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Advancements in food quality monitoring: integrating biosensors for precision detection

Soumitra Nath *

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The integration of biosensors into food quality monitoring systems presents a promising approach to enhance food safety and quality assurance. Biosensors enable rapid, accurate, and on-site detection of contaminants, revolutionizing the management of food safety risks throughout the supply chain. This review provides insights into the current challenges, opportunities and future directions of biosensor technology in ensuring the integrity and safety of our food supply. Electrochemical, optical, and piezoelectric biosensors offer versatile platforms for food quality monitoring, each providing unique advantages in sensitivity, specificity, and detection capabilities. By harnessing these principles, biosensors offer valuable tools for detecting a wide range of contaminants, allergens and adulterants in food samples, thus improving food safety and quality assurance measures. However, biosensor implementation faces challenges such as sensitivity and specificity issues, matrix interference, and shelf-life concerns. Overcoming these challenges requires research and development efforts to improve biosensor design, optimization, and performance. Recent advances in biosensor technology, including nanotechnology integration, multiplexed detection and smartphone-based biosensors, offer exciting opportunities to improve and enhance food quality monitoring. Future perspectives include the development of improved sensing technologies, standardization, regulatory considerations, and integration with the Internet of Things (IoT) for real-time monitoring, paving the way for the revolutionization of food safety practices throughout the global food supply chain.

Sustainability spotlight statement

The integration of biosensors for precision detection in food quality monitoring represents a critical advancement in ensuring the safety and integrity of our food supply chain. Biosensors enable rapid, accurate and on-site detection of contaminants, mitigating the risks associated with foodborne illnesses and enhancing overall food quality assurance. This sustainable advancement aligns with the United Nations Sustainable Development Goal (SDG) 3: Good Health and Well-being, by promoting food safety and reducing the burden of food-related diseases. Additionally, by revolutionizing food safety practices and facilitating real-time monitoring, biosensor technology contributes to SDG 2: Zero Hunger, by ensuring access to safe and nutritious food for all. Through continuous research and development efforts, biosensors hold the potential to significantly improve food safety measures and promote sustainable development in the global food industry.

1. Introduction

Ensuring the safety and quality of food products is of paramount importance to public health, consumer confidence, and regulatory compliance. Food quality monitoring plays a crucial role in identifying and mitigating risks associated with contaminants, adulterants, and other factors that can compromise the integrity of the food supply chain. Traditional methods of food analysis often involve laboratory techniques that require time, which can delay the detection of hazards and increase the potential of consumer exposure to harmful substances.[1]

In recent years, biosensors have emerged as powerful tools for improving the efficiency and accuracy of food quality monitoring. These analytical devices integrate biological recognition elements with transducer components to detect and quantify specific analytes in food samples.[2] By harnessing the inherent specificity and sensitivity of biological interactions, biosensors offer rapid on-site detection capabilities that can replace traditional laboratory-based methods.[3] The role of biosensors in enhancing detection accuracy is multifaceted. Unlike conventional assays that rely on complex sample preparation and specialized equipment, biosensors offer simplicity, portability, and real-time monitoring capabilities. Biosensors enable rapid screening of large volumes of food samples, reducing the time and resources required for analysis.[3] Furthermore, they can detect target analytes in low concentrations, providing early warning signals of potential food safety hazards.[4]

This review aims to provide a comprehensive overview of the current state of the art in biosensor technology for food quality

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Department of Biotechnology, Gurucharan College, Cachar, Silchar, 788004, Assam, India. E-mail: nath.soumitra1@gmail.com; Tel: +91 9401374737

monitoring. It discusses the principles and mechanisms underlying biosensor operation, highlighting their ability to achieve high sensitivity and specificity in detecting various contaminants and adulterants.

2. Principles and mechanisms of biosensor operation

The principle of a biosensor revolves around the selective recognition of a target analyte by a biological receptor that initiates a measurable signal indicative of the analyte's concentration or presence. The bioreceptor, also known as the recognition element, is composed of biomolecules or biological entities specifically designed to interact with the target analyte.[5] This interaction induces a biochemical or biophysical change, which serves as the basis for detection. The bioreceptor is coupled with a transducer responsible for converting the bioreceptor–analyte interaction into a measurable signal.[6] The signal is then amplified by an amplifier, enhancing its detectability and improving the signal-to-noise ratio.[7] Finally, the processed signal is analyzed and interpreted by a processor,[8] and the results are displayed in a human-readable format, allowing users to interpret the findings.[2] Therefore, the integration of the bioreceptor, transducer, amplifier, processor, and display forms the foundation of a biosensor system, enabling accurate and efficient detection of target analytes.

The first biosensor was developed by Leland C. Clark, Jr in 1956 for oxygen detection, earning him the title "father of biosensors". His invention, known as the "Clark electrode," revolutionized the field. In 1962, Clark demonstrated an amperometric enzyme electrode for glucose detection.[9] This was followed in 1969 by the development of the first potentiometric biosensor for urea detection by Guilbault and Montalvo Jr.[10] The Yellow Springs Instrument Company (YSI) utilized Clark's technology to create the Model 23A YSI analyzer, which became the first commercially successful glucose biosensor in 1975.[11] This device enabled the direct measurement of glucose through the amperometric detection of hydrogen peroxide. In the glucose biosensor, the enzyme glucose oxidase is utilized as a bioreceptor, which interacts with glucose molecules present in the food sample.[12] This facilitates the conversion of glucose to gluconic acid and hydrogen peroxide (H_2O_2). This biochemical process generates a measurable signal, which is detected by a transducer. The transducer translates the signal into a current, with the magnitude of the current directly correlating with the glucose concentration in the sample. The amplified signal is then displayed on a digital screen, providing users with an accurate and real-time measurement of the glucose levels in the food sample (Fig. 1).

Soumitra Nath

Soumitra Nath received his M.Sc. in Biotechnology and PhD in Microbiology from Assam University, Silchar. He worked as a research fellow at the National Institute of Immunology in New Delhi. Currently, Dr Nath holds the position of Assistant Professor in the Department of Biotechnology at Gurucharan College, Silchar. He is also the co-coordinator of the Institutional Biotech Hub and Bioinformatics Centre, which is a research project funded by the Department of Biotechnology (DBT), New Delhi. His research focuses on environmental biotechnology and food microbiology, emphasizing waste treatment strategies, probiotics and antimicrobial studies.

