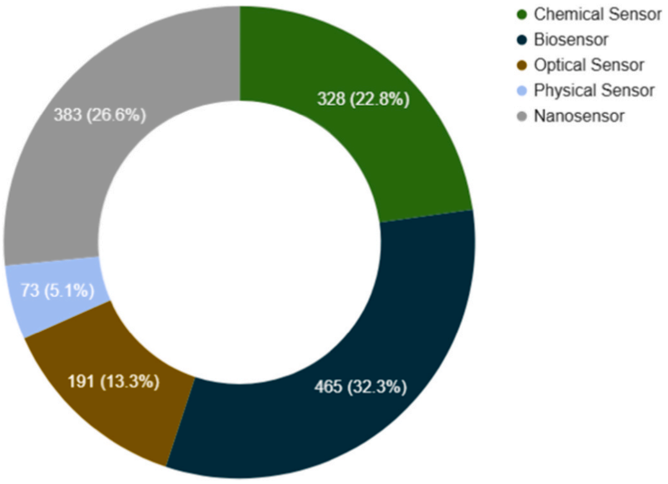

Fig. 5. Number of papers according to the type of sensor addressed.

literature, the analyzed papers were classified according to the type of sensor addressed in each study. The results are summarized in Fig. 5.

It should be noted that the total number of papers does not sum to 852, as a single study may address more than one sensor type, reflecting the increasingly interdisciplinary and integrated nature of food-sensing technologies. Accordingly, Fig. 6 provides a clearer representation of this distribution. The analysis indicates that more than half of the studies adopt an interdisciplinary approach, integrating two or more sensor technologies.

Furthermore, Fig. 7 provides an overview of studies focusing on a single sensor category. The results show that when treated as stand-alone solutions, biosensors (109 papers) and nanosensors (111 papers) dominate the literature. age, contaminants, pathogens, and biochemical changes in food matrices (Paliwal et al., 2025; Singh, Pandey, et al., 2025). In contrast, chemical sensors (33) appear less frequently as stand-alone topics. This aligns with the broader trend observed in the literature, where chemical sensing mechanisms are often combined with biological recognition elements or nanomaterials, making purely chemical approaches increasingly uncommon in modern food-sensor research. A similar pattern is observed for optical sensors (28 papers). While optical techniques are effective for detection and analysis, they are typically coupled with biochemical or chemical sensing mechanisms, such as fluorescence-based biosensing or spectroscopic chemical detection, resulting in relatively few studies addressing optical sensors in isolation (Archana et al., 2025; Radha et al., 2022). Physical sensors (16 papers) are the least common stand-alone solutions. Parameters such as temperature, humidity, or pressure are crucial for monitoring storage and transport conditions but do not directly detect spoilage or contaminants. As a result, physical sensors are rarely the primary focus of a study and are more commonly employed as complementary tools within broader monitoring systems.

Table 1 extends this analysis by illustrating how different sensor categories are combined within the same studies. Overall, a high number of papers address biosensors (465) and chemical sensors (328), and nanosensors (383) are frequently used to enhance sensitivity, selectivity, and detection limits through nanomaterial integration (Kendre et al., 2024, pp. 119–144; Sharma et al., 2024). The strongest co-occurrence is observed between chemical sensors and biosensors (232 papers). This coincidence is expected, as many biosensing mechanisms rely on chemical transduction principles, and food contaminants or spoilage markers often exhibit both chemical and biochemical characteristics (Hu et al., 2016; Tsegay et al., 2024). Similarly, the substantial overlap between biosensors and nanosensors (200 papers) reflects the extensive use of nanomaterials to improve biosensor performance in terms of sensitivity, specificity, and limits of detection (Daimary et al., 2025; Sharma, Agrawal, et al., 2025). Nanosensors frequently co-occur with chemical sensors (146 papers), as nanostructured materials significantly enhance chemical detection capabilities (Pavase et al., 2018; Sukhavattanakul et al., 2025).

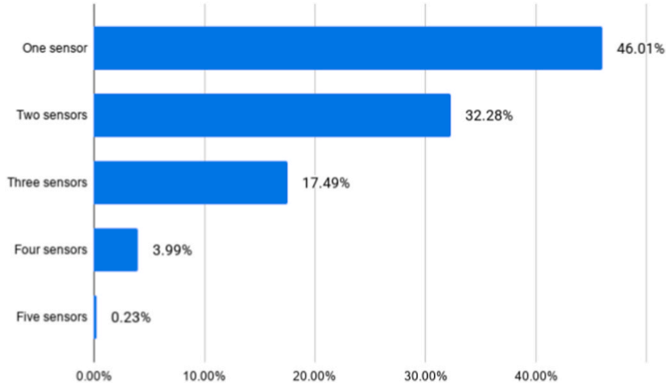

Fig. 6. Distribution of studies by number of sensors addressed.

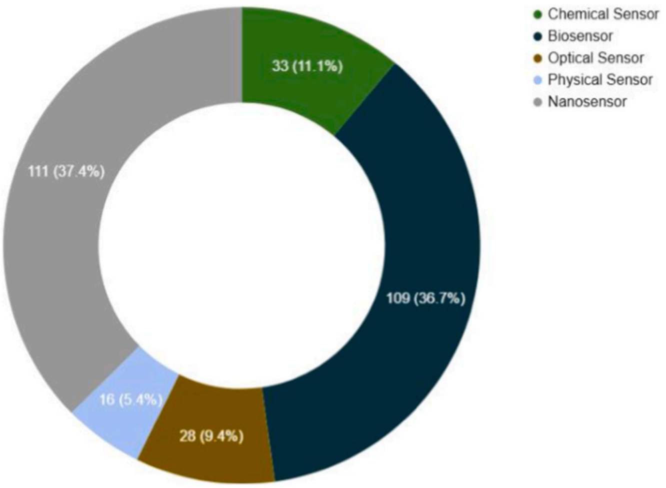

Fig. 7. Number of papers focused on a single sensor category.

Combinations involving optical sensors, such as biosensor-optical (92 papers) and chemical-optical (90 papers), highlight the role of optical readout techniques, including fluorescence, colorimetry, and spectroscopy, in amplifying or visualizing chemical and biochemical reactions (Ashrafi & Mohanty, 2025; Kaur et al., 2024). These approaches improve detection accuracy and interpretability but are typically integrated within broader sensing systems rather than used independently. Co-occurrences involving physical sensors are consistently lower across all categories. This effect reflects their indirect role in assessing food conditions: while physical parameters are essential for contextual monitoring, they rarely serve as primary indicators of contamination or spoilage. Their limited overlap with nanosensors (25 papers) suggests that some nanomaterial-based devices incorporate physical sensing elements (Nazir & Kwon, 2022; Zhang et al., 2023), though the topic remains a relatively minor research direction.

A visual overview supporting the data in Fig. 8. This figure presents a normalized (percentage-based) representation of sensor distribution across studies addressing one, two, three, or four sensor categories, to make potential structural trends more visible. The predominance of biosensors remains stable regardless of the degree of technological integration, confirming their foundational analytical role. It emerges that nanosensors are pivotal, particularly in multi-sensor configurations, reinforcing their role as performance-enhancing elements embedded within broader sensing platforms. Conversely, physical sensors consistently exhibit a lower relative representation in the analyzed literature. This trend should not be interpreted as a reduction in their operational relevance within storage and logistics contexts. Rather, it indicates that physical parameters are not often the primary analytical target in food safety research. Still, they are typically adopted as complementary elements, providing essential environmental and contextual information that supports and enhances the interpretation of chemical and biological detection results. These findings suggest that this research stream is increasingly shifting toward application-driven integration strategies, as real-world food supply chains require simultaneous monitoring of multiple parameters under variable environmental conditions. Thus, this emerging paradigm is not focused on optimizing isolated sensing principles but on designing interoperable, multi-layered architectures aligned with Industry 4.0 goals, where biological specificity, nanomaterial-enhanced sensitivity, and digital connectivity converge to enable robust, real-time, and scalable food monitoring systems.

The results presented in Figs. 5 and 7, and Table 1, and summarized in Fig. 8, provide more than a descriptive overview of sensor frequencies, but they reveal a structural pattern in the evolution of food sensing research within the Industry 4.0 framework. Particularly, the significant predominance of biosensors across single-sensor and multi-

Table 1
Heat map with the number of papers focused on the multi-sensor approach.

	Chemical Sensor	Biosensor	Optical Sensor	Physical Sensor	Nanosensor
Chemical Sensor	-	232	90	27	146
Biosensor	232	-	92	31	200
Optical Sensor	90	92	-	17	86
Physical Sensor	27	31	17	-	25
Nanosensor	146	200	86	25	-

Legend

1

232

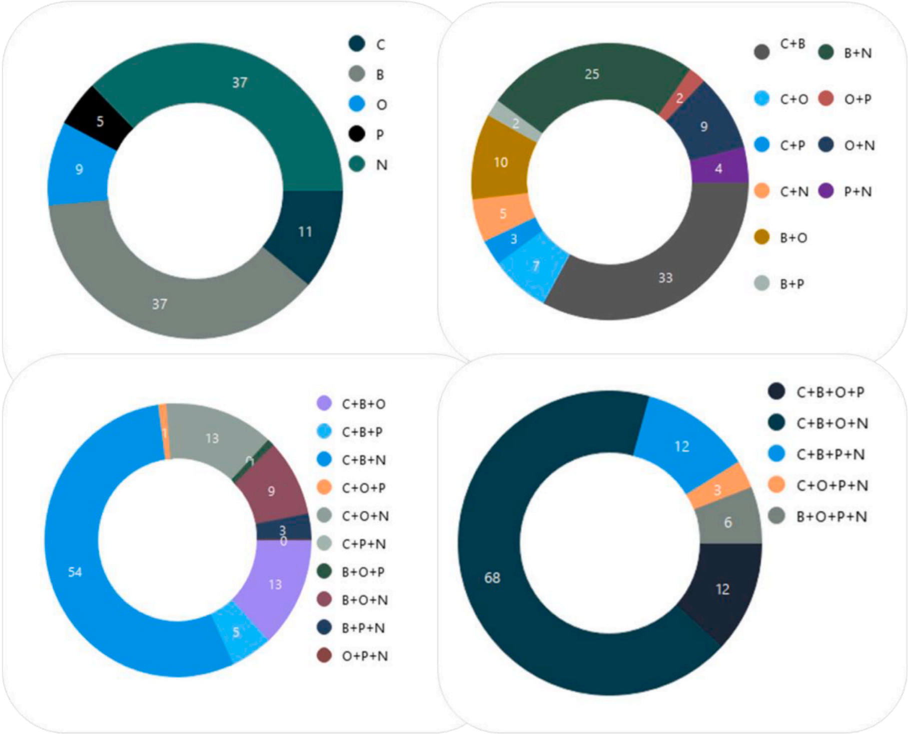

Fig. 8. Distribution of the sensors (% analyzed in papers that address one, two, three, and four sensors. C = chemical sensor; B = biosensor; O = optical Sensor; P = physical sensor; N = nanosensor.

sensor studies reflects a clear trend toward the detection of biologically and chemically relevant hazards. Since most food safety risks are associated with pathogens, toxins, allergens, and biochemical degradation products, sensing strategies based on biological recognition elements intrinsically play a pivotal role. Their high selectivity and adaptability to different food matrices make them suitable not only as stand-alone analytical tools but also as core components within integrated monitoring systems. Besides, the strong co-occurrence of biosensors with nanosensors and with chemical or optical sensors indicates a progressive technological convergence, showing nanosensors, as well as biosensors and chemical or optical sensors, indicates a progressive technological convergence, demonstrating that sensor technologies are no longer developed as isolated devices but as integrated hybrid architectures. Nanomaterials are frequently incorporated to enhance sensitivity, improve signal stability, and reduce detection limits, while optical and EC transduction mechanisms are employed to strengthen signal readability and quantitative accuracy. Thus, this convergence reflects a broader transition from discipline-specific sensor development toward performance-driven integration, which addresses the intrinsic complexity and variability of food systems by combining complementary detection principles and strategies.

