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# Smart biosensors for food safety 4.0: a review

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ABSTRACT

Food contamination remains a critical global challenge driven by intensive agriculture, environmental pollution, complex supply chains, and climate-related disruptions. Conventional analytical techniques such as chromatography, mass spectrometry, and immunoassays provide high accuracy but are limited by cost, time, and laboratory dependence. Biosensors have emerged as rapid and sensitive alternatives; however, most existing reviews focus primarily on sensor classifications rather than their systemic role in modern food safety frameworks. This review critically examines recent advances in biosensors for detecting food contaminants—including heavy metals, pesticides, allergens, mycotoxins, and foodborne pathogens—while emphasizing the transition toward intelligent biosensing systems. Particular attention is given to the integration of nanomaterials, aptamers, DNAzymes, and whole-cell biosensors with machine learning, Internet of Things (IoT), and data-driven analytics, enabling real-time, on-site, and predictive monitoring. By framing biosensors within the concept of Food Safety 4.0, this review highlights how intelligent biosensors shift food safety management from reactive detection to proactive risk prediction and decision support. Remaining challenges related to sensor stability, data reliability, regulatory validation, and scalability are discussed, alongside future directions for deploying biosensors as interconnected components of global food surveillance systems.

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## 1. Introduction

Food safety has emerged as one of the most critical global challenges in the twenty-first century, driven by the intensification of agricultural practices, globalization of food supply chains, climate change, and increasing consumer awareness of food quality and health risks.

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Food contaminants—including heavy metals, pesticide residues, allergens, mycotoxins, and foodborne pathogens—pose serious threats to public health, economic stability, and regulatory credibility worldwide (1,2). The complexity of modern food systems has significantly increased the probability of contamination at multiple points along the farm-to-fork continuum, necessitating more robust, rapid, and adaptive monitoring strategies.

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Traditional analytical methods such as high-performance liquid chromatography (HPLC), gas chromatography (GC), mass spectrometry (MS), and enzyme-linked immunosorbent assays (ELISA) remain the gold standards for contaminant detection due to their high sensitivity and specificity. However, these techniques are inherently limited by high operational costs, time-consuming sample preparation, reliance on centralized laboratories, and the need for highly trained personnel (3,4). As a result, conventional methods are often unsuitable for real-time, on-site, or continuous monitoring, particularly in low-resource settings and dynamic food supply environments.

In response to these limitations, biosensors have gained considerable attention as promising alternatives for food contaminant detection. Biosensors integrate biological recognition elements—such as enzymes, antibodies, nucleic acids, aptamers, or whole cells—with physicochemical transducers to convert biochemical interactions into measurable signals (5). Over the past two decades, biosensor technologies have advanced rapidly, offering improved sensitivity, portability, cost-effectiveness, and response time compared to conventional analytical platforms (6).

Most existing reviews on food safety biosensors have focused on classification schemes based on biorecognition elements or transduction mechanisms, as well as their applications for specific contaminant groups (7,8). While these contributions provide valuable technical insights, they often treat biosensors as standalone analytical devices, emphasizing detection performance metrics such as limits of detection, linear range, and selectivity. However, such an approach no longer fully reflects the evolving role of biosensors in contemporary food safety systems.

Recent developments indicate a paradigm shift from passive contaminant detection toward intelligent, interconnected, and predictive biosensing platforms. The emergence of the Food Safety 4.0 concept—aligned with Industry 4.0—has redefined food safety management as a data-driven, real-time, and risk-based process (1). In this framework, biosensors function not merely as detection tools but as data-generating nodes within integrated digital ecosystems that combine artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), and cloud-based analytics (9).

AI-assisted biosensors enable advanced signal processing, pattern recognition, and multi-analyte discrimination in complex food matrices, addressing long-standing challenges such as signal noise, cross-reactivity, and matrix interference (8). Machine learning algorithms enhance biosensor performance by extracting hidden patterns from large datasets, enabling predictive analytics and early warning systems for contamination events. Simultaneously, IoT-enabled biosensors facilitate continuous monitoring and real-time data transmission across the food supply chain, improving traceability, transparency, and regulatory compliance (10).

The COVID-19 pandemic further underscored the importance of rapid, decentralized, and intelligent sensing technologies for biological risk management, accelerating the adoption of point-of-care and smart biosensors across food and environmental monitoring sectors. These developments highlight the urgent need to reconceptualize biosensors not simply as analytical

instruments, but as strategic components of proactive food safety governance.

Despite these advances, significant challenges remain, including the stability of biological recognition elements, data quality and standardization, algorithm transparency, regulatory acceptance, and large-scale deployment. Addressing these issues requires a multidisciplinary perspective that integrates materials science, biotechnology, data science, and regulatory frameworks.