3. Components of a biosensor for food quality monitoring

Biosensors have become essential in food quality monitoring, combining biological recognition elements with transducer components to detect and measure specific analytes in food samples. A schematic diagram depicting the various components of biosensor operation is presented in Fig. 2, while Table 1 summarizes the principles, uses, and disadvantages associated with these components.

3.1. Recognition element or bioreceptor

Recognition elements are biomolecules that selectively bind to the target analyte, initiating a biological response that is transduced into a measurable signal. Common recognition elements used in biosensors include enzymes, antibodies, nucleic acids (*e.g.*, DNA or RNA), whole cells, and molecularly imprinted polymers (MIPs).[5] These biomolecules exhibit high specificity for their target analytes, allowing selective detection of desired compounds. The immobilization of recognition elements on the biosensor surface is crucial for maintaining their stability and activity, ensuring reliable and reproducible detection performance.

3.2. Transducer

The transducer in a biosensor converts the bioreceptor–analyte interaction into a measurable signal, facilitating detection and quantification. It serves as the interface between the biological recognition event and the output signal, translating biochemical or biophysical changes into electrical, optical, acoustic, or thermal signals that can be processed and analyzed.[6] Various types of transducers are used in biosensors, including electrochemical, optical, acoustic, and thermal transducers, each offering specific advantages depending on the nature of the analyte and the desired sensitivity and selectivity.[2] The choice of transducer greatly influences the performance and capabilities of the biosensor system, affecting factors such as detection limit, response time, and compatibility with different sample matrices.

3.3. Amplifier

An amplifier serves to increase the strength or magnitude of the signal generated by the transducer in response to the

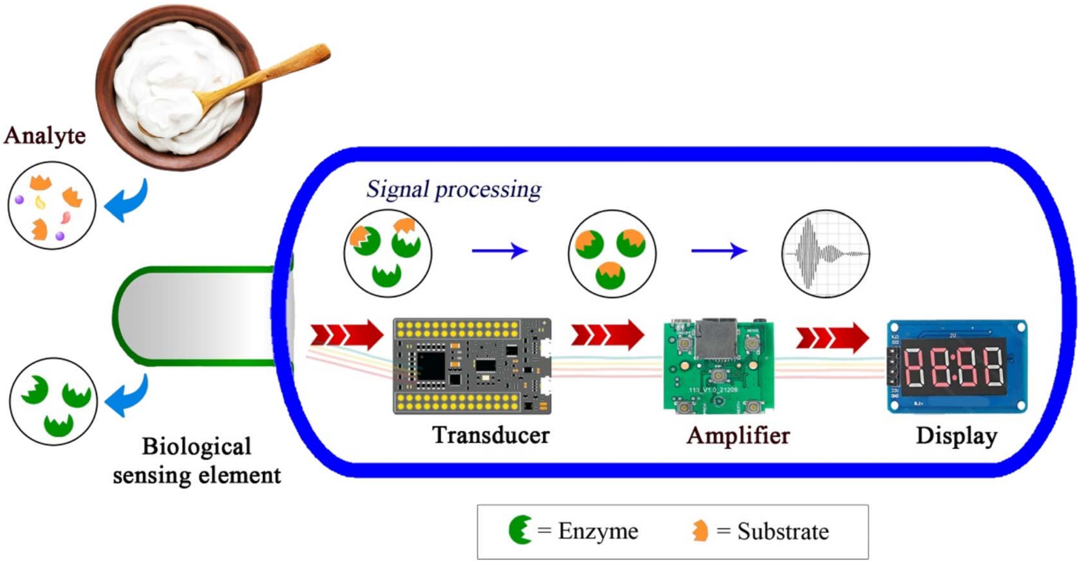

Fig. 1 Schematic diagram illustrating biosensor operation principles, highlighting recognition element–analyte interaction and signal transduction.

bioreceptor–analyte interaction.[7] It plays a critical role in enhancing the detectability and accuracy of the biosensor by amplifying the weak electrical, optical, acoustic, or thermal signals produced by the transducer. Amplifiers can be designed to operate across a wide range of frequencies and can be tailored to suit the specific requirements of the biosensor system.

3.4. Processor

The processor serves as the central computational unit responsible for data analysis, signal processing and decision-making. It processes the raw data obtained from the amplifier and converts them into meaningful information. Biosensor processors can range from simple microcontrollers to more

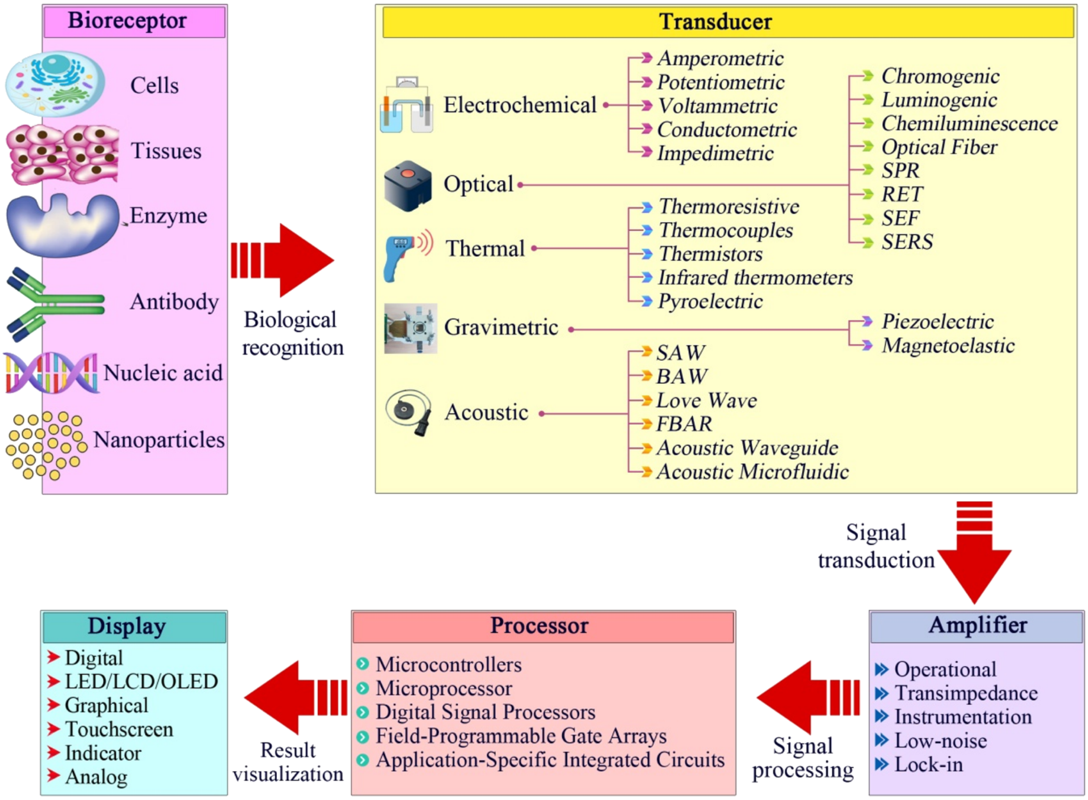

Fig. 2 Overview of biosensor components.