As shown in Table 2, every sensing technology has its own advantages and limitations, which are dependent on the underlying principle of operation and the target analyte of interest. As such, current research efforts are focusing more on the development of hybrid sensing techniques, where more than one sensing modality is employed to enhance the accuracy of the sensing technology, particularly in applications where single modalities may fall short in sensitivity or specificity.

3.3. Examples of applications of sensors and industry 4.0 technologies in the food industry

In the conventional food industry, proper control of operational variables, including temperature, humidity, and gas concentration, is often considered critical, especially in processes like fermentation and drying. To address this challenge, integrating sensors with Industry 4.0 technologies, such as the IoT, AI, blockchain, cloud computing, big data analytics, and DT, enables sustainable, data-driven, and real-time production systems aimed at enhancing productivity and manufacturing efficiency.

Table 3 offers an in-depth assessment of the main digital technologies that support and enhance the functionality of sensor systems within the food industry. Each technology plays a distinct yet complementary role in enabling data-driven, intelligent, and connected food systems. The table outlines their primary functions, key applications, and the benefits they bring to sensor-based monitoring and control.

Table 2
Summary of sensor technologies used for food quality and safety monitoring.

Sensor Technology	Advantages	Limitations	Target Analytes	References
Chemical Sensors	High sensitivity; fast detection; simple design	Interference from complex food matrices; limited selectivity	Heavy metals, pesticides, toxins, spoilage gases	(Saputra et al., 2025; Skowronkova et al., 2024; Wei et al., 2024)
Biosensors	High specificity; rapid pathogen detection	Limited stability of biological elements; sensitive to environmental conditions	Bacteria, toxins, allergens, metabolites	(Tsegay et al., 2024; Vallinayagam et al., 2022; Wang et al., 2022)
Optical Sensors	Non-destructive; real-time detection; high sensitivity	Affected by light interference and sample turbidity	VOCs, mycotoxins, pesticide residues, spoilage indicators	(Santos et al., 2019; Sun et al., 2025; Zhang et al., 2023)
Physical Sensors	Robust; simple operation; widely used in monitoring	Cannot detect specific chemical or biological contaminants	Temperature, humidity, pressure	(Melesse, 2026; Satpati et al., 2017; Soltani Firouz et al., 2021)
Nanosensors	Very high sensitivity; trace-level detection	Complex fabrication; stability issues	Pathogens, heavy metals, pesticides, toxins	(Singh, Kumar, et al., 2024; Srivastava et al., 2018; Zhou et al., 2023)

The implementation of these technologies may improve food quality, safety, and efficiency across the entire value chain, from production and processing to distribution and consumption. IoT-based sensors play a central role in transforming the conventional food industry to smart food factories, as, when integrated with microcontrollers and cloud-based interfaces, they can provide decentralized and automated quality assessment, rapid spoilage detection, and continuous, wireless monitoring of environmental and process parameters across the food supply chain (Konfo et al., 2024). Kumar et al. (Kumar, Kannampilly, & Joy, 2024) proposed the use of edible electronic sensors to monitor food in real time and prevent spoilage, discussing different types of such sensors and their applications in detecting spoilage in both liquid and solid foods. On the other hand, Konfo et al. (Konfo et al., 2024) investigated how integrating IoT with RFID and Near Field Communication (NFC) technologies has transformed food quality monitoring by enabling real-time tracking, data analysis, and proactive actions to reduce waste and ensure freshness.

AI and ML have made food manufacturing systems even better at analyzing and optimizing. These technologies can process large datasets produced by IoT-enabled sensors to classify food properties and quality, detect anomalies, predict shelf life, and forecast contamination risks (Guliy et al., 2025). Integration of computer vision, electronic noses, and electronic tongues using AI enhances objectivity and efficiency in quality control operations, hence reducing manual inspection demands significantly (Peveler, 2024). The combination of IoT and ML technologies supports automation, self-regulation, and real-time alerts during processing, reducing manual intervention and operational failures (Alam et al., 2025). Kadian et al. (Kadian et al., 2024) proposed a low-cost, ML-enabled, microneedle-based colorimetric pH sensing patch for monitoring food freshness and wound health, combining 3D printing, autonomous fluid sampling, and smartphone integration for accurate and user-friendly pH detection. Grasso et al. (Grasso et al., 2025) investigated coffee samples' EC fingerprints using ML to reveal patterns and classifications within complex chemical data.

DL is a sophisticated subset of ML that uses multi-layered neural network architectures, often referred to as Deep Neural Networks (DNNs), to process and interpret data (Alam et al., 2025). The core characteristic that distinguishes DL models from traditional ML models is their ability to automatically extract and learn complex, hierarchical feature representations directly from raw data, without requiring explicit programming for feature engineering (Deng et al., 2025). This

Table 3
Digital enabling technologies supporting the sensor ecosystem.

Digital Enabler	Functionality	Use Cases	Advantages	Limitations
IoT	Wireless sensor network, remote diagnostics (Kolupula et al., 2024)	Storage/transport monitoring, alerts (Griesche & Baeumner, 2020; Singh et al., 2017)	Scalable, mobile-accessible (Wang, Lan, et al., 2025; Wei et al., 2025)	Bandwidth, energy, and security (de Souza Carvalho et al., 2025; Garg et al., 2024)
ML	Predictive analysis, pattern recognition (Cosme et al., 2025; Parakh et al., 2025)	Shelf-life, quality prediction (Bala et al., 2023; de Souza Carvalho et al., 2025)	Fast, adaptive decisions (Bala et al., 2023; Parakh et al., 2025)	Data dependency, model drift (Patil & Meshram, 2023; Peveler, 2024)
DL	Auto extract complex hierarchical features (Deng et al., 2025; He et al., 2024)	Image recognition, complex classification, real-time diagnostics (Bhuiyan et al., 2024; Deng et al., 2025)	Superior accuracy, robust, auto feature extraction, scalable (He et al., 2024; Parakh et al., 2025)	Requires large data, high compute, black box interpretability (He et al., 2024; Parakh et al., 2025)
3D Printing	Layer-by-layer formation, Computer-Aided Design (CAD), and automated deposition of materials (Koukouviti et al., 2026; Paul et al., 2024)	Creates affordable, customised sensors for rapid analysis at point-of-need (Koukouviti et al., 2026)	Cost-Effectiveness, on-site/point-of-need fabrication and use of rapid prototyping, reduced material waste (Rivas-Macho et al., 2023; Skowronková et al., 2024)	Requirement of post-processing, slow printing speeds, material constraints, and vulnerability to contamination (Paul et al., 2024; Rivas-Macho et al., 2023)
Cloud	Storage, computation, and analysis platform (Lazaro et al., 2023; Singh et al., 2017)	IoT, environmental monitoring and public safety, smart agriculture and diagnosis (Lazaro et al., 2023; Singh et al., 2017)	Facilitates advanced analysis, supports high-efficiency/large-scale processing (Wei et al., 2025)	Security, interoperability issues, regulatory complexity, and operational costs (Garg et al., 2024)
Blockchain	Real-time tracking of products, enhanced transparency, automated data collection, and ensured accountability (Radogna et al., 2022)	Tracking the supply chain and ensuring Hazard Analysis and Critical Control Points (HACCP) compliance (Niyigaba et al., 2025)	Enhanced safety and traceability, fraud Prevention, economic efficiency, and consumer confidence (Niyigaba et al., 2025; Radogna et al., 2022)	-
Big Data	Data integration and analysis, real-time traceability, and chemical/biological Sensing (Ghaffari, 2024; Singh et al., 2017)	Food safety and quality, supply chain management (SCM), anti-counterfeiting, and public health (Ghaffari, 2024; Singh et al., 2017)	Increased efficiency, economic growth, enhanced safety, and low cost (chipless passive RFID tags) (Ghaffari, 2024; Singh et al., 2017)	Health and safety concerns (radio frequency radiation), energy requirements, and data security (Ghaffari, 2024; Singh et al., 2017)
DT	-	-	-	-

intrinsic capability allows DL systems to handle massive volumes of complex data and identify hidden, non-linear relationships that traditional analysis might miss (Alam et al., 2025). Architectures commonly associated with DL include Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and ANNs with multiple layers (Deng et al., 2025). For example, Bhuiyan et al. (Bhuiyan et al., 2024) proposed a custom CNN integrated into an IoT system to classify both meat species and freshness using high-resolution images of beef and mutton. This DL approach outperformed traditional ML models, such as Support Vector Machines (SVM) and k-Nearest Neighbors (k-NN), demonstrating superior capability in managing complex image-based analyses. Similarly, Han et al. (Han et al., 2025) applied DL to an e-nose to monitor and predict egg liquid spoilage by detecting volatile gases. Results showed that egg solution stored at room temperature became unsuitable for consumption once H_2S levels exceeded 1 ppm, demonstrating the system's effectiveness for food safety monitoring.

Recent advancements in Industry 4.0 technologies have revolutionized the field of food technology by enabling new methods of customization, precision, and environmental friendliness. The integration of smart sensors within 3D-printed food systems and packaging materials enables continuous, real-time monitoring and adaptive process control. Advanced techniques such as fused deposition modelling and direct ink writing are being adopted to develop functional structures embedded with biosensors, colorimetric indicators, and humidity- or temperature-responsive elements (Paul et al., 2024). Rivas-Macho et al. (Rivas-Macho et al., 2023) proposed the design and 3D printed a microfluidic EC biosensor for rapid, sensitive, and specific on-site detection of *Listeria monocytogenes* in food samples. Skowronková et al. (Skowronková et al., 2024) investigated the use of 3D printing to develop a low-cost gas detection system, optimizing a 3D-printed chromatographic column to distinguish between ethanol and methanol.

Cloud computing is a key technology integral to the IoT that provides a robust platform for data management and advanced processing (Singh et al., 2017). It involves the centralized storage of data across the globe and facilitates easy access and sophisticated analysis. Data is transmitted to cloud-based platforms or cloud systems where advanced computational processes, often utilizing sophisticated algorithms and AI, analyze the information to generate valuable insights (Lazaro et al., 2023). The mobile device (like a smartphone) frequently acts as the user interface for transmitting data to and retrieving information from these cloud services (Singh et al., 2017). Singh et al. (Singh et al., 2017) proposed a cloud-based framework for food quality monitoring and supply chain traceability, highlighting the role of cloud computing in managing the large volume of data generated by food industry sensors. Tools such as RFID and NFC tag sensors monitor spoilage, transmitting data. This information, together with product identification and traceability data, is sent through the IoT infrastructure to cloud platforms, which store global-scale datasets and run advanced analytical algorithms. The system integrates field-level production data into the broader supply chain, enabling real-time insights on product integrity, logistics, and inventory in e-grocery networks.

Therefore, the integration of sensor and digital technologies forms a comprehensive framework for predictive, automated, and verifiable food monitoring, transforming passive data collection into intelligent decision-support systems capable of anticipating risks, ensuring regulatory compliance, and improving operational efficiency across the food value chain, ultimately enabling a more sustainable, efficient, and consumer-oriented model of food manufacturing and distribution. To make sure that the implementation goes well, several problems need to be solved, such as data interoperability, cybersecurity, infrastructure investment, and workforce training (Dey & Ahmed, 2025). These barriers are critical for small and medium-sized enterprises (SMEs), which often lack the technical expertise and financial resources required to adopt advanced digital solutions (Rawat et al., 2024; Singh, Sharma, & Rawat, 2024).

As can be described from Table 3, Technologies such as blockchain, big data, and DT are included because the authors consider them relevant; however, only a few papers address these topics. Based on the author's experience, implementing these technologies in the food industry remains challenging due to several structural and technological factors. The food sector is characterized by fragmented supply chains involving many heterogeneous actors, often with low levels of digitalization, especially in primary production. This situation limits the availability, quality, and standardization of data required for advanced digital solutions. Implementing these technologies requires significant investments in digital infrastructure and data management systems, which may be difficult for many small and medium-sized enterprises in the sector to sustain. Additional challenges arise from the natural variability of biological processes and from organizational barriers related to data sharing and governance. These limitations largely reflect the current level of technological maturity of the sector; future improvements in digital infrastructure, standardization, and collaboration across the supply chain may progressively facilitate the adoption of these technologies.