Accordingly, this review aims to provide a critical and forward-looking synthesis of recent advances in biosensors for food contaminant detection, with a particular emphasis on their transformation within the Food Safety 4.0 paradigm. Rather than offering a purely descriptive overview, this article highlights the transition from conventional detection-based biosensors to intelligent, predictive, and interconnected biosensing systems capable of supporting real-time decision-making and risk management throughout the global food supply chain.

## 2. Conceptual framework of biosensors in food safety 4.0

### 2.1. From conventional biosensors to food safety 4.0 systems

Historically, biosensors for food safety have been developed as analytical tools designed to detect specific contaminants with high sensitivity and selectivity. These conventional biosensors typically operate in a linear workflow, in which a biological recognition event is converted into an electrical or optical signal and interpreted independently of broader contextual data (4,5). While effective at the analytical level, such systems are inherently reactive, providing contamination information only after an event has occurred.

The emergence of Food Safety 4.0, inspired by the principles of Industry 4.0, represents a paradigm shift toward real-time, data-driven, and predictive food safety management (1). In this framework, biosensors are no longer isolated detection devices but are embedded within cyber–physical food systems, where biological sensing, digital infrastructure, and intelligent analytics converge. Food Safety 4.0 emphasizes continuous monitoring, early warning, traceability, and proactive risk mitigation across the entire food supply chain.

This transformation redefines the functional role of biosensors. Rather than simply answering the question “Is a contaminant present?”, intelligent biosensors address higher-order questions such as “What is the contamination trend?”, “What is the predicted risk?”, and “What intervention is required?” (9). Consequently, biosensors become strategic components of decision-support systems rather than stand-alone analytical endpoints.

### 2.2. Structural components of intelligent biosensing systems

An intelligent biosensing system within the Food Safety 4.0 paradigm can be conceptualized as a multi-layer architecture, consisting of four interdependent layers: (i) biological sensing, (ii) signal transduction and enhancement, (iii) data intelligence, and (iv) decision and action.

At the biological sensing layer, recognition elements such as enzymes, antibodies, aptamers, DNAzymes,

and whole cells selectively interact with target analytes. Recent advances emphasize the use of synthetic and programmable bioreceptors, including nucleic acid-based constructs and engineered cells, to improve specificity, robustness, and adaptability under variable food matrix conditions (8).

The signal transduction and enhancement layer converts biorecognition events into measurable outputs through electrochemical, optical, piezoelectric, or thermal mechanisms. Integration with nanomaterials—such as graphene, gold nanoparticles, quantum dots, and metal–organic frameworks—has significantly enhanced signal amplification, sensitivity, and miniaturization (7). Hybrid transduction strategies are increasingly adopted to enable multiplex detection and reduce false positives.

The data intelligence layer constitutes a defining feature of Food Safety 4.0 biosensors. Machine learning algorithms are applied to raw biosensor signals to perform noise filtering, pattern recognition, feature extraction, and anomaly detection. These models enable biosensors to operate effectively in complex and variable food matrices, overcoming one of the major limitations of conventional biosensing platforms (8). Importantly, intelligent systems can learn from historical data, allowing adaptive calibration and predictive modeling of contamination risks.

The decision and action layer integrates biosensor outputs with IoT infrastructure, cloud computing, and digital dashboards. This layer supports real-time alerts, automated responses, regulatory reporting, and traceability mechanisms. In advanced implementations, biosensors are directly linked to control systems that trigger corrective actions such as product segregation, processing adjustments, or supply chain interventions (10).