Table 1 Various components of biosensors, detailing their principles, uses, advantages and disadvantages

Name of the component	Principle	Uses	Advantages	Disadvantages	References
1. Bioreceptor					
Enzymes	Catalyze reactions, generating measurable signals	Detect glucose, cholesterol, metabolites	High specificity, rapid response, stability	Limited to specific reactions, sensitivity affected	84
Antibodies	Bind antigens, form complexes for detection	Detect proteins, viruses, bacteria	Exceptional specificity, detect low concentrations	Costly production, potential cross-reactivity	85
Nucleic acids (DNA/RNA)	Hybridize with targets, sequence detection	Identify DNA sequences, pathogens	High specificity, detect SNPs, rapid detection	Requires target sequence, susceptible to degradation	20
Living cells/cell components	Respond to analytes, monitor changes	Detect toxins, pollutants, biomarkers	Reflect integrated cellular responses, real-time monitoring	Variable responses, maintenance required, complex interpretation	86
Whole organisms	Exhibit physiological responses to analytes	Monitor environment, detect toxins	Capture broad responses, real-world relevance	Ethical concerns, limited applicability, complex interpretation	87
Molecularly imprinted polymers (MIPs)	Synthetic polymers with tailored binding	Detect small molecules, drugs, toxins	High selectivity, simple synthesis, versatility	Limited to compatible targets, lower binding affinity	53
2. Transducer					
Electrochemical biosensor	Measures changes in electrical properties	Detect ions, molecules, enzymes	High sensitivity, rapid response, low cost	Signal interference, electrode fouling	84
Optical biosensor	Measures changes in light properties	Detect biomolecules, fluorescence	High sensitivity, real-time monitoring	Limited to transparent or translucent samples	32a
Acoustic biosensor	Measures changes in sound waves	Detect biomolecules, cells	Non-invasive, real-time detection	Limited to liquid-phase samples	88
Thermal biosensor	Measures changes in heat or temperature	Detect gases, biomolecules	Simple design, rapid response	Sensitivity affected by environmental factors	89
Gravimetric biosensor	Measures changes in mass or weight	Detect mass changes due to analyte binding	High sensitivity, label-free detection	Requires precise environmental control	90
3. Amplifier					
Operational amplifier (Op-Amp)	Amplifies voltage difference between inputs	Signal conditioning, filtering	High gain, low noise, wide bandwidth	Requires external power supply	91
Transimpedance amplifier	Converts current into voltage for detection	Photodetection, electrochemical sensing	High sensitivity, low noise, wide dynamic range	Limited to current-based transduction	92
Instrumentation amplifier	Amplifies differential input signal	Bioimpedance measurements	High common-mode rejection, precise gain control	More complex circuitry, higher cost	93
Low-noise amplifier	Amplifies weak signals with minimal noise	Low-level signal detection	Enhances signal-to-noise ratio, improves sensitivity	Limited to specific frequency ranges	94
Lock-in amplifier	Amplifies signals at a specific frequency	Phase-sensitive detection	Rejects noise, improves signal detection in noisy environments	Requires reference signal for operation	95
4. Processor					
Microcontroller	Integrated circuit with CPU, memory, and I/O	Data analysis, signal processing	Low cost, low power consumption	Limited computational capabilities	91
Microprocessor	Central processing unit for general-purpose tasks	Complex data analysis, algorithm execution	High computational power, flexibility	Higher cost, higher power consumption	93
Digital signal processor (DSP)	Specialized processor for signal processing	Noise filtering, signal enhancement	High-speed signal processing, real-time analysis	Limited flexibility for general-purpose tasks	96
Field-programmable gate array (FPGA)	Programmable logic device for custom logic circuits	Customized data processing, hardware acceleration	High-speed parallel processing, low latency	Steeper learning curve, higher development cost	96
Application-specific integrated circuit (ASIC)	Custom-designed integrated circuit for specific tasks	Specialized data processing, low power consumption	High performance, optimized for specific applications	Higher development cost, less flexibility for changes	97
5. Display					
Digital display	Numerical representation of data	Quantitative analysis, concentration readout	Clear, easy-to-read output	Limited visualization capabilities	68 and 98
LED/LCD display					99

Table 1 *(Contd.)*

Name of the component	Principle	Uses	Advantages	Disadvantages	References
	Light-emitting diodes or liquid crystal display	Real-time monitoring, data visualization	Bright, energy-efficient, customizable	Limited display size, may require backlight	
OLED display	Organic light-emitting diodes	Portable devices, low-power applications	High contrast, wide viewing angles	Limited lifespan, potential burn-in	100
Graphical display	Graphical representation of data	Trend analysis, pattern recognition	Intuitive visualization, detailed information	Higher cost, more complex interface	101
Touchscreen display	Interactive display with touch input	User interaction, menu navigation	User-friendly interface, intuitive controls	Susceptible to damage, calibration issues	68
Analog display	Represents data using continuous variables (*e.g.*, dial)	Continuous monitoring, visual indication	Intuitive representation, immediate feedback	Limited precision, less suitable for precise readings	98
Indicator display	Provides simple visual indication of status or threshold	Alerting, binary status indication	Easy to understand, low power consumption	Limited information, may require additional interpretation	102

powerful microprocessors, depending on the complexity of the biosensing system and computational requirements.[8] They may perform tasks such as noise filtering, signal averaging, calibration, pattern recognition and data storage. Additionally, processors can facilitate communication with external devices or networks, enabling real-time monitoring, remote operation, and data sharing.[13]

3.5. Display

A display in the context of biosensors serves as an interface for presenting the results of the biosensing process to the user or operator.[2] A display can range from simple digital readouts to more sophisticated graphical interfaces, depending on the complexity of the biosensor system and the requirements of the end-user.[8] The choice of display is crucial in ensuring effective communication of the biosensor output, allowing quick decision-making and action based on the detected information.