Notably, the analysis shows that only Niyigaba et al. (Niyigaba et al., 2025) and Radogna et al. (Radogna et al., 2022) discuss blockchain. This technology provides an extra layer of security and transparency by enabling sensor-verified data to be stored on decentralized systems and in irreversible ledgers. More in detail, Radogna et al. (Radogna et al., 2022) investigated the contribution of blockchain in ensuring traceability, transparency, and security in the supply chains of wine and kimchi by providing immutable and verifiable records that guarantee compliance with HACCP principles and enhance trust throughout production, logistics, and storage processes.

Only Singh et al. (Singh et al., 2017) and Ghaffari (Ghaffari, 2024) specifically address Big Data and other Industry 4.0 technologies that enable the integration, correlation, and visualization of data from various sources, including sensors, equipment, external databases, and customer feedback. In food systems, Big Data approaches help identify inefficiencies, maximize business processes, and enable data-driven policy-making and strategic decision-making. Coupled with AI and IoT platforms, big data analytics is key to advanced forecasting, demand planning, and individualized nutrition services. Ghaffari (Ghaffari, 2024) investigated the use of big data in supporting ML and DL approaches for efficient, accurate, and non-destructive seed quality assessment and variety classification.

Among the analyzed papers, no studies were identified that explicitly focus on the application of DT technologies integrated with sensor systems in the food industry. This can be explained by the intrinsic complexity of DT implementation in food systems, which are characterized by high variability of raw materials, biological and chemical dynamics, short product lifecycles, and strict regulatory constraints. While manufacturing sectors usually employ highly standardized and repeatable processes, the food industry faces major difficulties with the development of accurate, real-time virtual replicas continuously synchronized with sensor data. The adoption of DT technologies typically requires mature digital infrastructures, high data availability, and advanced modeling capabilities that are not yet widely established across food supply chains, particularly among SMEs. Current research efforts appear to prioritize enabling technologies, such as IoT, ML, or cloud computing, that represent necessary precursors to full DT implementation. This finding suggests that DTs remain in an emerging and largely unexplored research area within the context of sensor-based food systems, representing a promising direction for future research.

4. Benefits of sensor technologies in the food sector

The implementation of smart sensor technologies across the food supply chain has become a cornerstone of the modern agri-food industry. Their integration with I4.0 technologies such as IoT, AI, and cloud computing should not be considered just a technical capability improvement but also a strategic facilitator of intelligent, data-based food processes since they enable initiative-taking decision-making, predictive control, and a higher level of traceability. By allowing continuous monitoring, real-time data acquisition, and advanced analytics, they are transforming traditional processes into intelligent, adaptive, and transparent ecosystems that aim to improve food quality, safety, and efficiency while advancing sustainability goals and empowering consumers. Thus, Fig. 9 conceptually illustrates this integration by positioning sensors as core elements of this ecosystem. Sensors are distributed across all stages of the food supply chain, including production, processing, packaging, transportation, and storage. At each stage, they are designed to capture critical parameters related to food quality, safety, and environmental conditions, such as chemical contaminants, spoilage indicators, temperature, humidity, light exposure, and other quality-related attributes. These sensing devices continuously generate real-time data, forming the primary data flow that feeds the digital ecosystem. Through IoT connectivity, sensor data are transmitted to decentralized and centralized data infrastructures, where they are aggregated, filtered, and contextualized. This data stream constitutes a critical input for monitoring, analysis, and decision-making processes, enabling the timely detection of anomalies, degradation patterns, or unsafe conditions along the supply chain. On top of this data flow, Industry 4.0 technologies, including advanced data analytics, ML, cybersecurity, and visualization tools, support the transformation of raw sensor data into actionable information. The integration of these digital enablers allows predictive insights, automation of control actions, and end-to-end traceability of food products. The sensor-driven architecture depicted in Fig. 9 enables the development of a smart food system capable of real-time monitoring, adaptive control, and seamless communication across the entire value chain.

This section does not aim to provide an exhaustive or highly detailed analysis of every sensor application across the various processes of the food supply chain. It offers a general yet comprehensive overview of how smart sensors impact the main stages of the food supply chain. The discussion highlights their role and beneficial effects in improving safety, efficiency, sustainability, and traceability from cultivation to consumption.

4.1. Primary production

At the production stage, sensors are essential for optimizing production efficiency and minimizing environmental impact. IoT-based soil and environmental monitoring systems continuously monitor key parameters such as soil moisture, nutrient levels, light intensity, temperature, and humidity (Konfo et al., 2024). This real-time data properly supports farmers in the decision-making process regarding irrigation, fertilization, and pesticide application. For instance, precision agriculture, supported by these sensors, reduces water and chemical use while maximizing yield and resource efficiency (Rahman et al., 2025). Biosensors and gas sensors are increasingly used to detect pesticide residues, heavy metals, or microbial contamination at the field level, ensuring that raw materials meet safety standards before entering the supply chain (Feroci et al., 2025; Salomón-Flores et al., 2025). Another intriguing application is related to early detection of plant diseases or pest infestations through image-based and chemical sensors that enable rapid interventions, reducing losses and improving crop resilience. (Wang et al., 2022). Thus, the implementation of smart sensors contributes to more sustainable and data-driven farming practices that preserve natural resources while maintaining consistent product quality.

4.2. Processing and manufacturing

In food processing and manufacturing, sensor systems are central to

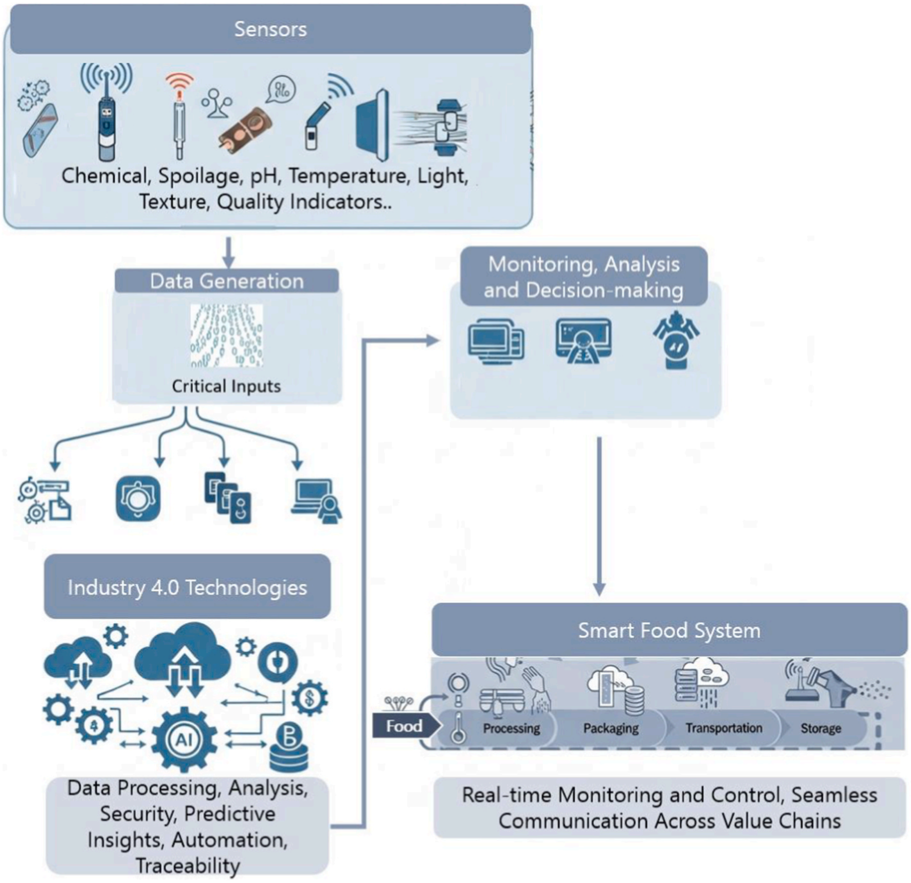

Fig. 9. Conceptual food sensor integration in the Industry 4.0 framework.

maintaining control over operations subject to strict regulations. Parameters such as temperature, pressure, vibration, and humidity are monitored to ensure that production lines operate within optimal and compliant conditions (Cai et al., 2021; Nirgund et al., 2022). Biosensors and chemical sensors are adopted to detect pathogens, allergens, toxins, or unwanted chemical residues in real time, providing immediate feedback for corrective actions, while their integration into IoT-based platforms is mainly being used for automated quality monitoring and predictive maintenance (Konfo et al., 2024). In this scenario, the adoption of AI and ML algorithms may provide additional benefits. They enable real-time analysis of sensor data, support health monitoring of equipment, detect process deviations, and help prevent potential failures before they occur. This data-driven approach may improve compliance with food safety regulations, ensure consistent product quality, and reduce downtime (Bhatt et al., 2023; Gharibzahedi & Altintas, 2024). Smart sensors are increasingly applied to process optimization and energy management, particularly through thermal and flow sensors in pasteurization or sterilization units that regulate heat and airflow conditions to improve energy efficiency (Cho et al., 2022; Machado et al., 2025).

4.3. Storage and transportation

Storage and transportation are crucial stages of the food supply chain, as they require maintaining products in optimal conditions to preserve quality and prevent spoilage. chain, as they require maintaining the products in optimal conditions, aiming at preserving food quality and preventing spoilage. Smart sensors in cold chain logistics are adopted to monitor temperature, humidity, and gas composition to ensure the integrity of perishable goods such as meat, seafood, fruits, and dairy (Bhatt et al., 2023; Fathima et al., 2022). Here, real-time data transmission from wireless sensor networks is adopted to trigger alerts when deviations occur, allowing immediate corrective actions before any adverse effect on the quality of the product (Srivastava et al., 2018; Vallinayagam et al., 2022). The resulting benefits include reduced food waste, improved inventory management, and enhanced accountability across the supply chain. In transportation, geolocation and environmental data are incorporated into IoT-based tracking systems to provide end-to-end traceability and transparency (Paliwal et al., 2025; Soltani Firouz et al., 2021). AI-driven predictive analytics also support energy optimization in refrigerated transport and storage, contributing to lower emissions and more sustainable distribution systems (Dey & Ahmed, 2025).

4.4. Retail and consumption

Sensor technologies facilitate product transparency at the retail and consumer levels and enable customers to make informed decisions. In this stage of the food supply chain, advancements are related to smart packaging equipped with embedded sensors or indicators that provide real-time information on product freshness, gas exchange, and storage conditions (Annanouch et al., 2021; Singh, Kumar, et al., 2024). An intriguing and easy-to-use solution is colorimetric or pH-sensitive labels that change color when spoilage occurs, providing visual confirmation of food quality and helping avoid the inadvertent consumption of unsafe food (Cho et al., 2022; Shaibani et al., 2018). RFID tags and NFC sensors enable digital traceability of products. They allow retailers and consumers to access information about origin, production, and handling conditions via smartphones. This capability can reduce reliance on conservative expiration dates, extend shelf life, and decrease unnecessary food disposal. When integrated into traceability platforms like blockchain, sensor-verified data enables rapid contamination source identification, batch-level separation, and focused recalls (Gharibzahedi & Altintas, 2024). In this context, it is worth mentioning that recent research has begun to explore the potential of sensor-based Digital Product Passports (DPPs) for food systems, since they can be beneficial for addressing traceability issues or zero-km initiatives (Lekawska-Andrinopoulou et al., 2024; Lopes & Barata, 2024). However, although food products are currently excluded from the ongoing EU regulatory framework on DPPs (at present, food assets fall outside the scope of the Ecodesign for The Sustainable Products Regulation (European Commission, 2022) suggests (European Commission, 2022), preliminary studies suggest that integrating smart sensors within digital passport architectures could provide significant advantages. Sensors can constantly collect information about the source, processing, storage conditions, and environmental factors. Producers, regulators, and consumers can all access this information to create a dynamic digital passport (Pracucci & Giovanardi, 2025). dynamic digital passport that producers, regulators, and consumers can all access (Pracucci & Giovanardi, 2025). continuously capture data on origin, processing, storage conditions, and environmental parameters, which can then feed into a dynamic digital passport accessible to producers, regulators, and consumers (Pracucci & Giovanardi, 2025). This would enhance traceability, auditability, and transparency while supporting more informed and sustainable decision-making.