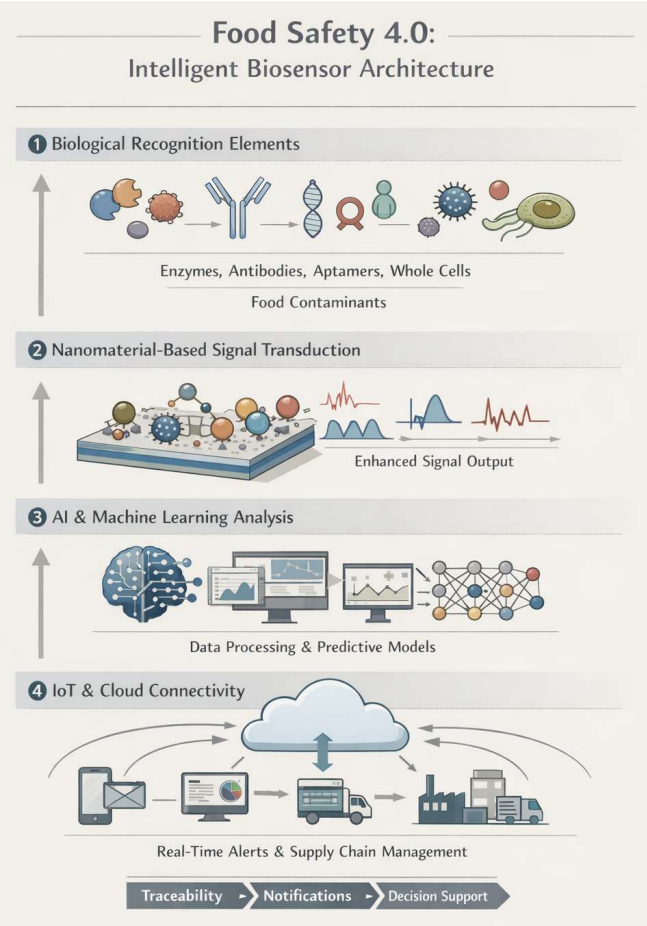



**Figure 1.** Conceptual framework of intelligent biosensors in Food Safety 4.0 (developed by the author)

Conceptual architecture of intelligent biosensors within the Food Safety 4.0 paradigm, illustrating the integration of biological recognition, signal transduction, data intelligence (AI/ML), and IoT-enabled decision-making for real-time and predictive food safety management.

### 2.3. Role of artificial intelligence and machine learning in biosensor intelligence

Artificial intelligence plays a pivotal role in transforming biosensors from passive detectors into

intelligent monitoring systems. Machine learning (ML) algorithms—including supervised, unsupervised, and deep learning approaches—enable biosensors to process high-dimensional and non-linear datasets generated during real-world food analysis (8,11).

Supervised learning models have been widely applied for quantitative analyte prediction, contaminant classification, and calibration transfer across different food matrices. For example, optical and electrochemical biosensors integrated with ML models have been successfully used to quantify pesticide residues and heavy metals in complex food samples by compensating for matrix interference and signal drift (15,20). In pathogen detection, ML-assisted biosensors have demonstrated improved discrimination between pathogenic and non-pathogenic strains based on multivariate signal features, enabling rapid and reliable on-site diagnosis (10,11).

Unsupervised learning techniques facilitate anomaly detection and clustering, allowing early identification of abnormal contamination patterns. Sensor array systems, such as optoelectronic nose platforms combined with pattern recognition algorithms, have been reported to distinguish food spoilage and contamination signatures through collective response fingerprints rather than single-analyte specificity (12-15).

Deep learning architectures, particularly convolutional neural networks, have shown promise in optical and imaging-based biosensors where complex spectral or visual features must be extracted. Recent studies demonstrated that deep learning-enabled biosensors could achieve high accuracy in multi-contaminant classification and concentration prediction from fluorescence, colorimetric, and spectroscopic signals (8,11).

Beyond analytical accuracy enhancement, AI contributes to predictive food safety by enabling biosensors to forecast contamination risks based on temporal trends, environmental conditions, and supply chain variables. Such predictive applications have been proposed for early warning of mycotoxin outbreaks and microbial contamination events by integrating biosensor outputs with contextual data streams (16-20). This predictive capability represents a fundamental departure from conventional food safety monitoring, aligning biosensors with risk-based regulatory frameworks increasingly adopted by food authorities worldwide.

### 2.4. IoT-enabled biosensors and digital food traceability

The integration of biosensors with IoT infrastructure enables continuous, distributed, and scalable food safety monitoring. IoT-enabled biosensors function as interconnected nodes that transmit real-time data across production, processing, storage, and distribution environments (1,20). Wireless communication technologies and smartphone-based interfaces have further expanded the accessibility and deployment of biosensing platforms, facilitating real-time decision-making at different points of the food supply chain.

Several studies have demonstrated practical applications of IoT-enabled biosensors in the food industry. For example, electrochemical and optical biosensors integrated with wireless communication modules have been applied for real-time monitoring of microbial contamination and spoilage indicators in

cold-chain systems, enabling rapid intervention during storage and transportation (10,15). In fresh food supply chains, IoT-connected biosensors have been reported for continuous detection of pathogens and chemical hazards, allowing contamination events to be identified earlier than conventional batch testing approaches (11,20).

Such connectivity supports digital traceability systems, where biosensor data are linked to product identity, origin, processing conditions, and logistics information. Smart packaging platforms incorporating biosensors and IoT connectivity have been proposed to transmit quality and safety information directly to cloud-based databases and end-users, improving transparency and consumer confidence (15,20). This capability enhances accountability while facilitating rapid response to contamination events.