4. Applications of biosensors in the detection of food contaminants

Biosensors play a pivotal role in detecting and quantifying various contaminants in food samples, offering rapid, sensitive, and selective analysis capabilities. Biosensor technology is essential for the detection and monitoring of food contaminants in food, such as chemicals, biological agents and physical substances (Table 2). Therefore, this technology plays a pivotal role in maintaining the safety and quality of food throughout the supply chain.

4.1. Pesticides and herbicides

Pesticides and herbicides are widely used in agriculture to enhance crop yield and protect against pests and weeds. However, their residues in food products pose significant health risks to consumers. Biosensors offer efficient tools for detecting pesticide and herbicide residues in food samples, ensuring food safety and regulatory compliance. A notable example is the enzyme biosensor, which utilizes acetylcholinesterase enzyme to detect organophosphate pesticides such as chlorpyrifos in fruits and vegetables.[14] Scientists have also developed immunosensors that employ specific antibodies to detect glyphosate, a commonly used herbicide, in food matrices.[15] These biosensors enable rapid, sensitive and selective pesticide and herbicide residue detection through electrochemical, optical or piezoelectric transduction methods.[16] The use of biosensors in real-time monitoring enhances food safety measures, protecting consumers from potential health hazards associated with pesticide and herbicide contamination.

4.2. Heavy metals

Heavy metals, such as lead, cadmium, and mercury, pose significant health risks in food products.[17] These heavy metals can be detected by biosensors, which offer sensitive and rapid detection methods for heavy metal contamination in food samples. Yuan, *et al.*[18] developed an ultrasensitive electrochemical aptasensor for simultaneous quantitative detection of lead and cadmium in fruit and vegetable samples. In another study, Shakya and Singh[19] explored various optical methods, including fiber grating, modal interference, fluorescence, optical absorbance, surface plasmon and surface-enhanced Raman scattering, for heavy metal ion detection in water samples. These biosensors enable real-time monitoring of heavy metal contamination through precise and selective transduction methods.

4.3. Pathogenic microorganisms

Rapid and sensitive detection of pathogenic microorganisms is necessary to prevent food spoilage and foodborne diseases. Biosensors, utilizing enzymatic, immunological and molecular recognition elements, are mostly used to specifically detect surface antigens, genetic sequences or metabolic by-products of pathogenic microorganisms. Studies have shown that DNA-

Table 2 Overview of various types of biosensors, and their applications for food quality monitoring

Biosensor type	Application/ detection	Analyte	Biological element	Transducer	Display system	References
Enzyme-based biosensor	Pesticide residues	Pesticides	Enzymes (*e.g.*, acetylcholinesterase)	Electrochemical (enzyme-modified electrodes)	Digital display for quantification	103
	Mycotoxins in grains	Mycotoxins	Enzymes (*e.g.*, peroxidase)	Optical (*e.g.*, fluorescence)	Digital display for quantification	104
	Glucose levels in beverages	Glucose	Glucose oxidase	Electrochemical (glucose sensor)	Digital display for quantification	105
	Lactose in dairy products	Lactose	β-Galactosidase	Electrochemical (lactose biosensor)	Digital display for quantification	106
	Alcohol content in beverages	Ethanol	Alcohol dehydrogenase	Electrochemical (alcohol sensor)	Digital display for quantification	107
Antibody-based biosensor	Allergen in food products	Allergens	Monoclonal antibodies	Optical (*e.g.*, surface plasmon resonance) or electrochemical (*e.g.*, ELISA)	Graphical display for qualitative/ quantitative analysis	108
	Pathogenic bacteria in meat and milk	Bacteria	Polyclonal antibodies	Electrochemical (immunosensors)	Graphical display for qualitative/ quantitative analysis	109
	Gluten in food products	Gluten	Monoclonal antibodies	Optical (*e.g.*, SPR)	Digital display for quantification	110
	Aflatoxins in spices	Aflatoxins	Monoclonal antibodies	Electrochemical (immunosensors)	Graphical display for qualitative/ quantitative analysis	111
	Foodborne viruses in water	Viruses	Polyclonal antibodies	Optical (*e.g.*, ELISA) or electrochemical (*e.g.*, biosensors)	Graphical display for qualitative/ quantitative analysis	112
Nucleic acid-based biosensor	Viral contamination in water	Viruses	DNA or RNA probes	Fluorescent or electrochemical	Digital display for quantitative analysis	113
	GMO in food products	Genetically modified organisms	DNA probes	Electrochemical or optical	Digital display for quantitative analysis	114
	Antibiotic resistance genes	Antibiotic resistance genes	DNA probes	Electrochemical or optical	Digital display for quantitative analysis	113
	Foodborne pathogens	Bacteria	DNA probes or aptamers	Electrochemical or optical	Digital display for qualitative/ quantitative analysis	115
	Allergen-related gene sequences	Allergens	DNA probes or aptamers	Electrochemical or optical	Digital display for quantitative analysis	116
Whole cell-based biosensor	Milk quality	Bacteria	Genetically modified bacterial cells	Optical or electrochemical	Real-time monitoring systems displaying cellular responses	117
	Yeast and mold in beverages	Yeast, mold	Yeast cells	Electrochemical (yeast cell biosensors)	Real-time monitoring systems displaying cellular responses	118
	Bacterial contamination	Bacteria	Engineered bacterial strains	Optical or electrochemical	Real-time monitoring systems displaying cellular responses	119
	Chemical detection in solution	Caffeine	*Pseudomonas alcaligenes* immobilized on a cellophane membrane	Optical or electrochemical	Real-time monitoring systems with short read-time	87
	Bacterial pathogens in meat	Bacteria	Engineered bacterial strains	Optical or electrochemical	Real-time monitoring systems displaying cellular responses	24 and 120
Molecularly imprinted polymer (MIP) based biosensor	Pesticide residues in fruits	Pesticides	Molecularly imprinted polymers	Electrochemical or optical	Graphical display for qualitative/ quantitative analysis	121
	Antibiotics in milk	Antibiotics	Molecularly imprinted polymers	Electrochemical or optical	Digital display for quantification	122

Table 2 (*Contd.*)

