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APPLICATION OF BIOSENSORS IN DETECTION AND QUANTIFICATION OF FOODBORNE PATHOGENS AND FOOD PRODUCTS

[1]Osawe, P. O. and [1x]Enerijiofi, K. E.
[1]Department of Biological Sciences, College of Basic, Applied and Health Sciences, Glorious Vision University, Ogwa, Edo State, Nigeria,
[1x]Corresponding author email: kingsleyenerijiofi@gmail.com; https://orcid.org/0000-0001-7513-4052

Abstract
Foodborne diseases are a major global public health burden with 600 million cases and 420,000 deaths with 30% of the deaths in children under 5 years of age annually. The foodborne diseases are caused by foodborne pathogens and other contaminants that are present in ready to eat food. The traditional culture method of detection are reliable, time-consuming, labour-intensive and unsuitable for real time monitoring. Recently, biosensors have emerged as a promising tools for rapid detection and quantification of food borne infectious agents. They integrate both the biological recognition elements and the signal transduction systems, with its merits being very fast, sensitive, and on-site detection of pathogens in a variety of food matrices. In this review, the authors examined the current improvements in biosensor technologies, such as surface plasmon resonance, phage-based probes, surface-enhanced Raman spectroscopy and nanomaterial-assisted technologies, in identifying and quantifying the presence of the major foodborne pathogens like *Salmonella*, *Listeria monocytogenes*, and *Brucella abortus*. The case studies showed that biosensors are beneficial in real-time, label-free detection, distinguishing between viable and non-viable cells, multiplexed analysis, and machine learning to analyze complex data. The integration of these technologies into food supply systems could significantly improve pathogen surveillance systems and reduce foodborne disease outbreak. They would play a significant role in monitoring pathogens, thereby alleviating the outbreak of foodborne diseases, globally.
Keywords: Disease outbreak, Food quality control, Nanomaterial-based sensors, Public Health, Rapid detection

INTRODUCTION

The issue of food safety is a fundamental global issue because of the high prevalence of foodborne pathogens that are associated with food leading to significant economic and public health set-backs globally. Contamination of food by pathogenic bacteria such as *E. coli* can cause may cause severe illnesses, such as gastrointestinal infections, sepsis, and in some cases, death (Bai *et al.*, 2022; Ravindhiran *et al.*, 2023). There are also chemical contaminants, which impair the quality and safety of food, with significant impact on human health, and food supply chains (Patriarca and Pinto, 2017; Veenuttranon *et al.*, 2025; Enerijiofi *et al.*, 2024a). Their identification, surveillance, and measurement are thus of utmost importance in safeguarding food, quality management, and adherence to the set standards. Although microbiological and chemical detection methods are effective, they are time-consuming as samples preparations may require a lot of labour, and certain laboratory equipment could be necessary (Enerijiofi *et al.,* 2023; Barba *et al.*, 2017; Islam *et al.*, 2016). This has created a growing demand for rapid, sensitive and cost effective analytical tool that can detect food borne pathogens in on-site and real time.

Biosensors have emerged as a promising technological solutions to these challenges. By definition, a biosensor is an analytic device that consists of a biological recognition unit and a physicochemical transducer to generate a signal that is proportional to the concentration level of the target analyte (Qiu *et al.*, 2023). More broadly in food safety, biosensors have frequently been used to detect and quantify bacterial and viral pathogens as well as toxins in direct relation to food matrices by avoiding the traditional steps of sample enrichment or culture (Yang *et al.*, 2021). The modularity of biosensor frameworks enables it to be combined with optical, electrochemical, piezoelectric, and magnetic systems which enables building high-throughput, portable and usability systems (Hong *et al.*, 2024; Vo *et al.*, 2019). It is worth noting that nanotechnology, microfluidics and artificial intelligence have further advanced the sensitivity, selectivity, and multiplexing of biosensors such that multiple pathogens or toxins can be detected at small sample volumes (Quan *et al.*, 2024; Huang *et al.*, 2021).
Some biosensors, especially the ones that are integrated with smartphone-assisted readouts or paper-based platforms, allow quick detection, usually within minutes, therefore, allowing real-time decision-making in food processing, distribution, and retail settings (Hong *et al.*, 2024; Yang *et al.*, 2021). On the same note, deep learning-enhanced digital microfluidics chips have not only facilitated multiplex detection of viable pathogens but have also integrated automation with superior analysis capability (Quan *et al.*, 2024). Apart from bacterial pathogens which biosensors can be used to detect, there are also the mycotoxins which are secondary metabolites of fungi and their enormous presence in foodstuffs promptly necessitates the need to ensure multiple mycotoxin detection techniques (Patriarca and Pinto, 2017; Veenuttranon *et al.*, 2025).