From a regulatory perspective, IoT-enabled biosensors provide verifiable, time-stamped datasets that support compliance, audits, and evidence-based decision-making. Pilot implementations of digital food monitoring systems combining biosensors, IoT, and cloud analytics have shown potential for strengthening inspection efficiency and supporting risk-based regulatory frameworks by enabling continuous surveillance rather than episodic laboratory testing (1,20).

2.5. Implications for global food safety governance

The conceptual shift toward intelligent biosensing has profound implications for food safety governance. By enabling real-time surveillance and predictive analytics, biosensors support proactive risk management strategies aligned with modern regulatory paradigms. Moreover, intelligent biosensors democratize food safety monitoring by reducing dependence on centralized laboratories, thereby improving surveillance capacity in low- and middle-income regions.

However, the deployment of intelligent biosensors also raises critical challenges, including data standardization, algorithm transparency, cybersecurity, and regulatory validation. Addressing these challenges requires harmonized standards and interdisciplinary collaboration among scientists, regulators, and industry stakeholders.

## 3. Biosensors for major food contaminants: From target-specific detection to predictive monitoring

3.1. Heavy metals: Toward intelligent and climate-responsive sensing

Heavy metal contamination—including lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As)—remains a persistent threat to food safety due to industrial pollution, intensive agriculture, and climate-driven changes in soil and water chemistry. Conventional detection techniques offer high accuracy but lack portability and real-time capability, limiting their utility for rapid field-based risk assessment (4).

Recent advances in biosensor development for heavy metals have focused on nucleic acid-based recognition elements, particularly aptamers and DNAzymes, owing to their high specificity, chemical stability, and compatibility with miniaturized platforms (7). DNAzyme-based biosensors have demonstrated exceptional selectivity for metal ions such as $Pb^{2+}$ and $Hg^{2+}$, enabling low detection limits in complex food matrices.

Within the Food Safety 4.0 paradigm, the novelty lies in integrating these biosensors with machine learning-

assisted signal interpretation. AI-based calibration models compensate for matrix interference and environmental variability, enabling more robust quantification across diverse food types. Moreover, temporal data generated by continuous biosensing systems can be combined with environmental parameters—such as rainfall, soil pH, and temperature—to support predictive modeling of heavy metal bioaccumulation, particularly under climate change scenarios (8).

3.2. Pesticide residues: From single-analyte detection to multi-residue intelligence

Pesticide residues are among the most strictly regulated food contaminants due to their potential chronic health effects and widespread agricultural use. Traditional biosensors for pesticide detection have largely relied on enzyme inhibition mechanisms, particularly acetylcholinesterase (AChE)-based systems, which provide rapid and sensitive detection of organophosphate and carbamate pesticides (6). These systems have been widely reported for rapid screening of pesticide residues in fruits and vegetables; however, their applicability remains limited in complex multi-residue scenarios.

Enzyme inhibition-based biosensors suffer from limited selectivity and susceptibility to false positives when exposed to mixtures of agrochemicals and food matrix interferences. To overcome this limitation, recent studies have shifted toward sensor array platforms combined with pattern recognition and machine learning algorithms, enabling discrimination of multiple pesticide residues based on collective signal fingerprints rather than single-analyte specificity (15). Optical and electrochemical sensor arrays have been successfully applied to classify and quantify different classes of pesticides in complex food samples using multivariate data analysis and supervised learning models (11,20).

Machine learning-enhanced biosensor arrays represent a critical innovation in this area. By analyzing multidimensional response patterns, supervised learning algorithms can simultaneously classify and quantify multiple pesticide residues, even under mixed-contaminant conditions (8,15). Such approaches have demonstrated improved robustness against matrix effects and sensor drift, addressing key limitations of conventional single-analyte biosensors.

Furthermore, integration with IoT infrastructure enables real-time pesticide residue monitoring along the supply chain. IoT-connected biosensor platforms have been proposed for continuous surveillance of pesticide contamination in agricultural products during storage and transportation, supporting dynamic compliance assessment and risk-based inspection strategies (1,20).These systems transform pesticide biosensing from episodic laboratory testing into continuous and distributed monitoring, thereby strengthening food safety governance in multi-residue exposure contexts.

3.3. Food allergens: Biosensors supporting regulatory compliance and consumer trust

Food allergens constitute a unique category of contaminants due to their potentially severe health consequences even at trace levels. Regulatory agencies worldwide mandate strict labeling and monitoring of major allergens, including peanuts, milk, eggs, soy, and gluten (2). Biosensors offer rapid, sensitive, and cost-effective alternatives to conventional immunoassays

for allergen detection, particularly for on-site screening in food processing environments.