Biosensor type	Application/ detection	Analyte	Biological element	Transducer	Display system	References
	Aflatoxins in nuts	Aflatoxins	Molecularly imprinted polymers	Optical	Digital display for quantification	123
	Histamine in fish	Histamine	Molecularly imprinted polymers	Electrochemical	Digital display for quantification	124
	Melamine in dairy products	Melamine	Molecularly imprinted polymers	Electrochemical or optical	Graphical display for qualitative/ quantitative analysis	121 and 125

based biosensors, employing nucleic acid probes, can detect specific genetic sequences of pathogens such as *Salmonella*, *Escherichia coli*, and viral agents like norovirus and hepatitis A virus.[20] Immunosensors that use antibodies can be used to recognize surface antigens of bacteria such as *Listeria monocytogenes*, *Salmonella*, *Campylobacter* spp., and *Escherichia coli*.[21] Immunosensors are also used to detect viral pathogens such as influenza virus and rotavirus in food samples.[22] Chai, *et al.*[23] developed magnetoelastic detection of *Salmonella typhimurium* (ME) biosensors, which hold promise for examining pathogens on food surfaces. The effectiveness of this technology was demonstrated by using a coil measurement technique with an E2 phage-coated ME biosensor. This specific biosensor was employed on tomato surfaces. In addition, enzymatic biosensors, whole cell-based biosensors, phage-based biosensors, and nanomaterial-based biosensors offer alternative approaches, each with unique advantages in terms of sensitivity, specificity, and application in food quality assessment.[24]

4.4. Allergens

Biosensors offer rapid and accurate detection of allergen and allergenic ingredients, ensuring food safety for individuals with sensitivities. These biosensors utilize various recognition elements, such as antibodies or aptamers, specifically targeting allergic proteins derived from common sources such as nuts, gluten, or shellfish.[25] For example, immunosensors can employ antibodies tailored to recognize specific allergenic proteins, allowing rapid and sensitive detection in food samples.[26] Additionally, DNA-based biosensors can target specific genetic sequences associated with allergenic ingredients, providing a reliable method for allergen detection.[27]

4.5. Mycotoxins

Mycotoxins are toxic compounds produced by certain molds that can contaminate various food products, posing serious health risks to consumers. Studies have shown that an electrochemical immunosensor can be used to detect aflatoxin B_1 in pistachios.[28] In another study, Jia, *et al.*[29] developed portable chemiluminescence optical fiber aptamer-based biosensors for analysis of multiple mycotoxins. In addition, studies have also shown promising results using immunological biosensors (utilizing antibodies specific to mycotoxins) and DNA-based biosensors (targeting genetic sequences associated with mycotoxin-producing molds).[30]

4.6. Food adulterants

Biosensors provide effective tools for detecting food adulterants, such as adulterated ingredients, counterfeit products, or dilution with cheaper substitutes. Electrochemical biosensors have been used to detect the presence of melamine in dairy products.[31] Similarly, optical biosensors have been used to detect synthetic colors and dyes in beverages and food products,[32] ensuring compliance with regulatory standards and protecting consumer health.

4.7. Food quality parameters

Biosensors are also used to assess various quality parameters in food products, such as freshness, ripeness, and nutritional content. Biosensors equipped with enzymatic recognition elements can detect specific biomarkers associated with freshness and spoilage in food products in real time, allowing timely decisions regarding shelf life and product distribution.[33] Biosensors play a crucial role in determining the optimal harvesting or processing time for fruits and vegetables.[34] Enzymatic biosensors targeting key ripening indicators, such as ethylene or specific enzymes involved in fruit softening, can accurately monitor ripeness levels.[35] In addition, whole cell-based biosensors allow the quantification of proteins, fats, carbohydrates, vitamins, and minerals, providing nutritional profiles of food samples.[36] A biosensor can also be used to assess food freshness using electronic noses (e-noses), which utilize arrays of chemical sensors to detect volatile compounds emitted during food spoilage.[37] These e-noses have been successfully employed to assess the freshness of various perishable food products, including fish, meat, and dairy products, by analyzing changes in odour profiles associated with microbial growth or chemical degradation.

5. Challenges and limitations in biosensor implementation

Despite their promising capabilities, the widespread adoption of biosensors in food quality monitoring encounters several

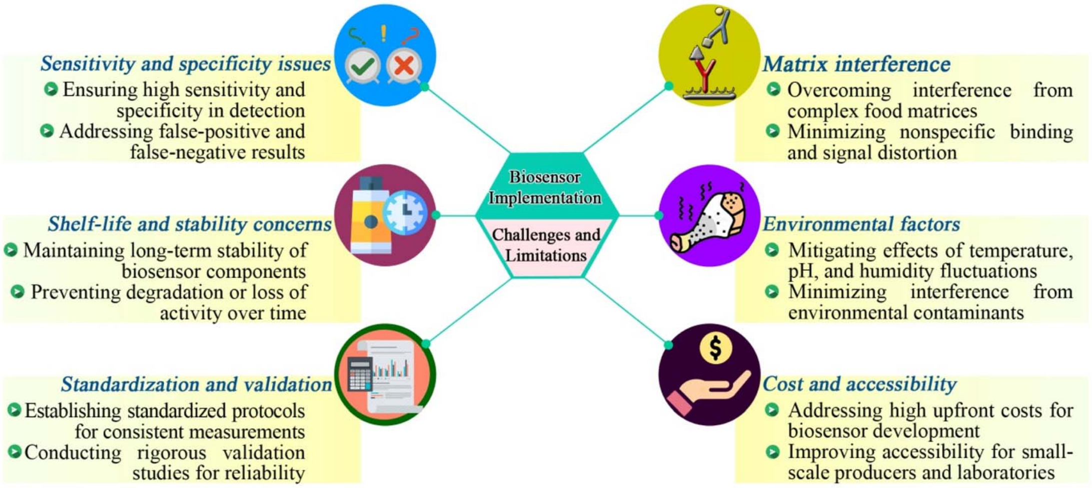

Fig. 3 Challenges and limitations encountered in the widespread adoption of biosensors for food quality monitoring.