Standardization of sensor design regarding contact materials used in packaging is critical to ensure consumer safety. Advances in food-grade and biodegradable materials enable safe direct-contact application that meets regulatory standards while maintaining functionality (Dumitru et al., 2016). The use of low-cost materials and processes improves access to sensor-enabled safety devices. Advances in paper-based sensors, printable biosensors, and low-cost nanomaterial platforms are leading to increased cost reductions for safety monitoring, making these benefits accessible to resource-limited manufacturers and communities. In this scenario, developing sensors that are reusable, modular, and biodegradable promotes sustainable manufacturing practices and aligns with the principles of the circular economy. Recent breakthroughs using additive manufacturing and 3D printing technologies have made the affordable fabrication of sustainable sensors using paper substrates, biopolymers, and plant-based pigments possible. (Paul et al., 2024; Rivas-Macho et al., 2023). This development is especially relevant to SMEs, where complexity and cost have traditionally prevented uptake.

At the household level, IoT-enabled smart appliances, such as refrigerators and storage units, can monitor food conditions, alert users of forthcoming expiration, and optimize temperature settings. (Kaushal et al., 2023).

5. Challenges, opportunities, and future perspectives

The integration of sensor-based smart monitoring systems is a breakthrough in the evolution of the food industry toward Industry 4.0. As the systems continue to develop and become more digitally integrated, their impact extends beyond technological efficiency. They also influence wider systemic concerns, inform theoretical models, guide practical applications, and highlight potential research areas that affect scalability and operational effectiveness. However, despite significant advances, numerous barriers hinder the widespread adoption of such technologies. The high initial cost requirements and ongoing operational expenses, particularly those associated with nanomaterial-based sensor systems that possess multifunctionality and multiplexing properties, significantly limit their availability in a sector primarily composed of SMEs (Rawat et al., 2024; Singh, Sharma, & Rawat, 2024; Srivastava et al., 2018). While cost-reductive alternatives, paper-based, inkjet-printed, and biodegradable sensors arise (Dumitru et al., 2016; Zhang et al., 2017). Such platforms routinely suffer from mechanical durability, calibration stability, and large-scale manufacturability constraints. Another critical challenge lies in interoperability. The lack of standardized data exchange protocols and harmonized interface architectures prevents seamless integration between heterogeneous sensor platforms and enterprise systems, such as Enterprise Resource Planning (ERP) and SCM. This fragmentation hinders full automation, end-to-end traceability, and the realization of truly smart and connected food networks. (Bhuiyan et al., 2024; Eleftheriadou et al., 2017; Hussain et al., 2016).

Furthermore, regulatory uncertainty complicates the deployment of sensors in applications such as embedded sensing in food packaging, nanomaterials interacting with consumables, and cross-border legal compliance (Fathima et al., 2022). Concurrently, ethical issues such as data privacy, cybersecurity, algorithmic accountability, and informed consumer consent are becoming increasingly complex due to the pervasive presence of IoT- and AI-based monitoring systems (Gharibzahedi & Altintas, 2024; Rafi et al., 2025). They involve multifaceted challenges that necessitate coordination among various stakeholders, such as regulatory harmonization, investment in digital infrastructures by the public and private sectors, and the implementation of internationally agreed sensor validation and certification mechanisms. It is worth mentioning that sensor technologies are driving a reorganization of theoretical paradigms concerning digital transformation in agri-food systems. Decentralized, real-time, and anticipatory monitoring sensors drive the shift from static, linear food supply chains to dynamic, cyber-physical ecosystems. Quality assurance is proactive and integrated, rather than a retrospective, batch-oriented procedure (Awlqadr et al., 2025). This transition reshapes the value of production and distribution processes. Information, previously seen only as a secondary by-product, now becomes a strategic resource that promotes transparency, efficiency in operations, and trust in networked food systems. Therefore, the traditional theoretical approaches must be re-examined to account for data-driven value creation, algorithmic decision-making, and the distributed modes of governance that typify highly networked agri-food spaces (Zhang, Alizadeh Sani, et al., 2025).

For enterprises, especially SMEs, organizational agility and digital preparedness are emerging as the imperatives for competitive success (Bhatt et al., 2023). Businesses should carefully assess their capability to integrate sensor networks into their infrastructure, operations, and information systems. Adopting modular, interoperable sensor architectures allows for scalable, incremental implementation with lower financial and operational risk (Dey & Ahmed, 2025; Mousavi et al., 2024). In this context, policymakers can play a crucial role in enabling the integration of technologies by creating strict validation protocols, safety measures, and standardization systems that enhance the deployment of sensors. This role is especially important in applications like intelligent packaging, ecological monitoring, and interaction with food products. At the same time, fiscal instruments and incentive models, from subsidies and tax rebates to public-private partnerships, are used to reduce entry barriers for SMEs.

From a technological point of view, future innovations should be cheap, easy to use, and able to adapt to different situations. Advances in additive manufacturing, biodegradable substrates, wireless communication, and AI-enabled plug-and-play modules are promising for small producers and rural settings with limited resources. (Gulia et al., 2025; Singh, Kumar, et al., 2024). Localized deployment strategies should consider the local digital infrastructure, the availability of labor skills, regulatory environments, and clients' needs. Here, the use of readiness assessment instruments that analyze technical, institutional, and policy aspects can improve implementation effectiveness in a range of different socio-economic situations. (Flauzino et al., 2022; Radogna et al., 2022).

Research gaps remain. Despite progress in different sensor prototypes and early systems, there is still limited information on their performance in real-field operational conditions that cover inherent complexities. Factors like product heterogeneity, environmental interference, matrix effects, and microbial cross-contamination need further investigation to ensure the reliability, specificity, and reproducibility of sensors through extensive deployment (Cho et al., 2025; Lasarte-Aragonés et al., 2023). Emerging technologies like wearable food-sensing devices, ingestible sensors, and AI-powered edge computing devices are creating new possibilities but require interdisciplinary research between materials science, human-machine interfaces, embedded systems, and food analytics. Likewise, understanding consumer attitudes toward smart labels, data ownership, data sharing preferences, and algorithmic mediation in food choice remains vital for guaranteeing public trust and equitable access to digitalized food systems (Flores-Rangel et al., 2024; Konfo et al., 2024). Therefore, future research streams should focus on the development of affordable, modular sensor kits tailored directly to the needs of SMEs and decentralized food systems. There is an urgent need to focus on integrating AI and sensor technology. This integration would enhance collaboration between policymakers, technologists, and industry actors. It is also essential for creating transparent, resilient, and inclusive food systems that fully harness the potential of digital transformation.

6. Conclusions

Sensor technologies radically transform the technological, operational, and thinking paradigms of current food industry practices. When embedded in digital infrastructures, they play crucial roles as enablers of Food Industry 4.0 by allowing real-time, non-intrusive, and highly accurate monitoring of key quality and safety parameters. Such systems improve predictive management, process optimization, and transparency, thus contributing to the reduction of inefficiencies along the value chain. With this background, the present paper conducted both a bibliometric and a content-based analysis to examine the current research landscape of I4.0-driven sensor technologies in the food industry. The former aims to provide a broad overview of the investigated topic by analyzing existing literature, exploring the temporal evolution of research outputs, and examining the geographical distribution of scientific contributions. Keyword co-occurrence analysis was employed to identify the main thematic clusters that characterize ongoing research trends. Then, the content-based analysis interprets the insights emerging from these clusters, providing a comprehensive understanding of the main sensor technologies used in food applications, the digital platforms that enable their integration within the Food Industry 4.0 framework, and the associated benefits and challenges throughout the entire food supply chain. This integration within the Food Industry 4.0 framework, along with its associated benefits throughout the entire food supply chain and the challenges related to practical implementation, is essential. This paper discusses the role of IoT within the Food Industry 4.0 framework, the associated benefits along the entire food supply chain, and the benefits and challenges related to its practical implementation. The results achieved show that the research on sensor technologies in the food industry has significantly increased over the past five years. This growth reflects the rising global interest in digital transformation and data-driven food quality monitoring, boosted by the specific national and international policies, such as the European F2F strategy. The bibliometric analysis highlighted that Asia and Europe are the most active regions in this field, with China, India, and several EU countries emerging as leading contributors. These regions have prioritized innovation in smart and sustainable food systems, supported by public research programs and industrial initiatives promoting digital integration across the entire supply chains. The keyword co-occurrence analysis revealed five major thematic clusters: (1) sensor typologies and detection principles; (2) food storage and control; (3) human health hazards; (4) food safety through digital technologies; and (5) smart packaging for food quality control. The general overview that emerged from these clusters delineates a multidimensional research landscape where technological innovation, safety assurance, and process optimization converge under the Industry 4.0 paradigm. The content-based analysis confirmed that chemical, biosensor, optical, physical, and nano-enabled sensors are the most frequently studied technologies. Their integration with digital enablers such as IoT, AI, blockchain, big data, 3D printing, and cloud computing supports the development of intelligent and predictive monitoring. ecosystems. These solutions enhance process transparency, energy efficiency, and real-time traceability while supporting sustainability and regulatory compliance. The analysis revealed that most technological applications and research efforts are concentrated in large-scale industrial contexts, whereas SMEs, which dominate the agri-food sector, still face substantial barriers to adoption due to costs, technical expertise, and infrastructural gaps. There are still systemic barriers, such as the need for economic scalability, interoperability, regulatory consistency, and ethical data management. There are still systemic barriers, such as the need for economic scalability, interoperability, regulatory consistency, and ethical data management. Barriers remain in economic scalability, interoperability, regulatory consistency, and ethical data management. The theoretical results of this research support the idea that the digital transformation of food systems represents not only a trend toward automation but, more importantly, a necessary evolution towards decentralized, data-driven, and collaborative networks.

Successful implementation of smart monitoring systems requires coordinated strategies that address technological maturity, institutional capacity, and inclusive policy frameworks. Such strategies are of critical importance for the involvement of small and medium-sized enterprises, as well as other stakeholders, in the economies of the developing world. From a research perspective, the following can be expected for the near future: closing the gap between ideas and practice by testing the sensor's performance under real, ever-changing, risky environments. In summary, sensor technology plays a significant role in driving the digital revolution of the food industry, providing benefits for monitoring, contamination detection, traceability, and decision-making using Industry 4.0 technologies, the Internet of Things, and artificial intelligence. A combined effort involving AI integration, user-centered design principles, ethical data stewardship, and global regulatory harmonization will be essential in the development of sustainable, inclusive, and dependable smart food systems. The readiness of the food sector for smart regulation depends not only on technological advancements but also on the overall ability to balance innovation and the needs of society, ethical considerations, and global sustainability goals.

CRediT authorship contribution statement

Mattia Braggio: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Tsega Y. Melesse:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Simone Arena:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation. **Pier Francesco Orrù:** Project administration. **Federico Briatore:** Writing – original draft, Visualization, Conceptualization.

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Abbreviations

Supply Chain Management	SCM
Radio Frequency Identification	RFID
Metal-Organic Frameworks	MOFs
Near Field Communication	NFC
Hazard Analysis And Critical Control Points	HACCP
Small And Medium-Sized Enterprises	SMEs
Internet Of Things	IoT
Deep Learning	DL
Machine Learning	ML
Artificial Intelligence	AI
Digital Twins	DT
Surface Plasmon Resonance	SPR
Silver Nanoparticles	AgNPs
Molecularly Imprinted Polymers	MIPs
Hydrogen Sulphide	H_2S
Electrochemical	EC
Gold Nanoparticles	AuNPs
Carbon Nanotubes	CNTs
Quantum Dots	QDs
Convolutional Neural Networks	CNNs
Artificial Neural Networks	ANNs
Farm To Fork	F2F
Genetically Modified Organisms	GMOs

Data availability

Data will be made available on request.