Recent developments have focused on multiplex allergen biosensors capable of detecting multiple allergenic proteins within a single analytical platform. Optical and electrochemical biosensors employing antibody- or aptamer-based recognition elements have demonstrated high sensitivity for allergen detection in complex food matrices, enabling rapid analysis of milk proteins, peanut allergens, and gluten residues in processed foods (11,15). Sensor array approaches combined with pattern recognition algorithms have further enabled the discrimination of different allergenic proteins based on collective signal responses rather than single-target specificity (20).

Within the Food Safety 4.0 framework, allergen biosensors are increasingly integrated into in-line and at-line monitoring systems, allowing continuous verification of allergen control during food production. AI-assisted signal interpretation enhances discrimination between structurally similar proteins and overlapping immunochemical responses, thereby reducing cross-reactivity and false alarms (8). Pilot studies on intelligent biosensing platforms have shown that real-time allergen monitoring can support dynamic risk management and rapid corrective actions in food processing lines, strengthening both regulatory compliance and quality assurance practices (1,20).

These intelligent allergen monitoring systems support not only regulatory compliance but also consumer trust, as real-time allergen surveillance becomes an integral component of transparent food labeling and digital food safety systems.

### 3.4. Mycotoxins: From detection to early-warning systems

Mycotoxins, produced by toxigenic fungi such as *Aspergillus*, *Fusarium*, and *Penicillium*, pose serious risks to food safety and security, particularly in cereal-based products and animal feed. Climate change has significantly altered fungal growth patterns, increasing the unpredictability and geographical spread of mycotoxin contamination (1).

Biosensors for mycotoxin detection have evolved rapidly, employing antibodies, aptamers, and molecularly imprinted polymers as recognition elements. Electrochemical and optical biosensors have demonstrated high sensitivity and low detection limits suitable for regulatory thresholds for aflatoxins, ochratoxin A, and fumonisins in grains and processed foods (7,6,11). Recent studies have also reported multiplex biosensing platforms capable of detecting multiple mycotoxins simultaneously, addressing the frequent co-occurrence of these contaminants in agricultural products (8,20).

The key innovation in this domain lies in the integration of biosensor data with predictive analytics. Machine learning-assisted biosensors have been proposed to correlate real-time detection signals with environmental and agronomic variables, enabling early-warning systems for mycotoxin outbreaks before contamination levels exceed regulatory limits (15,20). Such predictive biosensing platforms represent a paradigm shift from reactive testing toward proactive contamination prevention, particularly under climate-driven variability in fungal ecology (1,11).

### 3.5. Foodborne pathogens: Intelligent biosensors for rapid and decentralized surveillance

Foodborne pathogens—including *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli*—remain leading causes of food-related illness globally. Conventional pathogen detection methods are time-intensive, often requiring enrichment and laboratory confirmation, which delays response to contamination events.

Recent biosensor innovations emphasize point-of-care and on-site pathogen detection, utilizing nucleic acid probes, bacteriophages, and whole-cell recognition strategies. AI-assisted biosensors have demonstrated enhanced discrimination between pathogenic and non-pathogenic strains, reducing false positives and improving reliability (10).

In the context of Food Safety 4.0, pathogen biosensors are increasingly deployed as distributed surveillance networks, particularly in high-risk food sectors. Lessons from the COVID-19 pandemic have accelerated the acceptance of decentralized biosensing technologies, highlighting their importance for biosecurity and public health resilience.

Evolution of biosensors for major food contaminants from conventional target-specific detection toward intelligent, multiplexed, and predictive monitoring systems enabled by artificial intelligence and IoT integration.

## 4. Strengths, limitations, and regulatory challenges of intelligent biosensors in food safety

### 4.1. Key strengths of intelligent biosensing platforms

The integration of biosensors with artificial intelligence, IoT, and advanced data analytics has fundamentally strengthened their role in modern food safety systems. One of the most significant advantages of intelligent biosensors is their ability to deliver real-time and on-site monitoring, thereby reducing reliance on centralized laboratory testing and accelerating decision-making processes (10).