Multi-target electrochemical biosensors have been constructed to limitless quantification of co-contaminated mycotoxins to overcome the shortcomings of the conventional chromatographic methods, and are able to monitor food products more effectively along the supply chain (Veenuttranon *et al.*, 2025). Moreover, when used with biosensor monitoring, mild processing interventions are also useful in recognizing food quality as well as the level of pathogen inactivation and tainted contamination, which also contributes to the food quality control strategies (Barba *et al.*, 2017; Bhowmik *et* al., 2023; Lake *et al.*, 2023).

The other prominent developmental trend in the field of biosensor-based detection of foodborne pathogens is the mode of combining machine learning and artificial intelligence. Such strategies can be used when analyzing complex biosensor data, better signal-to-noise, more pathogen identification, predictive modeling of contamination risks (Yang *et al.*, 2021). Moreover, biosensor platform plus nanomaterials (G-quadruplexes, gold nanoparticles, or graphene-based constructs) have enhanced sensitivity and have allowed amplifying colorimetric, fluorescent, or electrochemical signals, which are practical in the field and convenient in rapid screening (Huang *et al.*, 2021; Yeo *et al.*, 2024).

Consequently, the review presents the concepts, recent advances and practical uses of biosensors in the detection and or quantification of foodborne pathogens and contaminants, the significance of which in facilitating real-time monitoring of food safety, enhancing the health safety of the people, and the quality and integrity of foodstuffs.

The Concept of Biosensor

A biosensor is a very specific analyzer that identifies and measures biological or chemical ions in complicated matrices. It presents a biological recognition component with a physicochemical transducer to generate a detectable signal that is proportional to the concentration of the target analyte (Naglot *et al.*, 2017; Chen *et al.*, 2022). The biological recognition component may be in different forms, such as enzymes, antibodies, nucleic acids, aptamers, or entire cells and this attribute is the one that interacts specifically with the analyte of interest. Instead, this biological interaction is being converted into electrical, optical, thermal, or mechanical signal by the transducer, measured and interpreted correctly (Rizal & Belotelov, 2019; Hojjat Jodaylami *et al.*, 2025).

Biosensors have found tremendous application in various fields especially in food safety, clinical diagnostics and environmental monitoring. They find numerous applications in the food industry to detect pathogenic bacteria, e.g. *Escherichia coli*, *Salmonella* spp., *Listeria monocytogenes*, and metabolic toxins produced by microorganisms e.g., *Pseudomonas cocovenenans* (Cheng *et al.*, 2023; Ma *et al.*, 2025). The traditional methods of detecting these pathogens such as culture-based and polymerase chain reaction (PCR) are usually associated with long processing times, extensive laboratory infrastructure as well as staff. However, to overcome the shortcomings, biosensors can provide an alternative method that is fast, sensitive, and inexpensive as they ensure real-time observation of food products and can make immediate decisions in their quality control and protection against diseases (Chen *et al.*, 2022; Sun *et al.*, 2025).

There are different varieties of biosensors which are designed to fit the analytical needs. They include surface plasmon resonance (SPR) biosensor, which has proven to be an effective biomolecular interaction detection device, with no labeling required. Surface plasmon waves are oscillations of conduction electrons at the interface between a metal and a dielectric medium, to which the phenomenon of the SPR-based systems are exploiting any variation in the refractive index during a biomolecular binding event (Mondal and Zeng, 2021; Chen *et al.*, 2023). This label-free detection technique gives real-time kinetic measurements of molecular interactions and is therefore very useful in research and practice involving food safety, clinical diagnostics and environmental analysis (Murugan *et al.*, 2024; Naglot *et al.*, 2017). The varieties of SPR such as grating-coupled SPR and magneto-optic SPR have been improved further to produce high-specificity sensitivity to detect small quantities of pathogens and toxins (Rizal and Belotelov, 2019; Murugan *et al.*, 2024).

Another essential category of biosensors used, in particular, in the field of pathogen detection, is nucleic acid-based biosensors. These sensors have been used to identify target genetic material on viable and dead cells by use of complementary DNA or RNA sequences to interrogate rapid and precise target genetic material in foodborne microorganisms (Chen *et al.*, 2022; Cao *et al.*, 2024). Combining molecular recognition by use of polymerase chain reaction (PCR) and the biosensing system has enhanced sensitivity and specificity greatly allowing the detection in complex foods where other background interferences can otherwise lead to a flawed study. Likewise, fluorescence immunoassays integrate both the selectivity of antibodies with optical detection techniques to enable simultaneous identification of several items in the food sample that ensures multiplex detection information which is very beneficial in food quality control (Cheng *et al.*, 2023).