References

Abedi-Firoozjah, R., Ebdali, H., Soltani, M., et al. (2024). Nanomaterial-based sensors for the detection of pathogens and microbial toxins in the food industry; a review on recent progress. *Coordination Chemistry Reviews, 500*. https://doi.org/10.1016/j.ccr.2023.215545

Ador, M. S. H., Bhattacharjee, P., Kabir, S., et al. (2024). Review of new developments in different types of sensors over the past 15 years. In *Comprehensive mater. Processing* (2nd ed., pp. 1–13). Elsevier. V12:100-V12:116.

Aisa, R., Cabeza, J., & Martin, J. (2023). Automation and aging: The impact on older workers in the workforce. *The Journal of the Economics of Ageing, 26*, Article 100476. https://doi.org/10.1016/j.jeoa.2023.100476

Akhavan-Mahdavi, S., Mirbagheri, M., Assadpour, E., et al. (2024). Electrospun nanofiber-based sensors for the detection of chemical and biological contaminants/hazards in the food industries. *Advances in Colloid and Interface Science, 325*, Article 103111. https://doi.org/10.1016/j.cis.2024.103111

Al-Hilphy, A. R., Al-Asadi, M. H., Al-Hmedawy, N. K., et al. (2022). Effects of electrical field stimulation on the physicochemical and sensory attributes of aged chicken meat. *Journal of Food Process Engineering, 45*. https://doi.org/10.1111/jfpe.14032

Alagumuthu, G., Gubendiran, B., Govindharajan, M., & Noorjahan, S. E. (2025). Allium cepa L. - A natural naked eye colorimetric sensor for distinctive detection of Fe2+ and Fe3+ in aqueous medium. *Chemosphere, 387*. https://doi.org/10.1016/j.chemosphere.2025.144683

Alam, M. M., Al-Bahrani, H. A., Khujaniyozova, O., et al. (2025). Influence of machine learning technology on the development of electrochemical, optical, and image analysis-based methods for biomedical, food, and environmental analysis. *Microchemical Journal, 218*. https://doi.org/10.1016/j.microc.2025.115407

Alcácer, V., & Cruz-Machado, V. (2019). Scanning the industry 4.0: A literature review on technologies for manufacturing systems. *Engineering Science and Technology, an International Journal, 22*, 899–919. https://doi.org/10.1016/j.jestch.2019.01.006

Ali, R., & Saleh, S. M. (2024). Design a friendly nanoscale chemical sensor based on gold nanoclusters for detecting thiocyanate ions in food industry applications. *Biosensors, 14*. https://doi.org/10.3390/bios14050223

Ali, Q., Zheng, H., Rao, M. J., et al. (2022). Advances, limitations, and prospects of biosensing technology for detecting phytopathogenic bacteria. *Chemosphere, 296*. https://doi.org/10.1016/j.chemosphere.2022.133773

Amalraj, A., Ayyanu, R., Aham, E. C., et al. (2025). Engineering two-dimensional-copper phenolic nanosheet from CuO nanosphere for enhanced peroxidase activity in smartphone-based Thiophanate-Methyl detection via analyte-inhibition mechanism. *Langmuir, 41*, 6959–6976. https://doi.org/10.1021/acs.langmuir.4c05271

Annanouch, F. E., Casanova-Cháfer, J., Alagh, A., et al. (2021). Nanosensors for food logistics. In *Nanosensors for smart agriculture* (pp. 657–683). Elsevier.

Anweshan, u., Das, P. P., Dhara, S., & Purkait, M. K. (2023). Nanosensors in food science and technology. In *Advances in smart nanomaterials and their applications* (pp. 247–272). Elsevier.

Apetrei, R.-M., Guven, N., & Camurlu, P. (2023). Functionalized nanofibers as sensors for monitoring food quality. In *Functionalized nanofibers* (pp. 401–436). Elsevier.

Apetrei, C., Maximino, M. D., Martin, C. S., & Alessio, P. (2018). Sensors based on conducting polymers for the analysis of food products. In T. J. Gutiérrez (Ed.), *Polymers for food applications* (pp. 757–792). Cham: Springer International Publishing.

Arana, M., & Tao, S. (2025). An optical fiber caffeic acid sensor using a molecularly-imprinted chitosan membrane as a transducer. *Food Chemistry, 492*. https://doi.org/10.1016/j.foodchem.2025.145414

Archana, P., Mayil Vealan, S. B., & Sekar, C. (2025). Qualitative and quantitative detection of cyanide in forage crop and fibre dietary products by colorimetric and fluorescent sensor based on corn silk derived carbon dots-rutin system. *Food Chemistry, 493*. https://doi.org/10.1016/j.foodchem.2025.145978

Ashrafi, T. M. S., & Mohanty, G. (2025). Surface plasmon resonance sensors: A critical review of recent advances, market analysis, and future directions. *Plasmonics, 20*, 6825–6845. https://doi.org/10.1007/s11468-024-02740-4

Awlqadr, F. H., Altemimi, A. B., Qadir, S. A., et al. (2025). Emerging trends in nano-sensors: A new frontier in food safety and quality assurance. *Heliyon, 11*, Article e41181. https://doi.org/10.1016/j.heliyon.2024.e41181

Bala, K. G., Mannan Shaikh, A. H. A., Tiwari, M., et al. (2023). Artificial intelligence and nanotechnology in biosensors. In *Handb. of res. on adv. Funct. Mater. For orthop* (pp. 47–64). Appl. IGI Global.

Balbinot, S., Shrivastav, A. M., Vidic, J., et al. (2021). Plasmonic biosensors for food control. *Trends in Food Science and Technology, 111*, 128–140. https://doi.org/10.1016/j.tifs.2021.02.057

Banerjee, A., Maity, S., & Mastrangelo, C. H. (2021). Nanostructures for biosensing, with a brief overview on cancer detection, IoT, and the role of machine learning in smart biosensors. *Sensors, 21*, 1–34. https://doi.org/10.3390/s21041253

Beladona, S. U. M., Saputra, R. R., Patah, A., & Kumalasari, M. R. (2025). The versatility of metal-organic frameworks-based biosensor for antioxidant detection. *Talanta Open, 12*. https://doi.org/10.1016/j.talo.2025.100566

Benedetto, G., & Mirica, K. A. (2024). Conductive framework materials for chemiresistive detection and differentiation of toxic gases. *Accounts of Chemical Research, 57*, 2775–2789. https://doi.org/10.1021/acs.accounts.4c00319

Bhardwaj, S. K., Deep, A., Bhardwaj, N., & Wangoo, N. (2023). Recent advancements in nanomaterial based optical detection of food additives: A review. *Analyst, 148*, 5322–5339. https://doi.org/10.1039/d3an01317k

Bhatt, P., Mutturi, S., & Thakur, M. S. (2023). Spectroscopy based In-Line monitoring and control of food quality and safety. In *Food eng. Ser* (pp. 339–382). Springer.

Bhuiyan, Z. W., Haider, S. A. R., Haque, A., et al. (2024). IoT based meat freshness classification using deep learning. *IEEE Access, 12*, 196047–196069. https://doi.org/10.1109/ACCESS.2024.3520029

Bonyadi, F., Kavruk, M., Ucak, S., et al. (2024). Real-time biosensing bacteria and virus with quartz crystal microbalance: Recent advances, opportunities, and challenges. *Critical Reviews in Analytical Chemistry, 54*, 2888–2899. https://doi.org/10.1080/10408347.2023.2211164

Cai, C., Mo, J., Lu, Y., et al. (2021). Integration of a porous wood-based triboelectric nanogenerator and gas sensor for real-time wireless food-quality assessment. *Nano Energy, 83*. https://doi.org/10.1016/j.nanoen.2021.105833

Cheli, F., Bontempo, V., Pinotti, L., et al. (2018). Feed analysis and animal nutrition: Electronic nose as a diagnostic tool. *Chemical Engineering Transactions, 68*, 223–228. https://doi.org/10.3303/CET1868038

Chen, Z., Liu, Z., Liu, J., & Xiao, X. (2023). Research progress in the detection of common foodborne hazardous substances based on functional nucleic acids biosensors. *Biotechnology and Bioengineering, 120*, 3501–3517. https://doi.org/10.1002/bit.28555

Chen, B. H., & Stephen Inbaraj, B. S. (2016). Nanomaterial-based sensors for mycotoxin analysis in food. In *Novel approaches of nanotechnol. in food* (pp. 387–423). Elsevier.

Cho, Y. K., Choi, Y., Kim, S., et al. (2025). Scalable electrochemical system for rapid on-site detection of food allergens. *Biosensors and Bioelectronics, 273*, Article 117142. https://doi.org/10.1016/j.bios.2025.117142

Cho, T.-F., Yassoralipour, A., Lee, Y.-Y., et al. (2022). Evaluation of milk deterioration using simple biosensor. *Journal of Food Measurement and Characterization, 16*, 258–268. https://doi.org/10.1007/s11694-021-01145-9

Cosme, F., Rocha, T., Marques, C., et al. (2025). Innovative approaches in sensory food science: From digital tools to virtual reality. *Applied Sciences, 15*, 4538. https://doi.org/10.3390/app15084538

Daimary, M., Mohanta, Y. K., Al-Sehemi, A. G., & Sarma, H. (2025). Potential applications of microbial nano biosensors. In *Microbial nanotechnology for sustainable future: Industrial and environmental perspectives* (pp. 103–120). CRC Press.

de Souza Carvalho, J., Artifon, W., da Silva, A., et al. (2025). Digital transformation of microalgae production: A review of potential optimization strategies for Chlorella vulgaris through intelligent control. *Algal Research, 90*. https://doi.org/10.1016/j.algal.2025.104216

Deng, Z., Yun, Y.-H., Duan, N., & Wu, S. (2025). Artificial intelligence algorithms-assisted biosensors in the detection of foodborne pathogenic bacteria: Recent advances and future trends. *Trends in Food Science and Technology, 161*. https://doi.org/10.1016/j.tifs.2025.105072

Dey, B., & Ahmed, R. (2025). A comprehensive review of AI-driven plant stress monitoring and embedded sensor technology: Agriculture 5.0. *Journal of Industrial Information Integration, 47*. https://doi.org/10.1016/j.jii.2025.100931

Dias, C., Fernandes, D., Costa, J., et al. (2024). In-situ electrochemically synthesized "artificial" Gly m TI antibody for soybean allergen quantification in complex foods. *Analytica Chimica Acta, 1332*. https://doi.org/10.1016/j.aca.2024.343340

Dirpan, A., Yolanda, D. S., & Djalal, M. (2023). Is the use of biosensor in monitoring food quality experiencing an uplift trend over the last 30 years?: A bibliometric analysis. *Heliyon, 9*, Article e18977. https://doi.org/10.1016/j.heliyon.2023.e18977

Dodevska, T. (2025). A review on Xanthine oxidase-based electrochemical biosensors: Food safety and quality control applications. *Chemosensors, 13*. https://doi.org/10.3390/chemosensors13050159

Dos Santos, R. P. N., Viana Costa, L., e Silva, F., et al. (2025). Refractive index-sensitive optofluidic nanosensor using plastic optical fiber decorated with mono/bimetallic plasmonic nanoparticles. *Optics Laser Technology, 183*. https://doi.org/10.1016/j.optlastec.2024.112309

Dumitru, L. M., Irimia-Vladu, M., & Serdar Sariciftci, N. S. (2016). Biocompatible integration of electronics into food sensors. *Comprehensive Analytical Chemistry, 74*, 247–271. https://doi.org/10.1016/bs.coac.2016.04.009

Eleftheriadou, M., Pyrgiotakis, G., & Demokritou, P. (2017). Nanotechnology to the rescue: Using nano-enabled approaches in microbiological food safety and quality. *Current Opinion in Biotechnology, 44*, 87–93. https://doi.org/10.1016/j.copbio.2016.11.012

European Commission. (2022). Proposal for ecodesign for sustainable products regulation. https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en. (Accessed 11 April 2025).

European Commission Farm to fork strategy. European commission farm to fork Strategy—for a fair, healthy and environmentally-friendly food system. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en. (Accessed 4 November 2025).