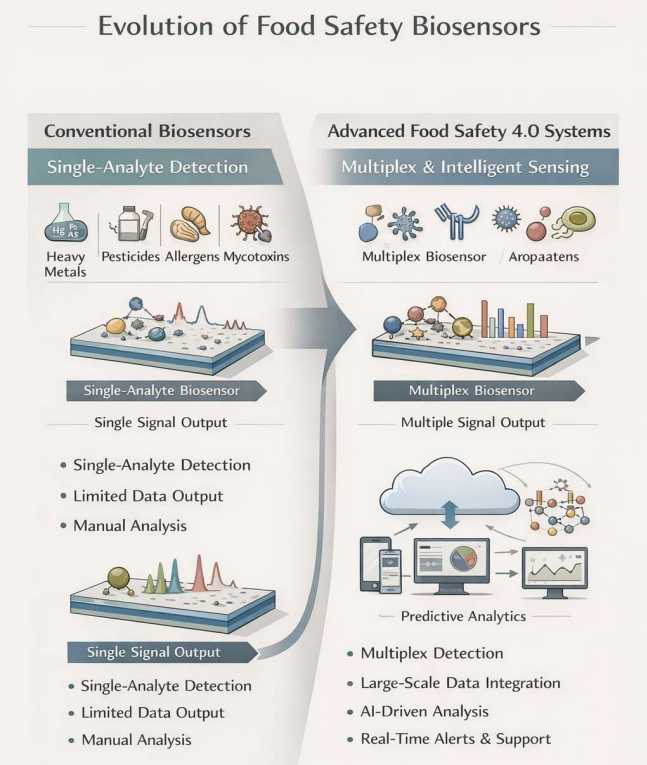



**Figure 2.** Evolution of biosensors for major food contaminants from conventional detection to intelligent and predictive monitoring under the Food Safety 4.0 paradigm (developed by the author).

Another critical strength lies in the enhanced analytical performance achieved through AI-assisted signal processing. Machine learning algorithms improve sensitivity, selectivity, and robustness by compensating for signal drift, environmental variability, and complex food matrix effects. This capability is particularly valuable in real-world applications where conventional biosensors often fail to maintain accuracy outside controlled laboratory conditions (8).

Intelligent biosensors also enable multiplex and multi-contaminant detection, addressing a major limitation of

traditional single-analyte sensors. By analyzing collective signal patterns rather than isolated responses, these systems provide a more holistic assessment of food safety risks, which is increasingly important given the prevalence of mixed contaminant exposure in global food supply chains.

From a systems perspective, IoT-enabled biosensors enhance traceability, transparency, and accountability across the food supply chain. Continuous data generation supports dynamic risk assessment, targeted interventions, and evidence-based regulatory oversight. Collectively, these strengths position intelligent biosensors as essential components of Food Safety 4.0 infrastructures.

4.2. Technical and operational limitations

Despite their promise, intelligent biosensors face several technical and operational limitations that constrain widespread adoption. One persistent challenge is the stability and reproducibility of biological recognition elements, particularly under harsh processing, storage, and environmental conditions. Enzymes and antibodies may suffer from denaturation or loss of activity, limiting sensor lifespan and reliability in industrial settings (4).

Food matrix complexity remains another significant obstacle. Variations in pH, temperature, ionic strength, and the presence of interfering substances can adversely affect biosensor performance. Although AI-based calibration models mitigate some of these effects, their effectiveness depends on the availability of high-quality training data and careful model validation.

Operational challenges also include sensor fouling, maintenance requirements, and scalability. Many biosensing platforms perform well in laboratory-scale demonstrations but encounter difficulties during long-term deployment or mass production. Additionally, power consumption and data transmission reliability present practical constraints for continuous monitoring applications, particularly in decentralized or resource-limited environments.

4.3. Data reliability, algorithm transparency, and ethical considerations

The increasing reliance on AI and machine learning introduces new challenges related to data reliability, algorithm transparency, and ethical governance. Biosensor outputs are only as reliable as the data used to train and validate predictive models. Inconsistent data quality, sensor drift, and biased datasets can lead to erroneous predictions, potentially undermining food safety decisions.

Algorithm transparency is a particularly critical issue in regulatory contexts. Black-box machine learning models may offer high predictive accuracy but lack interpretability, making it difficult for regulators and stakeholders to understand or trust decision outcomes. The adoption of explainable AI (XAI) approaches is therefore essential to ensure accountability and facilitate regulatory acceptance (8).

Ethical considerations also arise from continuous data collection and surveillance across food systems. Issues related to data ownership, privacy, and cybersecurity must be addressed to prevent misuse or unauthorized access to sensitive information, especially when biosensor networks span multiple stakeholders and jurisdictions.

4.4. Regulatory and standardization challenges

Regulatory validation represents one of the most significant barriers to the implementation of intelligent biosensors in food safety. Existing regulatory frameworks are largely designed around traditional analytical methods, emphasizing standardized protocols, laboratory-based validation, and fixed performance metrics. Intelligent biosensors, by contrast, are adaptive, data-driven, and context-dependent, challenging conventional regulatory paradigms.

The lack of harmonized standards for biosensor validation, data formats, and performance benchmarking complicates regulatory approval and cross-border acceptance. Furthermore, the dynamic nature of machine learning models raises questions about how sensor performance should be evaluated over time, particularly when models are continuously updated or retrained.