challenges and limitations (Fig. 3). A significant challenge is the need for biosensors to maintain high sensitivity and specificity in diverse food matrices, which can vary widely in composition and complexity.[38] Furthermore, ensuring the stability and shelf life of biosensor components, particularly biological recognition elements, presents another challenge.[39] Environmental conditions, such as temperature and pH, can impact the performance and longevity of biosensors, requiring careful storage and handling protocols.[40] In addition, standardization and regulatory considerations pose challenges in ensuring the consistency and reliability of biosensor measurements for regulatory compliance and widespread acceptance in the food industry.[41]

5.1. Sensitivity and specificity issues

Sensitivity and specificity are fundamental parameters governing the performance of biosensors in food quality monitoring. In various studies, biosensors have faced challenges related to sensitivity and specificity, which have affected their applicability in real-world scenarios. Zachariasova, *et al.*[38] reported cross-reactivity of rapid immunochemical methods for the detection of mycotoxins towards metabolites and masked mycotoxins. In another study by Zhu, *et al.*,[42] a colorimetric biosensor was developed for the detection of aflatoxin B1 (AFB1) in food samples. Although the biosensor demonstrated excellent sensitivity, it showed limited performance in complex food matrices due to interference from matrix components, resulting in reduced specificity. Therefore, enhancing the sensitivity and specificity of biosensors often requires optimization of the recognition elements, immobilization methods, and transduction techniques to minimize false-positive or false-negative results.

5.2. Matrix interference

Several studies have reported matrix interference that interferes with biosensor performance. Li, *et al.*[43] developed a surface-enhanced Raman scattering-based lateral flow immunosensor to determine the concentration of colistin in milk within 20 min. However, the biosensor encountered matrix interference from milk proteins, which led to background signal noise and hindered the detection of colistin. Many studies have documented and addressed such analytical challenges for detecting various compounds in food matrix.[44]

5.3. Shelf-life and stability concerns

Shelf-life and stability concerns are significant challenges in biosensor development, particularly in the context of food quality monitoring, where long-term performance and reliability are crucial.[39] The enzyme-based biosensor developed for detecting various compounds in food samples has stability concerns with the immobilized enzyme, which has decreased activity over time due to enzyme denaturation.[45] To address this issue, many studies have investigated different enzyme immobilization techniques, such as cross-linking and encapsulation, to protect the enzyme from degradation and maintain its activity during storage.[46] Researchers also developed a DNA-based biosensor for the detection of genetically modified organisms (GMOs) in food products. The biosensor utilized DNA probes immobilized on gold nanoparticle-modified electrodes to capture target DNA sequences from GMO samples. However, concerns arose regarding the stability of immobilized DNA probes, which could undergo degradation or structural changes over time, leading to a decrease in sensitivity and detection efficiency.[47]

5.4. Interference from environmental factors

Environmental factors such as temperature, pH, and humidity significantly impact the performance of biosensors. Variations in temperature can alter enzymatic activity in biosensors, affecting their sensitivity. Higher temperatures can increase enzyme activity, leading to higher current signals in glucose sensors, while lower temperatures reduce enzymatic reactions.[12] Temperature changes can also affect the refractive index in optical biosensors and alter oscillation frequencies in piezoelectric biosensors, causing inaccurate measurements.[48]

Fluctuations in pH levels impact the stability and sensitivity of biosensors, particularly those with carbon nanotube-based electrodes for heavy metal detection, as changes in pH can affect the electrochemical properties and response signals of these sensors.[40] High humidity levels degrade sensor components, reducing their lifespan and reliability.[49] This is especially problematic for optical biosensors, where uncontrolled light exposure and moisture can introduce noise and affect accuracy. Additionally, complex food matrices can introduce chemical interference, reducing the selectivity and accuracy of biosensors.

5.5. Standardization and validation

Standardized protocols and validation procedures are of vital importance to ensure the reliability and comparability of biosensor measurements. Biosensor data management comprises the food safety knowledge system, the testing management system, and the dissemination of food safety information. It also integrates data from food factory inspections, government inspections, testing organizations, and consumer purchasing information into a comprehensive food safety and nutrient testing database. Using these data, relevant information can be extracted to address the challenges of risk sharing encountered by food stakeholders. Furthermore, collaborating with various stakeholders can help mitigate food safety issues effectively.[50] Regulatory challenges for biosensors include establishing universally accepted protocols for calibration, validation, and performance assessment. Specific challenges include ensuring consistent sensitivity and specificity across diverse food matrices, addressing the lack of standardized procedures for the detection and quantification of various contaminants, and meeting stringent regulatory requirements for biosensor approval and market entry. Additionally, biosensors must undergo rigorous testing to prove their equivalence or superiority to traditional microbiological methods, such as culture-based assays and polymerase chain reaction (PCR).[51] Jeyaraman and Eltzov[52] developed a 3D-printed, colorimetric biosensor for detecting *Bacillus licheniformis* in food samples. The sensor uses a casein-based gelatin film that liquefies in response to the pathogen's enzymes, causing a visible dye signal. It detects concentrations as low as 1 CFU per mL within 9.3 hours, offering a cost-effective and efficient alternative to conventional detection methods. In another study, Arreguin-Campos, *et al.*[53] developed screen-printed electrodes (SPEs) functionalized with surface imprinted polymers (SIPs) and combined them with the heat transfer method (HTM) for real-time detection of *Escherichia coli* in dairy products. The sensor achieved a detection limit of 180 CFU per mL, with high reproducibility and sensitivity. Selectivity tests against *C. sakazakii*, *K. pneumoniae*, and *S. aureus* showed specific responses to *E. coli*. The sensor also successfully detected *E. coli* in spiked milk without additional sample preparation, indicating its potential for routine, on-site food safety monitoring. The results were compared against recently reported biosensors for *E. coli* detection based on antibodies, aptamers, and thermal imprinted polymers, highlighting the common biological receptors employed and demonstrating the effectiveness of the SIP-coated SPEs. Moreover, organizations like the International Organization for Standardization (ISO) and the Food and Drug Administration (FDA) are working on guidelines to ensure the accuracy, sensitivity, and specificity of biosensors. ISO 16140-2 outlines the validation process for alternative methods in food microbiology, which is now being adapted for biosensor technologies.[54] These standardization efforts aim to facilitate the wider adoption of biosensors by ensuring their reliability and accuracy in real-world applications, thereby enhancing food safety and quality assurance across the global food supply chain.