Fan, P., Liu, L., Guo, Q., et al. (2017). Three-dimensional N-doped carbon nanotube@ carbon foam hybrid: An effective carrier of enzymes for glucose biosensors. *RSC Advances, 7*, 26574–26582. https://doi.org/10.1039/c7ra02592k

Fathima, A., Chiome, T. J., Archer, A. A., et al. (2022). Smart use of nanomaterials as sensors for detection and monitoring of food spoilage. In: Application of nanotechnol. In *Food science, processing and packaging* (pp. 169–188). Springer International Publishing.

Fdez-Sanromán, A., Bernárdez-Rodas, N., Rosales, E., et al. (2025). Biosensor technologies for water quality: Detection of emerging contaminants and pathogens. *Biosensors, 15*. https://doi.org/10.3390/bios15030189

Feroci, M., Grasso, G., Dragone, R., & Curulli, A. (2025). Electrochemical (Bio)Sensors for toxins, foodborne pathogens, pesticides, and antibiotics detection: Recent advances and challenges in food analysis. *Biosensors, 15*. https://doi.org/10.3390/bios15070468

Flauzino, J. M. R., Nguyen, E. P., Yang, Q., et al. (2022). Label-free and reagentless electrochemical genosensor based on graphene acid for meat adulteration detection. *Biosensors and Bioelectronics, 195*. https://doi.org/10.1016/j.bios.2021.113628

Flores-Rangel, G., León-Martínez, L. D. D., Mizaikoff, B., & Roque-Jiménez, J. A. (2024). Nanosensors applied within the food industry. In *Nanobiotechnology for sustainable food management* (1st ed., pp. 319–339). Boca Raton: CRC Press.

Franca, A. S., & Oliveira, L. S. (2021). Applications of smartphones in food analysis. In *Smartphone-based detection devices* (pp. 249–268). Elsevier.

Full, J., Baumgarten, Y., Delbrück, L., et al. (2021). Market perspectives and future fields of application of odor detection biosensors within the biological transformation—a systematic analysis. *Biosensors, 11*. https://doi.org/10.3390/bios11030093

Gabrieli, G., Muszynski, M., & Ruch, P. (2023). Electronic noses and tongues: Current trends and future needs. In *Digital sens. Science: Applications in new product development* (pp. 117–133). Elsevier.

Garcia-Hernandez, C., Garcia-Cabezon, C., Rodriguez-Mendez, M. L., & Martin-Pedrosa, F. (2025). Electronic tongue technology applied to the analysis of grapes and wines: A comprehensive review from its origins. *Chemosensors, 13*. https://doi.org/10.3390/chemosensors13050188

Garg, S., Rumjit, N. P., & Roy, S. (2024). Smart agriculture and nanotechnology: Technology, challenges, and new perspective. *Advanced Agrochem, 3*, 115–125. https://doi.org/10.1016/j.aac.2023.11.001

Garg, D., Singh, D., Sharma, R., et al. (2022). Applications of nanomaterials for greener food analysis. In *Green chem. Analysis and sample preparations: Proced., instrumentation, data metrics, and sustainability* (pp. 471–511). Springer International Publishing.

Ghaffari, A. (2024). Precision seed certification through machine learning. *Technology in Agronomy, 4*. https://doi.org/10.48130/tia-0024-0013

Gharibzahedi, S. M. T., & Altintas, Z. (2024). State-of-the-art sensor technologies for tracking SARS-CoV-2 in contaminated food and packaging: Towards the future techniques of food safety assurance. *TrAC, Trends in Analytical Chemistry, 170*, Article 117473. https://doi.org/10.1016/j.trac.2023.117473

Gopal, G., Roy, N., & Mukherjee, A. (2023). Recent developments in the applications of GO/rGO-Based biosensing platforms for pesticide detection. *Biosensors, 13*. https://doi.org/10.3390/bios13040488

Graboski, A. M., Paroul, N., Steffens, J., & Steffens, C. (2021). Nanosensors for food quality control especially essential oils. In *Nanosensors for smart manufacturing* (pp. 273–288). Elsevier.

Grasso, S., Di Loreto, M. V., Zompanti, A., et al. (2025). Intelligent electrochemical sensing: A new frontier in on-the-fly coffee quality assessment. *Chemosensors, 13*. https://doi.org/10.3390/chemosensors13010024

Griesche, C., & Baeumner, A. J. (2020). Biosensors to support sustainable agriculture and food safety. *TrAC, Trends in Analytical Chemistry, 128*, Article 115906. https://doi.org/10.1016/j.trac.2020.115906

Gulia, V., Dhull, S. S., Kamboj, H., et al. (2025). Pushing limits: Integrating smart nanosensors and the internet of things in agriculture. *Rendiconti Lincei, 36*, 479–497. https://doi.org/10.1007/s12210-025-01337-1

Guliy, O. I., Chumakov, D. S., Evstigneeva, S. S., et al. (2025). Nanozymes: A dual approach to bacterial colorimetric and luminescent detection and to bacterial pathogen killing. *Biosensors and Bioelectronics, 288*. https://doi.org/10.1016/j.bios.2025.117835

Guo, Y., Zhang, X., Wang, R., & Wang, J. (2025). Revealing the nano-empowered fluorescent sensor arrays for the food safety point-of-care testing: An overview of mechanism and applications. *Trends in Food Science and Technology, 165*. https://doi.org/10.1016/j.tifs.2025.105282

Han, Y., Yin, Z., Zhuang, H., et al. (2025). Synergistic effects of photoactivation and photothermal in MXene heterostructures for the enhanced H2S detection capability. *Advanced Functional Materials*. https://doi.org/10.1002/adfm.202509735

He, Q., Huang, H., & Wang, Y. (2024). Detection technologies, and machine learning in food: Recent advances and future trends. *Food Bioscience, 62*. https://doi.org/10.1016/j.fbio.2024.105558

Hong, B., Qin, T., Wang, W., et al. (2024). Phage tailspike protein coated gold nanoparticles combined with smartphone for rapid bacterial detection and photothermal sterilization. *Talanta, 276*. https://doi.org/10.1016/j.talanta.2024.126268

Hu, L., Xu, J., Qin, Z., et al. (2016). Detection of bitterness in vitro by a novel male mouse germ cell-based biosensor. *Sensors and Actuators. B, Chemical, 223*, 461–469. https://doi.org/10.1016/j.snb.2015.08.105

Huang, D., Ma, H., Wang, J., et al. (2024). Mof-mediated paper-based (bio)sensors for detecting of food and environmental pollutants: Preparation strategies and emerging applications. *Microchemical Journal, 207*. https://doi.org/10.1016/j.microc.2024.111692

Hussain, B., Yuce, M., Ullah, N., & Budak, H. (2016). Bioconjugated nanomaterials for monitoring food contamination. In *Nanobiosensors* (pp. 93–127). Elsevier.

Ibraheem Shelash Al-Hawary, S., Omar, B. A., Askar, S., et al. (2023). Recent advances in nanomaterials-based electrochemical and optical sensing approaches for detection of food dyes in food samples: A comprehensive overview. *Microchemical Journal, 189*. https://doi.org/10.1016/j.microc.2023.108540

Jafarizadeh-Malmiri, H., Sayyar, Z., Anarjan, N., & Berenjian, A. (2019). *Nanobiotechnology in food: Concepts, applications and perspectives*. Springer International Publishing.

Kadian, S., Kumari, P., Sahoo, S. S., et al. (2024). Machine learning enabled microneedle-based colorimetric pH sensing patch for wound health monitoring and meat spoilage detection. *Microchemical Journal, 200*. https://doi.org/10.1016/j.microc.2024.110350

Karimi, K., Gharachorloo, M., & Fallah, A. (2025). Highly sensitive photoluminescence sensor based on chitosan biopolymer film for determination of hydrogen peroxide. *International Journal of Biological Macromolecules, 296*. https://doi.org/10.1016/j.ijbiomac.2025.139735

Kaur, K., Kaur, N., Swami, K., et al. (2025). Upconversion enabled innovation: Transfer of lab sensor to smartphone based field device. *Food Research International, 213*. https://doi.org/10.1016/j.foodres.2025.116547

Kaur, K., Singh, S. P., & Gill, N. S. (2024). Optical and electrochemical chemosensors for identification of carbon dioxide gas. In K. A. Wani (Ed.), *Advances in environmental engineering and green technologies* (pp. 42–77). IGI Global.

Kaushal, J. B., Raut, P., & Kumar, S. (2023). Organic electronics in biosensing: A promising frontier for medical and environmental applications. *Biosensors, 13*. https://doi.org/10.3390/bios13110976

Kendre, P. N., Pote, A. P., Jain, S., & Kayande, D. R. (2024). Sensing and biosensing with mesoporous silica nanoparticles (MSNs). *Mesoporous silica nanoparticles: Drug deliv. Catal. and Sens: Appl. De Gruyter*.

Kızılkurtlu, A. A., Demirbaş, E., & Ağel, H. E. (2023). Electrochemical aptasensors for pathogenic detection toward point-of-care diagnostics. *Biotechnology and Applied Biochemistry, 70*, 1460–1479. https://doi.org/10.1002/bab.2485

Kolupula, A. K., Gora, S. P., Bhanu Prakash, C., et al. (2024). Harnessing nanotechnology for advancements in fisheries and aquaculture: A comprehensive review. *Proceedings of the Indian National Science Academy, 90*, 799–820. https://doi.org/10.1007/s43538-024-00238-5

Konfo, T. R. C., Tchekessi, C. K. C., & Baba-Moussa, F. A. K. (2024). Status report on innovations and applications of smart bio-systems for real-time monitoring of food quality. *Applied Food Research, 4*. https://doi.org/10.1016/j.afres.2024.100546

König, A. (2022). An in-hive soft sensor based on phase space features for Varroa infestation level estimation and treatment need detection. *Journal of Sensors and Sensor Systems, 11*, 29–40. https://doi.org/10.5194/jsss-11-29-2022

Koukouviti, E., Koulopoulou, C., Anastasiou, N., et al. (2026). 3D printed electrochemical dual-sensor biodevice for the simultaneous determination of glucose and ethanol in wines. *Food Control, 181*. https://doi.org/10.1016/j.foodcont.2025.111784

Kress-Rogers, E., & Brimelow, C. J. B. (Eds.). (2010) (2. ed.)*Repr. 2010Instrumentation and sensors for the food industry*. Cambridge: Woodhead [u.a.].

Kulkarni, M. B., Umapathi, R., Ayachit, N. H., et al. (2025). Nanosensors in the food industry and agriculture. *Applications of Biosensors in Healthcare, 3*, 751–768. Elsevier.

Kumar, S. N., Kannampilly, N. J., & Joy, J. (2024). Edible electronics for smart detection of food spoilage. In *Edible electronics for smart technology solutions* (pp. 149–166). IGI Global.

Kumar, J. V., Karthika, D., Rosaiah, P., et al. (2024). Fabrication of SnO2/NGO hybrid nanocomposite as an effective photocatalyst for binary dye degradation under sunlight illumination. *Process Safety and Environmental Protection, 188*, 398–405. https://doi.org/10.1016/j.psep.2024.05.088

Kushwaha, R., Puranik, V., Agarwal, R., & Kaur, D. (2022). Application of biosensors in food safety. In *Biosensors in food safety and quality* (1st ed., pp. 227–241). Boca Raton: CRC Press.

Lasarte-Aragonés, G., Soriano-Dotor, L., López-Lorente, Á. I., et al. (2023). Flurescence sensors for the food industry. In *Encyclopedia of sensors and biosensors* (pp. 549–567). Elsevier.