Biosensors have also been exceptionally developed by nanotechnology and new materials. As an example, engineered nanomaterials, including magnetic carbon dots (MDC) or nitrogen-doped mesoporous carbon nanospheres (N-MMCNs) has been used to capture and detect foodborne pathogens selectively with higher sensitivity and selectivity (Sun *et al.*, 2025). With high surface area biorecognition element immobilization and efficient signal transduction to potential pathogen elimination, these nanostructured platforms show multifunctional properties beyond mere and simple detection (Enerijiofi et al., 2024c). Moreover, biosensors in conjunction with computational tools and artificial intelligence assist with highly throughput and real-time application of advanced data processing, signal amplification, and multiplexed analysis in both laboratory and field use (Gomes *et al.*, 2025; Yao *et al.*, 2022).

Types of Biosensors used in Detecting Foodborne Pathogens in Food Products.

The biosensors have become the central analytical devices in the detection and measurement of food pathogens as they provide rapid, sensitive, and specific alternative to traditional microbiological methods. This versatility and flexibility means that there is a wide selection of types of biosensor, each suited to specific detection principles, analyte of interest, and foods.

Surface Plasmon Resonance (SPR)-Based Biosensors

SPR based sensors are among the most widely used biosensing platforms in food safety as they can detect the sample label-free, in real-time (Bergwerff and Knapen, 2006; Qu *et al.*, 2020). The SPR biosensors take advantage of the resonance occurrence of conduction electrons within a metal-dielectric interface by detecting changes in the refractive index taking place due to molecular binding events. It is sensitive enough to detect the bacterial pathogens including *Escherichia coli, Salmonella enterica*, *Listeria monocytogenes* and *Vibrio cholerae* without the necessity to use fluorescent or enzyme labels (Baccar *et al.*, 2010; Vaisocherova-Lisalova *et al.*, 2016). The SPR biosensors may be sub-classified according to optical configurations, as well as surface functionalization schemes. Such SPR sensors as fiber-optic sensors, use optical fibers with metal films like gold or silver coating on the fibers to enable plasmon excitation. Successfully applied to detect *Staphylococcus aureus* and *E. coli* as a label-free bioreceptor and they exhibit high sensitivity and rapid response time (Wang *et al.*, 2024; Kaushik *et al.*, 2019). Moreover, SPR immunosensors also use antibodies that are immobilized on the sensor surface which specifically bind to selected target pathogens and offers specificity even in complex food (Baccar *et al.*, 2010; Liu *et al.*, 2016). Surface engineering developments, such as low-fouling surfaces and nanostructured materials, have also raised the robustness, as well as detection limit, of SPR sensors when used in food safety (Topor *et al.*, 2023; Rahmasari *et al.*, 2025).

Fluorescence-Based Immunosensors

They are also used in detecting pathogens. These sensors combine aptamers or the label with fluorophore labeled antibodies to give an optical measure of concentration of the specific microorganism. Multi-bacteria fluorescence immunoassays have been used to detect multiple foodborne bacteria in milk and other dairy products with the benefit of being able to be multiplexed and detected quickly (Cheng *et al.*, 2023).The use of ellipsometry-based immunosensors on pathogen surface detection has been developed on surface-sensitive optical measurements with antibody specificity to provide high-resolution detection of the pathogen (Bae *et al.*, 2004; Oh *et al.*, 2003).

In the recent years, also, label-free SPR immunosensors have found extensive application. These sensors are also labeled free and are very sensitive and specific. One example is phage tail proteins immobilised on SPR surfaces, which allow detection of *Salmonella enterica* in a short period and selectively; this demonstrates the possibility of phage-based biosensors to detect pathogens (Hyeon *et al.*, 2020).

Nanotechnology based Biosensors

The new generation of innovations in biosensors technologies has aimed at the development of more sensitive biosensors and multiplexing devices with the incorporation of nanomaterials (Enerijiofi *et al.,* 2024b). Potentiometric nanoparticles used to enhance SPR signals and increase pathogen detection efficiency has gold nanoparticles, molybdenum disulfide (MoS2) nanosheets, and biofunctionalized polypeptides (Ko *et al.*, 2009; Kaushik *et al.*, 2019). Such nanostructured interfaces, besides improving signal transduction, also permit the miniaturization and portability of biosensors, which is especially beneficial as it relates to food safety and monitoring on site and in real-time. The detection of plant pathogens, such as *Acidovorax avenae*, has been done using SPR imaging (SPRi) indicating that these platforms could be widely used on human pathogens (Puttharugsa *et al.*, 2011).