To address these challenges, regulatory agencies must evolve toward risk-based and performance-oriented validation frameworks that accommodate intelligent sensing technologies. Collaborative initiatives involving academia, industry, and regulators are essential for developing guidelines that balance innovation with safety, reliability, and public trust (1).

4.5. Bridging the gap between innovation and implementation

Closing the gap between laboratory innovation and real-world implementation requires a multidisciplinary approach that integrates technological development with regulatory science, systems engineering, and stakeholder engagement. Standardized reference materials, open datasets, and interoperable platforms are critical for accelerating validation and deployment.

Equally important is the alignment of intelligent biosensing technologies with the needs and capacities of end-users, including food producers, inspectors, and regulatory authorities. User-centered design, training programs, and clear communication of system limitations are necessary to ensure effective adoption and sustainable impact.

## 5. Future perspectives and research roadmap for intelligent biosensors in food safety

5.1. Transition from reactive detection to predictive food safety

The future of food safety biosensors lies in their transformation from reactive detection tools into predictive and preventive monitoring systems. Traditional biosensing approaches primarily focus on identifying contaminants after exposure has occurred. In contrast, intelligent biosensors integrated with artificial intelligence and big data analytics enable risk anticipation, allowing stakeholders to intervene before contamination reaches critical levels (1).

Predictive food safety relies on the continuous acquisition of biosensor data combined with contextual information such as environmental conditions, agricultural practices, storage parameters, and logistics variables. Machine learning models trained on longitudinal datasets can forecast contamination trends, identify emerging hotspots, and support early-warning systems for foodborne hazards. This shift aligns with global regulatory movements toward risk-based and preventive food safety frameworks, such as

Hazard Analysis and Critical Control Points (HACCP) and modernized food safety laws.

5.2. Emerging technologies shaping next-generation biosensors

Several emerging technologies are expected to shape the next generation of intelligent biosensors for food safety. Synthetic biology offers new opportunities for designing programmable and robust biological recognition elements, including engineered cells and modular genetic circuits that respond selectively to complex contaminant signatures (9).

Advances in nanotechnology continue to enhance biosensor sensitivity, multiplexing capability, and miniaturization. Novel nanomaterials—such as metal–organic frameworks, two-dimensional materials, and plasmonic nanostructures—enable enhanced signal amplification and multi-modal sensing. When coupled with AI-based data fusion, these materials support high-throughput and multi-analyte detection within compact platforms (7).

Another critical frontier is the integration of biosensors with digital twins of food systems. Digital twins replicate physical food production and supply chain processes in virtual environments, allowing biosensor data to be used for real-time simulation, scenario analysis, and optimization. Such integration could revolutionize food safety management by enabling predictive interventions at both local and systemic levels.

5.3. Explainable and trustworthy artificial intelligence

As biosensors increasingly rely on AI-driven analytics, the development of explainable and trustworthy AI (XAI) becomes essential. Regulatory authorities and industry stakeholders require transparent decision-making processes to ensure accountability, reproducibility, and public trust. Black-box models, while powerful, may hinder regulatory acceptance if their predictions cannot be interpreted or justified.

Future research should prioritize hybrid modeling approaches that combine data-driven machine learning with mechanistic understanding of biochemical interactions and food system dynamics. Explainable AI techniques—such as feature attribution, model simplification, and uncertainty quantification—will play a crucial role in bridging the gap between algorithmic performance and regulatory compliance (8,11).

5.4. Regulatory foresight and standardization pathways

Regulatory evolution is a decisive factor in determining the real-world impact of intelligent biosensors. Current food safety regulations are not fully equipped to evaluate adaptive, AI-enabled sensing systems that evolve over time. Therefore, regulatory foresight is required to establish flexible, performance-based validation frameworks that accommodate innovation while safeguarding public health.

Future regulatory pathways may involve continuous performance monitoring, post-market surveillance of biosensor systems, and standardized protocols for data governance and cybersecurity. International harmonization of standards will be particularly important as food supply chains become increasingly globalized. Collaborative pilot programs involving regulators, industry, and academic institutions can serve as testbeds for validating intelligent biosensors under real-world conditions (1).