5.6. Cost and accessibility

The cost of biosensor development, fabrication, and deployment can be prohibitive for small-scale producers, small laboratories, or developing countries with limited resources. High costs associated with biosensor instrumentation, consumables, and maintenance often limit access to these technologies, preventing their widespread adoption in food quality monitoring applications.[55] Additionally, the complexity of biosensor operation and data analysis can require specialized training and expertise, further restricting accessibility for end-users.[56] Collaborative initiatives by organizations such as the World Health Organization (WHO), Food and Agriculture Organization (FAO), European Food Safety Authority (EFSA), and United Nations (UN) aim to improve training and capacity-building efforts in biosensor technology.[41] Several economic models and cost-analysis studies can be considered to justify the investment in biosensor technologies. A Return on Investment (ROI) analysis can help determine the financial benefits relative to costs, such as evaluating savings from reduced food spoilage, lower recall expenses, and decreased labor costs due to testing automation. Patel, *et al.*[57] reported that implementing biosensors for pathogen detection in a mid-sized dairy operation led to a reduction in spoilage-related losses and an increase in consumer satisfaction due to improved safety assurances. Cost-Benefit Analysis (CBA) can compare the total expected costs with benefits derived from improved food safety and quality, monetizing factors like reduced incidences of foodborne illnesses and enhanced consumer confidence.[58] Total Cost of Ownership (TCO) analysis, which includes initial purchase costs, operating costs, maintenance, and training expenses over the lifespan of the biosensor technology, can provide a comprehensive view of the long-term financial benefits compared to traditional methods.[59] Scaling economies also play a significant role, as larger-scale adoption of biosensors can lead to reduced unit costs. Studies indicate that larger food enterprises can achieve these cost reductions, thereby serving as models for smaller enterprises.[60] Additionally, information on grants, subsidies, and financial incentives from government bodies and international organizations can alleviate the financial burden on small and medium-sized enterprises (SMEs), encouraging investment in biosensor technologies. Case studies of successful biosensor implementation in SMEs can highlight tangible benefits and provide a roadmap for biosensor adoption. Pilot programs showing positive investment outcomes can justify broader use. These economic models and case studies effectively demonstrate the financial viability and long-term benefits of biosensor technology, making a strong case for investment by small to medium-sized food enterprises.

6. Recent advances in the biosensor implementation for food quality monitoring

Recent advances in biosensor technology have revolutionized food quality monitoring by offering innovative solutions for rapid, sensitive, and on-site detection of various contaminants and quality parameters (Table 3). The integration of nanotechnology, smartphone connectivity, and multiplexing capabilities has enhanced biosensor performance, enabling real-time monitoring and analysis at different stages of the food supply chain.

6.1. Nanotechnology integration

The integration of nanotechnology into biosensor design has significantly enhanced their performance characteristics. Nanomaterials, such as nanoparticles, nanowires, and nanotubes, offer unique properties, including high surface-to-volume ratios, large surface areas, and tunable surface chemistry, which can be exploited to improve biosensor sensitivity and detection limits. Recent data indicate that these nanotechnology-integrated biosensors exhibit impressive performance characteristics. Liu, *et al.*[61] developed a dual-mode sensing mechanism for the simultaneous colorimetric and surface-enhanced Raman scattering (SERS) detection of melamine in milk. In another study, the colorimetric SERS platform achieved a detection limit as low as 0.05 parts per million (ppm) for melamine, ensuring precise detection of adulterants in food products. In another study, a SERS biosensor based on AuNPs and AgNPs demonstrated the ability to detect and differentiate strains of *Bacillus* species, and simultaneously screen *E. coli*, *Listeria monocytogenes*, and *Salmonella typhimurium* within 10 seconds of collection time.[62] The bimodal single-atom iron nanozyme biosensor exhibited a rapid response time of under 5 minutes for detecting volatile amines, contributing to the real-time assessment of food freshness.[63] Moreover, electrochemical biosensors comprising porous hollow cobalt-based oxides encapsulated with bimetallic PdAu nanoparticles for highly sensitive pesticide detection[64] offer better signal amplification and signal transduction, thereby enhancing the analytical performance of biosensors for food quality monitoring applications.

6.2. Multiplexed detection

Multiplexed biosensors capable of simultaneously detecting multiple analytes in a single assay have gained increasing

Table 3 Comparative analysis and real-world application efficiencies of biosensors

Biosensor type	Sensitivity	Specificity	Detection limit	Practical deployment challenges	References
Colorimetric SERS (melamine detection)	Moderate	High	Less than 0.25 ppm	Complexity in the preparation of SERS substrates, potential interference from food matrix, need for specialized equipment	126
Plasmonic resonance biosensor (allergen detection)	High	High	0.25 μg mL^{-1}	Sensitivity to environmental conditions, high cost of plasmonic materials, need for calibration	127
Electrochemical biosensor (pesticide detection)	High	High	0.14–2.05 ppb	Electrode fouling, signal interference from food matrix, maintenance of electrode materials	128
Multiplexed lateral flow immunoassay (pathogen detection)	Moderate to high	High	1.0–2.0 CFU per mL	Potential cross-reactivity in a multiplex format, difficulty in detecting low concentrations in complex samples	129
Smartphone-based magnetic nano biosensor (pathogen detection)	High	High	1.0 CFU per mL	Dependence on smartphone camera quality, variability under ambient light conditions, need for user training	130
Wearable biosensor (pesticide detection)	High	Moderate to high	0.48 ppb	Limited battery life, potential skin irritation, need for regular calibration and maintenance	131
Microfluidic biosensor (multiplex aflatoxin detection)	High	High	2.7–7.0 ng mL^{-1}	Complex fabrication process, potential clogging of microchannels, requirement for precise fluid control mechanisms	132
Enzymatic biosensor (glucose detection)	High	High	30 ppm	Enzyme stability over time, potential interference from other reducing sugars, need for regular calibration	133
SERS biosensor (bacterial detection)	High	High	10^2–10^4 CFU per mL	Need for uniform nanostructure fabrication, signal interference from complex food matrices, high cost of substrates	134

attention for their ability to provide comprehensive analysis and reduce assay time and cost. A lateral flow immunoassay has been developed to detect *Listeria monocytogenes*, *Salmonella typhimurium* and *Escherichia coli* in food samples using AuNPs as labels, coupled with multiplex PCR and test strips.[65] In another study, Shang, *et al.*[66] reported a nucleic acid extraction and real-time recombinase polymerase amplification (RPA) assay in a microfluidic biosensor for multiplex detection of foodborne bacteria. This fully integrated micro-platform (FID-MP) is designed for point-of-care testing (POCT) of multiplex pathogens. It incorporates nucleic acid extraction, RPA, and signal detection functionalities. The FID-MP platform allows for the simultaneous detection of up to eight bacteria, providing shorter testing times and greater portability.