Lazaro, A., Villarino, R., Lazaro, M., et al. (2023). Recent advances in batteryless NFC sensors for chemical sensing and biosensing. *Biosensors, 13*, 775. https://doi.org/10.3390/bios13080775

Lekawska-Andrinopoulou, L., Tsiakou, D., Chatzioannou, K., et al. (2024). Towards dynamic digital product passport: The approach for food sector. *E3S Web Conference, 585*, Article 08001. https://doi.org/10.1051/e3sconf/202458508001

Lenik, J. (2017). Cyclodextrins based electrochemical sensors for biomedical and pharmaceutical analysis. *Computers, Materials & Continua, 24*. https://doi.org/10.2174/0929867323666161213101407

Li, D., Wang, Y., Wang, J., et al. (2020). Recent advances in sensor fault diagnosis: A review. *Sensors and Actuators A: Physical, 309*, Article 111990. https://doi.org/10.1016/j.sna.2020.111990

Lopes, C., & Barata, J. (2024). Digital product passport: A review and research agenda. *Procedia Computer Science, 246*, 981–990. https://doi.org/10.1016/j.procs.2024.09.517

Lou-Franco, J., Zhao, Y., Nelis, J. L. D., et al. (2023). Smartphone-based immunochemical sensor exploiting peroxidase-like activity of ligand-capped gold nanostars: A proof-of-concept detection of Mycobacterium bovis. *Biosensors and Bioelectronics, 220*, Article 114857. https://doi.org/10.1016/j.bios.2022.114857

Ma, H., Pu, S., Jia, S., et al. (2025). Laser-assisted thermoelectric-enhanced hydrogen peroxide biosensors based on Ag2Se nanofilms for sensitive detection of bacterial pathogens. *Nanoscale, 17*, 5858–5868. https://doi.org/10.1039/d4nr04860a

Machado, A. C., Salvo-Comino, C., Rodríguez-Méndez, M. L., & Caseli, L. (2025). Enhancing biosensor capabilities through laccase immobilization in nanostructured Langmuir-Blodgett films for phenol detection. *Results in Surfaces and Interfaces, 18*. https://doi.org/10.1016/j.rsurfi.2024.100366

Mani, R., Jothi, J. V., Murugesan, B., et al. (2025). Smart sensors in food packaging: Sensor technology for real-time food safety and quality monitoring. *Journal of Food Process Engineering, 48*. https://doi.org/10.1111/jfpe.70120

Marty, J., & Ruel, S. (2024). Why is "supply chain collaboration" still a hot topic? A review of decades of research and a comprehensive framework proposal. *International Journal of Production Economics, 273*, Article 109259. https://doi.org/10.1016/j.ijpe.2024.109259

Matindoust, S., Baghaei-Nejad, M., Shahrokh Abadi, M. H. S., et al. (2016). Food quality and safety monitoring using gas sensor array in intelligent packaging. *Sensor Review, 36*, 169–183. https://doi.org/10.1108/SR-07-2015-0115

Mehrzad, A., & Verdian-Doghaei, A. (2024). Aptamer-based sensors diagnostic for food pathogens. In *Aptasensors for food safety: Fundam* (pp. 198–236). Appl. CRC Press.

Melesse, T. Y. (2026). Intelligent postharvest sorting of bananas using thermal imaging and deep neural network models. *Food and Bioprocess Technology, 19*, 80. https://doi.org/10.1007/s11947-025-04173-1

Melesse, T. Y., Bollo, M., Pasquale, V. D., & Riemma, S. (2022). Digital twin for inventory planning of fresh produce. *IFAC-PapersOnLine, 55*, 2743–2748. https://doi.org/10.1016/j.ifacol.2022.10.134

Mistewicz, K., & Nowak, M. (2016). Prevention of food spoilage using nanoscale sensors. In *Nanobiosensors* (pp. 245–288). Elsevier.

Mousavi, S. M., Kalashgrani, M. Y., Hashemi, S. A., et al. (2024). Overview of clinical applications of biosensors. In *Semiconducting polymer materials for biosensing applications* (pp. 291–324). Elsevier.

Mukherjee, S., Bhattacharyya, S., Ghosh, K., et al. (2021). Sensory development for heavy metal detection: A review on translation from conventional analysis to field-portable sensor. *Trends in Food Science and Technology, 109*, 674–689. https://doi.org/10.1016/j.tifs.2021.01.062

Mustafa, F., & Andreescu, S. (2018). Chemical and biological sensors for food-quality monitoring and smart packaging. *Foods, 7*. https://doi.org/10.3390/foods7100168

Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. *RSC Advances, 10*, 19309–19336. https://doi.org/10.1039/D0RA01084G

Nanda Kumar, D., Baider, Z., Blum, S. E., & Shtenberg, G. (2025). SiO2/Si interferometers designed for on-site botulinum neurotoxin serotypes B and C quantification and biological activity assessment. *Biosensors and Bioelectronics, 271*. https://doi.org/10.1016/j.bios.2024.117027

Nasiri, H., Abbasian, K., & Baghban, H. (2024). Sensing of lactose by graphitic carbon nitride/magnetic chitosan composites with surface plasmon resonance method. *Food Bioscience, 61*. https://doi.org/10.1016/j.fbio.2024.104718

Nasiri, R., Guagliano, G., van Gastel, D., et al. (2026). Electrochemical dual-sensing of lactate and glucose using NiO nanoparticles with cross-sensitivity calibration. *Talanta, 297*. https://doi.org/10.1016/j.talanta.2025.128678

Nazir, S., & Kwon, O. S. (2022). Micro-electromechanical systems-based sensors and their applications. *Applied Science and Convergence Technology, 31*, 40–45. https://doi.org/10.5757/ASCT.2022.31.2.40

Nirgund, J., Purana, K. N., Selvakumar, D., et al. (2022). Nanobiosensors for detection of bacteria: An overview of fiber-optics and Raman spectroscopy based biosensors. In *Handb. of microb. Nanotechnol* (pp. 91–132). Elsevier.

Niyigaba, T., Küçükgöz, K., Kołożyn-Krajewska, D., et al. (2025). Advances in fermentation technology: A focus on health and safety. *Applied Science, 15*. https://doi.org/10.3390/app15063001

Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing, 31*, 127–182. https://doi.org/10.1007/s10845-018-1433-8

Paliwal, T., Kesharwani, P., Yadav, R., et al. (2025). Emerging nanomaterial-based sensors for foodborne pathogen and toxin detection. *Food Research International, 221*. https://doi.org/10.1016/j.foodres.2025.117083

Pandey, V. K., Singh, G., Reetika, et al. (2024). Nanosensors in food shelf-life extension and quality monitoring. In *Advancements in nanotechnology for food and packaging* (pp. 79–102). Elsevier.

Pant, M., Kiran, K., Pande, V., et al. (2024). Use of nanobio- technological methods for the analysis and stability of food antimicrobials and antioxidants. In *Nanobiotechnology for food processing and packaging* (pp. 449–480). Elsevier.

Parakh, A., Awate, A., Barman, S. M., et al. (2025). Artificial intelligence and machine learning for colorimetric detections: Techniques, applications, and future prospects. *Trends in Environmental Analytical Chemistry, 48*. https://doi.org/10.1016/j.teac.2025.e00280

Patel, G., Pillai, V., Bhatt, P., & Mohammad, S. (2020). *Application of nanosensors in the food industry*. Nanosensors for Smart Cities. Elsevier.

Patil, D. D., & Meshram, D. A. (2023). Machine intelligence based assessment of nutritional olfactory features for controlling health hazards using electronic nose. *Revista de Gestão Social e Ambiental, 17*. https://doi.org/10.24857/rgsa.v17n8-013

Paul, A. A., Aladese, A. D., & Marks, R. S. (2024). Additive manufacturing applications in biosensors technologies. *Biosensors, 14*. https://doi.org/10.3390/bios14020060

Pavase, T. R., Lin, H., Shaikh, Q., et al. (2018). Recent advances of conjugated polymer (CP) nanocomposite-based chemical sensors and their applications in food spoilage detection: A comprehensive review. *Sensors and Actuators B: Chemical, 273*, 1113–1138. https://doi.org/10.1016/j.snb.2018.06.118

Peveler, W. J. (2024). Food for thought: Optical sensor arrays and machine learning for the food and beverage industry. *ACS Sensors, 9*, 1656–1665. https://doi.org/10.1021/acssensors.4c00252

Popov, A., Aukstakojyte, R., Gaidukevic, J., et al. (2021). Reduced graphene oxide and polyaniline nanofibers nanocomposite for the development of an amperometric glucose biosensor. *Sensors, 21*, 1–15. https://doi.org/10.3390/s21030948

Pracucci, A., & Giovanardi, M. (2025). Design of a sensor-based digital product passport for low-tech manufacturing: Traceability and environmental monitoring in bio-block production. *Sensors, 25*, 5653. https://doi.org/10.3390/s25185653

Radha, R., Vitor, R. F., & Al-Sayah, M. H. (2022). A fluorescence-based chemical sensor for detection of melamine in aqueous solutions. *Chemosensors, 10*. https://doi.org/10.3390/chemosensors10010013

Radogna, A. V., Latino, M. E., Menegoli, M., et al. (2022). A monitoring framework with integrated sensing technologies for enhanced food safety and traceability. *Sensors, 22*. https://doi.org/10.3390/s22176509

Rafi, Z., Khan, H., Husain, A., et al. (2025). Food contamination and the emerging application of nanobiosensors in food safety. *Journal of Food Science, 90*. https://doi.org/10.1111/1750-3841.70073

Ragavan, K. V., & Neethirajan, S. (2018). Nanoparticles as biosensors for food quality and safety assessment. In *Nanomater. For food appl* (pp. 147–202). Elsevier.

Raheel, A., Ali, S. Z., Waris, M., et al. (2021). Post-harvest MethodologyandTechnology for horticultural products in agricultural commercial areas of Pakistan. *Pakistan Journal of Agricultural Research, 34*, 700–705. https://doi.org/10.17582/journal.pjar/2021/34.4.700.705

Rahman, M. A., Karthikeyan, M., Johnson, I., et al. (2025). Ensuring food security through rapid and in-field detection of diseases in food crops using real time and portable sensors. *Analytical Biochemistry, 705*. https://doi.org/10.1016/j.ab.2025.115925

Rainbow, J., Judd-Cooper, E. P., Pope, S. J. A., et al. (2025). Electrochemical signal amplification for pathogen nucleic acid detection utilizing a cobalt-based DNA-binding metallo-intercalator. *Sensors and Diagnostics, 4*, 519–528. https://doi.org/10.1039/d4sd00322e

Ramezanzadeh, M. H., Seifi, M., & Shoja, S. (2019). A facile method toward potentially next-generation bacteria detectors using polymer/MWCNT/Au nanocomposite films: A possibility to detecting ability through the shift in resonance frequency. *Materials Research Express, 6*. https://doi.org/10.1088/2053-1591/aaf15c

Rawat, R., Sharma, M., & Singh, P. (2024). Biotechnology and its position in the mitigation of microbial problems in the food industry. In *Microb. Biotechnology in the food industry: Advances, challenges, and potential solutions* (pp. 103–127). Springer International Publishing.

Rivas-Macho, A., Eletxigerra, U., Díez-Ahedo, R., et al. (2023). Design and 3D printing of an electrochemical sensor for Listeria monocytogenes detection based on loop mediated isothermal amplification. *Heliyon, 9*, Article e12637. https://doi.org/10.1016/j.heliyon.2022.e12637

Rodriguez-Saona, L., Aykas, D. P., Borba, K. R., & Urtubia, U. A. (2020). Miniaturization of optical sensors and their potential for high-throughput screening of foods. *Current Opinion in Food Science, 31*, 136–150. https://doi.org/10.1016/j.cofs.2020.04.008

Rojas, M. L., Kubo, M. T. K., Caetano-Silva, M. E., et al. (2022). How food structure influences the physical, sensorial, and nutritional quality of food products. In *Food structure engineering and design for improved nutrition, health and well-being* (pp. 113–138). Elsevier.

Sachchan, T. K., & Sabharwal, P. K. (2024). Smart food packaging materials. In *Biodegradable and edible food packaging* (pp. 363–413). Elsevier.

Saldaña-Ahuactzi, Z., Gómez-Montaño, F. J., Morales-Chávez, J., et al. (2025). Advancing foodborne pathogen detection: A review of traditional and innovative optical and electrochemical biosensing approaches. *Microchimica Acta, 192*. https://doi.org/10.1007/s00604-024-06924-x

Salomón-Flores, M. K., Bazany-Rodríguez, I. J., Toledo-Jaldin, H. P., et al. (2025). Luminescent (bio)sensors for pesticide detection: An innovative tool for water monitoring. In *Soil improv. and water conservation biotechnology* (pp. 230–262). Bentham Science Publishers.