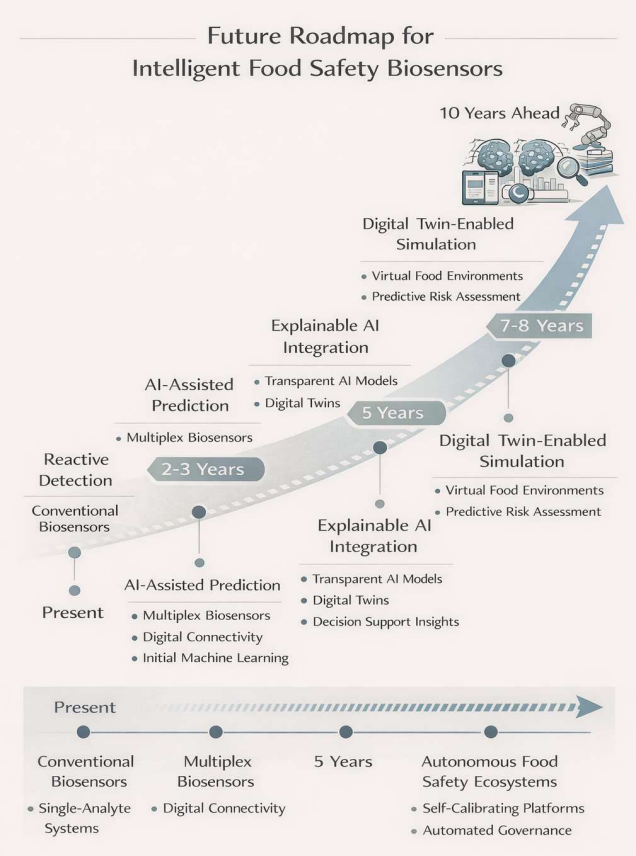



**Figure 3.** Research roadmap for intelligent biosensors in food safety illustrating the transition from reactive detection to predictive and autonomous systems (developed by the author).

### 5.5. Toward autonomous and resilient food safety ecosystems

In the long term, intelligent biosensors are expected to contribute to the development of autonomous food safety ecosystems. In such systems, biosensors continuously monitor food products and environments, AI algorithms assess risk in real time, and automated control mechanisms implement corrective actions without human intervention. These autonomous systems enhance resilience by reducing response times and minimizing human error.

Importantly, the adoption of intelligent biosensors must be inclusive and equitable. Scalable, low-cost, and user-friendly platforms are essential to ensure that advanced food safety technologies benefit low- and middle-income regions, where foodborne risks are often highest. Future research should therefore balance technological sophistication with accessibility and sustainability.

Future research roadmap illustrating the evolution of food safety biosensors from reactive detection to predictive, explainable, and autonomous systems integrated with AI, IoT, and regulatory frameworks.

## 6. Conclusion

This review critically examines recent advances in biosensors for food contaminant detection through the lens of the Food Safety 4.0 paradigm, highlighting a fundamental transformation from conventional, ad hoc detection tools to intelligent, interconnected, and predictive biosensor systems. While traditional biosensors have significantly improved the speed and accessibility of food safety analysis, their true potential will only be realized when integrated with artificial intelligence, Internet of Things (IoT) infrastructure, and data-driven decision-making frameworks.

Across major contaminant categories—including heavy metals, pesticide residues, allergens, mycotoxins, and foodborne pathogens—intelligent biosensors demonstrate enhanced analytical performance, multiplexing capability, and adaptability to complex food matrices. The incorporation of machine learning enables advanced signal interpretation, predictive modeling, and early-warning functionality, addressing long-standing challenges associated with environmental variability, matrix interference, and multi-contaminant exposure. These capabilities align biosensing technologies with modern risk-based food safety strategies and global regulatory priorities.

Beyond technical advancements, this review emphasizes the evolving role of biosensors as strategic components of digital food safety ecosystems. IoT-enabled biosensor networks support real-time monitoring, traceability, and transparency across global food supply chains, facilitating rapid response to contamination events and strengthening regulatory oversight. The integration of explainable and trustworthy artificial intelligence further enhances confidence in biosensor-driven decisions, promoting regulatory acceptance and stakeholder trust.

Despite these advances, significant challenges remain. Issues related to bioreceptor stability, data quality, algorithm transparency, cybersecurity, and regulatory harmonization continue to limit large-scale deployment. Addressing these barriers will require coordinated efforts across disciplines, including materials science, biotechnology, data science, and regulatory science. The development of standardized validation frameworks, open datasets, and interoperable platforms is essential to bridge the gap between laboratory innovation and real-world implementation.

Looking forward, intelligent biosensors are poised to play a pivotal role in the transition toward predictive, preventive, and ultimately autonomous food safety systems. Emerging technologies such as synthetic biology, digital twins, and explainable AI will further enhance biosensor functionality and resilience. Importantly, future research and policy initiatives must ensure that these technologies are accessible, scalable, and equitable, enabling their adoption across diverse socioeconomic and geographic contexts.

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**Authorship contribution**

Alfi Sophian: Conceptualization; Methodology; Formal analysis; Investigation; Writing – original draft; Writing – review & editing; Visualization; Supervision.

**Declaration of competing interest**

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

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