6.3. Smartphone-based biosensors

The integration of biosensors with smartphone technology has allowed on-site testing, remote monitoring, and real-time data analysis. Yin, *et al.*[67] have developed a smartphone-based fluorescent sensor to autonomously detect multiple pathogenic bacteria. Additionally, Li, *et al.*[68] demonstrated on-site rapid detection of *Listeria monocytogenes* in dairy products using smartphone-integrated device-assisted ratiometric fluorescent sensors. Another innovative approach involves a portable smartphone-assisted highly emissive magnetic covalent organic framework-based fluorescence sensor to detect *Salmonella typhimurium* in food samples.[69] These smartphone-based biosensors offer accessibility, affordability, and scalability, making them suitable for widespread deployment and promising on-site detection in food quality monitoring.[70]

6.4. Wearable biosensors

Wearable biosensors have the potential to revolutionize food monitoring by enabling continuous tracking of dietary intake and detecting food allergens in real-time. These wearable devices allow individuals to make informed dietary choices, leading to personalized dietary recommendations and improved overall health and well-being.[71] A wearable biosensor developed by Wang, *et al.*[72] enables non-invasive sweat analysis to monitor specific biomarkers associated with dietary intake and trace levels of metabolites. This device allows individuals to track multiple metabolites and nutrients throughout the day, including essential amino acids and vitamins, offering valuable insights into their dietary habits and nutritional intake. Furthermore, studies have demonstrated the development of wearable, flexible, glove-embedded non-enzymatic sensors for the multiplexed detection of pesticides in food samples.[73] The sensors, printed on three fingers of a rubber glove, exhibit high performance in detecting four classes of pesticides, namely carbendazim (carbamate), diuron (phenylamide), paraquat (bipyridinium), and fenitrothion (organophosphate). These sensors enable the selective detection of pesticides in real samples of apple, cabbage and orange juice, with multidimensional projections showcasing rapid, sensitive and on-site analysis.

7. Future perspectives and opportunities

The future of biosensors lies in the development of advanced sensing technologies that offer improved sensitivity, selectivity, and reliability. Continued research into novel recognition elements, such as engineered enzymes, aptamers, and synthetic receptors, holds promise for improving biosensor performance and expanding its applicability to a wider range of analytes. Additionally, advances in nanotechnology, microfluidics, and materials science enable the design of miniaturized, portable biosensors with improved detection limits and reduced sample volumes.[3] The integration of cutting-edge techniques, such as surface-enhanced Raman spectroscopy (SERS), nanomaterial-based amplification, and single-molecule detection, further enhances the analytical capabilities of biosensors, paving the way for more sensitive, rapid, and accurate detection of food contaminants and adulterants.[74] Furthermore, standardization of biosensor protocols, validation procedures and performance metrics is essential to ensure consistency, comparability, and reliability of results across different platforms and applications.[51] Regulatory agencies play a crucial role in establishing guidelines and standards for biosensor development, validation and deployment in food quality monitoring. Collaboration between industry stakeholders, academic researchers, and regulatory authorities is necessary to address regulatory challenges, streamline approval processes, and promote the widespread adoption of biosensors in food safety and quality assurance applications.[75]

Integrating intelligent sensors into Internet of Things (IoT) devices, utilizing wireless sensor networks (WSNs) technologies such as Wi-Fi, Bluetooth, Zigbee, and LoRA, is essential for the early detection of pathogens in plant health monitoring.[76] This integration generates extensive data, empowering decision-makers to efficiently oversee food safety and quality, thereby protecting public health. IoT-enabled biosensors deployed throughout the food supply chain enable real-time monitoring and analysis of crucial parameters such as temperature, humidity, pH, and microbial contamination at various stages of production, storage, and transportation.[77] Through wireless connectivity and cloud-based platforms, seamless data transmission, remote monitoring, and predictive analytics are facilitated, enabling proactive interventions and risk mitigation strategies. Emerging technologies like blockchain and AI enhance biosensor data integrity and decision-making processes by providing secure, transparent, and tamper-proof data management systems.[78] For example, IBM's Food Trust blockchain network has been implemented by companies like Walmart to track food products, ensuring transparency and traceability.[79] Blockchain technology ensures that biosensor data remain unaltered and traceable, while AI algorithms, such as those used in IBM Watson, analyze vast datasets to identify patterns and predict potential food safety issues, improving response times and decision accuracy.[80] Advancements in the fields of nanotechnology, artificial intelligence (AI), and machine learning (ML) facilitate precise food quality monitoring, thereby enhancing efficiency, minimizing risks, and ensuring regulatory compliance.[81] To ensure data privacy and security with the integration of IoT and cloud technologies in biosensor systems, measures such as end-to-end encryption, secure authentication protocols, and compliance with data protection regulations like GDPR are proposed.[82] These measures protect sensitive information and maintain the confidentiality and integrity of biosensor data. One such example is Intel's Secure Device Onboard (SDO) technology that automates and secures the onboarding of IoT devices to cloud platforms, ensuring secure communication and management throughout the device lifecycle.[83] Additionally, using AI-driven security solutions like those from Palo Alto Networks can detect and respond to unusual activities in real-time, safeguarding against potential breaches.[79c] These advancements revolutionize food quality control and safety, ushering in a new era of personalized nutrition, autonomous monitoring, and global collaboration, and marking a transformative paradigm shift in the food industry.

8. Conclusions

Biosensors represent a transformative technology with immense potential to improve food safety and quality monitoring. Their ability to provide rapid, accurate, and on-site detection of contaminants offers significant advantages over traditional analytical methods. Although biosensors offer versatile platforms for detecting various contaminants and analytes, their implementation faces challenges such as sensitivity and specificity issues, matrix interference, and regulatory considerations. However, ongoing research and development efforts, along with recent advances in nanotechnology, multiplexed detection, and integration of IoT, offer promising opportunities to overcome these challenges and revolutionize food safety practices. By addressing these opportunities and challenges, biosensors have the potential to enhance food safety, quality assurance, and regulatory compliance efforts, ensuring the integrity and safety of the global food supply chain for years to come.

Data availability

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of interest

The authors report that there are no competing interests to declare.

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