Sánchez, A. A., Riofrío, G., Castillo, D., et al. (2025). Biosensor for bacterial detection through color change in culture medium. *Biosensors, 15*. https://doi.org/10.3390/bios15080551

Sanni, S. E., Sadiku, E. R., Okoro, E. E., et al. (2023). Biocatalytic sensors: Potentials, maxims and mechanisms for optimal performance. In *Biomaterials-based sensors: Recent advances and applications* (pp. 177–220). Springer Nature.

Santos, A., Vaz, A., Rodrigues, P., et al. (2019). Thin films sensor devices for mycotoxins detection in foods: Applications and challenges. *Chemosensors, 7*, 3. https://doi.org/10.3390/chemosensors7010003

Saputra, H. A., Karim, M. M., Sahin, M. A. Z., et al. (2025). Chemical sensor technology for detection of 3-monochloropropane-1,2-diol in foodstuffs. *Critical Reviews in Analytical Chemistry*. https://doi.org/10.1080/10408347.2025.2565254

Satpati, B., Koley, C., & Datta, S. (2017). Sensor-less predictive drying control of pneumatic conveying batch dryers. *IEEE Access, 5*, 3547–3568. https://doi.org/10.1109/ACCESS.2017.2675625

Scognamiglio, V., Antonacci, A., Lambreva, M. D., et al. (2016). Application of biosensors for food analysis. In *Food saf.: Innov. Analyt. Tools for saf. Assess* (pp. 395–434). wiley.

Selva Sharma, A., Murugavelu, M., Varghese, A. W., et al. (2024). A review of biomolecules conjugated lanthanide up-conversion nanoparticles-based fluorescence probes in food safety and quality monitoring applications. *Critical Reviews in Food Science and Nutrition, 64*, 6129–6159. https://doi.org/10.1080/10408398.2022.2163975

Shaibani, P. M., Etayash, H., Jiang, K., et al. (2018). Portable nanofiber-light addressable potentiometric sensor for rapid Escherichia coli detection in Orange juice. *ACS Sensors, 3*, 815–822. https://doi.org/10.1021/acssensors.8b00063

Sharma, P., Agrawal, G., Bisht, A., & Mansi. (2025). *Nanotechnology and biosensors in food processing, packaging, and safety*. Springer.

Sharma, V., Chandra, R., Dutta, S., et al. (2024). Schiff base and organic ligand stabilized metal nanoparticles as potential chemosensors for hazardous metal ions: Design, principle, optical signaling mechanism and application. *Inorganica Chimica Acta, 573*. https://doi.org/10.1016/j.ica.2024.122321

Sharma, S., Gupta, S., Saini, A. K., et al. (2025). Electrochemical nanosensors: Revolutionizing vitamin detection. *Talanta, 291*. https://doi.org/10.1016/j.talanta.2025.127830

Sharma, P., Panghal, A., Gaikwad, V., et al. (2019). Nanotechnology: A boon for food safety and food defense. In *Nanotechnol. Life. Sci* (pp. 225–242). Springer Science and Business Media B.V.

Singh, H., Kumar, D., Deep, A., et al. (2024). Fluorescent nanosensors for detection of microbial toxins in food matrices: A review. *Journal of Food Measurement and Characterization, 18*, 7669–7699. https://doi.org/10.1007/s11694-024-02757-7

Singh, K., Maurya, K. K., & Malviya, M. (2025). Recent progress on nanomaterial-based electrochemical sensors for glucose detection in human body fluids. *Microchimica Acta, 192*. https://doi.org/10.1007/s00604-025-06972-x

Singh, P., Pandey, V. K., Sahu, M., et al. (2025). Microbial biosensors for rapid and accurate food quality monitoring: Detection of contaminants, pathogens, and spoilage indicators. *Journal of Food Safety, 45*. https://doi.org/10.1111/jfs.70032

Singh, P., Sharma, M., & Rawat, R. (2024). Using bioprocesses and biosystems for environmental protection, microbial detection, and prevention in the food industry. In *Microb. Biotechnology in the food industry: Advances, challenges, and potential solutions* (pp. 241–272). Springer International Publishing.

Singh, R., Singh, E., & Nalwa, H. S. (2017). Inkjet printed nanomaterial based flexible radio frequency identification (RFID) tag sensors for the internet of nano things. *RSC Advances, 7*, 48597–48630. https://doi.org/10.1039/c7ra07191d

Skowronková, N., Adámek, M., Zvonková, M., et al. (2024). Optimizing low-cost gas analysis with a 3D printed column and MiCS-6814 sensor for volatile compound detection. *Sensors, 24*. https://doi.org/10.3390/s24206594

Skowronkova, N., Adamek, M., Zvonkova, M., et al. (2024). Optimizing low-cost gas analysis with a 3D printed column and MiCS-6814 sensor for volatile compound detection. *Sensors, 24*, 6594. https://doi.org/10.3390/s24206594

Soltani Firouz, M., Mohi-Alden, K., & Omid, M. (2021). A critical review on intelligent and active packaging in the food industry: Research and development. *Food Research International, 141*. https://doi.org/10.1016/j.foodres.2021.110113

Sourkouhi, Z. S., Balasubramanian, V., & Zarifi, M. H. (2025). Optically modulated split ring resonator sensor for optical density analysis of liquid analytes in microwave regime. *IEEE Transactions on Microwave Theory and Techniques, 73*, 1610–1618. https://doi.org/10.1109/TMTT.2024.3461568

Srivastava, A. K., Dev, A., & Karmakar, S. (2018). Nanosensors and nanobiosensors in food and agriculture. *Environmental Chemistry Letters, 16*, 161–182. https://doi.org/10.1007/s10311-017-0674-7

Sukhavattanakul, P., Srikhao, N., Ummartyotin, S., & Narain, R. (2025). Sensing food spoilage with nanotechnology: A review of current research and challenges.

Measurement: Food, 18, Article 100221. https://doi.org/10.1016/j.meafoo.2025.100221

Sun, D., Xu, Z., Jin, L., et al. (2025). A novel cascaded reflective temperature-independent fiber-optic biosensor for trace vanillin concentration detection enhanced specificity with molecularly imprinted polymer. *Food Control, 173*. https://doi.org/10.1016/j.foodcont.2025.111217

Tarannum, N., Khatoon, S., & Kumar, D. (2023). Molecularly imprinted polymers in optical sensing—an outlook for future. In *Molecularly imprinted polymers (MIPs): Commercialization prospects* (pp. 217–232). Elsevier.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management, 14*, 207–222. https://doi.org/10.1111/1467-8551.00375

Tsegay, Z. T., Hosseini, E., Varzakas, T., & Smaoui, S. (2024). The latest research progress on polysaccharides-based biosensors for food packaging: A review. *International Journal of Biological Macromolecules, 282*, Article 136959. https://doi.org/10.1016/j.ijbiomac.2024.136959

Upadhyay, A., Agbesi, P., Arafat, K. M. Y., et al. (2024). Bio-based smart packaging: Fundamentals and functions in sustainable food systems. *Trends in Food Science and Technology, 145*. https://doi.org/10.1016/j.tifs.2024.104369

Vallinayagam, S., Paladhi, A. G., Pal, K., & Kyzas, G. Z. (2022). Multifunctional biosensor activities in food technology, microbes and toxins – A systematic mini review. *Process Biochemistry, 120*, 260–264. https://doi.org/10.1016/j.procbio.2022.06.019

Veerapandi, G., Arul, C., Lavanya, P., et al. (2025). Amine oxidase@Li-CaCu2O3 based electrochemical biosensor for the detection of tyramine in marine fishes and crab. *Electrochimica Acta, 542*. https://doi.org/10.1016/j.electacta.2025.147436

Wahid, A., Asiri, A. M., Al-Malki, E. S., et al. (2025). Facile selective phenolic sensor fabrication based on CuO@Nd2O3 nanocomposites. *Microchemical Journal, 218*. https://doi.org/10.1016/j.microc.2025.115324

Wang, Y., Lan, Z., Wang, J., et al. (2025). Advancement in functionalized electrospun nanofiber-based gas sensors: A review. *Sensors, 25*, 4896. https://doi.org/10.3390/s25164896

Wang, K., Lin, X., Zhang, M., et al. (2022). Review of electrochemical biosensors for food safety detection. *Biosensors, 12*. https://doi.org/10.3390/bios12110959

Wang, X.-Y., Liu, P.-P., Cai, H.-J., et al. (2025). PdRh bimetallic-loaded α-Fe2O3 nanospindles with Ppb-limit of 3-hydroxy-2-butanone biomarker detection: Particle dimension regulation and oxygen spillover effect. *Chemical Engineering Journal, 512*. https://doi.org/10.1016/j.cej.2025.162686

Wang, S., Yan, Z., Shen, F., et al. (2024). Novel aptasensor based on polyaniline functionalized carboxylated dobby carbon nanotubes and molybdenum disulfide for endotoxin detection. *Talanta, 276*. https://doi.org/10.1016/j.talanta.2024.126256

Wei, P., Han, W., Xie, L., et al. (2024). Recent advances in chemosensors based on transition metal phosphides for food safety detection. *Trends in Food Science & Technology, 151*, Article 104611. https://doi.org/10.1016/j.tifs.2024.104611

Wei, J., Peng, Q., Xie, Y., & Chen, Y. (2025). Intelligent gas sensors: From mechanism to applications. *Sensors, 25*. https://doi.org/10.3390/s25206321

Weston, M., Mazur, F., & Chandrawati, R. (2020). Monitoring of food spoilage using Polydiacetylene- and liposome-based sensors. In *Smart sensors for environmental and med. Applications* (pp. 81–102). wiley.

Xiao-Wei, H., Zhi-hua, L., Xiao-Bo, Z., et al. (2016). Detection of meat-borne trimethylamine based on nanoporous colorimetric sensor arrays. *Food Chemistry, 197*, 930–936. https://doi.org/10.1016/j.foodchem.2015.11.041

Yang, D., Chen, Y., Che, S., & Kai, K. (2025). Recent advances in non-enzymatic glucose sensors based on nanomaterials. *Coatings, 15*. https://doi.org/10.3390/coatings15080892

Zhang, F., Alizadeh Sani, M., Khezerlou, A., et al. (2025). Advances in aptasensors engineered with carbon nanomaterials for food safety monitoring. *Advances in Colloid and Interface Science, 346*. https://doi.org/10.1016/j.cis.2025.103665

Zhang, X., He, L., Zhang, G., et al. (2025). Innovative electrochemiluminescence biosensing platform with biocompatible interface for monitoring hydrogen peroxide metabolism and antibiotic stress response in Escherichia coli. *Analytica Chimica Acta, 1374*. https://doi.org/10.1016/j.aca.2025.344507

Zhang, Y., Northcutt, J., Hanks, T., et al. (2017). Polydiacetylene sensor interaction with food sanitizers and surfactants. *Food Chemistry, 221*, 515–520. https://doi.org/10.1016/j.foodchem.2016.09.168

Zhang, W., Sun, D.-W., Ma, J., et al. (2023). Simultaneous sensing of ammonia and temperatures using a dual-mode freshness indicator based on Au/Cu nanoclusters for packaged seafood. *Food Chemistry, 418*. https://doi.org/10.1016/j.foodchem.2023.135929

Zhang, J., Xiong, Q., & Xu, J. (2024). Research progress in non-precious metal oxide/compound-based electrodes for non-enzymatic electrochemical glucose sensor applications. *Materials Science in Semiconductor Processing, 181*. https://doi.org/10.1016/j.mssp.2024.108643

Zhou, J., Liu, Y., Du, X., et al. (2023). Recent advances in design and application of nanomaterials-based colorimetric biosensors for agri-food safety analysis. *ACS Omega, 8*, 46346–46361. https://doi.org/10.1021/acsomega.3c06409

Zhu, J., Luo, Z., Liu, Y., et al. (2022). Environmental perspectives for food loss reduction via smart sensors: A global life cycle assessment. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2022.133852