Other categories of biosensors are terahertz sensors, plasmon-enhanced photoluminescent sensors, which use similar mechanisms of energy transfer to enhance the signal intensity thereby detecting pathogens. The application of photoluminescent molecule-boosted metasurface plasmon resonance sensors to the highly sensitive detective purpose was reported Chen *et al.* (2025), and the probability of single-molecule-fitting plasmonics and molecular photophysics is shown. Moreover, sustained surveillance and multiplexed SPR systems have been created to trace various pathogens in intricate food products simultaneously, which can also serve as a highly important step in real-time food safety surveillance (Qu *et al.*, 2020). The different types of biosensors have their own benefits in terms of sensitivity, specificity, speed and multiplexing capabilities, and are therefore applicable to a variety of applications in food quality control, pathogen surveillance and protection of human health. Further development in these biosensors such as the surface functionalization, nanotechnology and multiplexed detections is expected to lead the next generation platforms that can be able to detect various pathogens in food products quickly and on site.

Table 1. Comparison of Major Biosensor Types Used in Foodborne Pathogen Detection

Biosensor Type	Recognition Element	Signal Transduction Mechanism	Key Advantages	Common Target Pathogens in Food
Surface Plasmon Resonance (SPR)	Antibodies, aptamers	Optical (refractive index change)	Label-free, real-time monitoring, high sensitivity	*Salmonella* spp., *Listeria monocytogenes*, *Brucella abortus*
Localized Surface Plasmon Resonance (LSPR)	Antibodies, nanoparticles	Optical (nanoparticle plasmon shift)	Enhanced sensitivity, miniaturization potential	*E. coli, Salmonella, Listeria*
Surface-Enhanced Raman Spectroscopy (SERS)	Whole-cell fingerprinting, antibodies	Raman signal enhancement	Molecular fingerprinting, viability differentiation	*Salmonella* spp*., E. coli*
Electrochemical Biosensors	Enzymes, antibodies, DNA probes	Current, voltage, impedance changes	Portable, cost-effective, rapid response	*Listeria, Salmonella, Campylobacter*
Phage-Based Biosensors	Bacteriophages	Optical or electrochemical	High specificity to live cells, rapid detection	*Listeria monocytogenes, Salmonella*
Nanomaterial-Enhanced Sensors	Antibodies, aptamers, nanostructures	Optical/electrochemical amplification	Ultra-low detection limits, multiplexing capability	Multiple foodborne pathogens

Mechanism of Using Biosensor in Detecting and Quantifying Pathogens in Food Products

Biosensors rely on the basic principle of converting biological recognition to a measurable signals. As regards to foodborne pathogen detection, it usually includes binding a pathogen or its biomarker into an optical, electrical or mechanical sensor surface then converting the interaction into quantifiable signal (Bergwerff and Knapen, 2006; Qu *et al*., 2020). The detection mechanism is mostly made up of three primary elements namely the biorecognition element, the transducer and the signal processing system. Specificity is achieved through the biorecognition component which only interacts with the target microorganism or molecular signature like surface antigens, nucleic acids or toxin. This interaction is then converted into a measurable signal that is amplified, processed, and interpreted by an analytical system, the transducer (Topor *et al*., 2023; Chen *et al*., 2025).

One of the most commonly used mechanisms is surface plasmon resonance (SPR)-based systems that is used to detect pathogens in real-time. In SPR, incident light is employed to drive the plasmons, which are coherent oscillations of electrons on a metal surface, typically that of gold. The local refractive index is altered when a pathogen binds to an immobilized aptamer or antibody on the sensor surface, creating a change in the resonance angle or wavelength (Baccar *et al*., 2010; Chen *et al*., 2025). This non-labeled identification system enables continuous monitoring of the binding process and gives kinetic information including affinity and dissociation, both essential to the dynamics of pathogen- sensor interactions (Bergwerff and Knapen, 2006; Qu *et al*., 2020).

Biosensors manufacturers improve the SPR-based biosensor by adding nanostructured surfaces and photoluminescent molecules to enhance signal sensitivity. Biosensor manufacturers enhance signal sensitivity further by introducing nonradiative energy transfer by utilizing nanostructured surfaces and photoluminescent molecules. Photoluminescent molecules have the ability to enhance plasmonic responses by transferring energy to the surface plasmids, and this can enhance the recorded signal of low concentrations of pathogens. On the same note, despite the fact that nanomaterials, such as silver/reduced graphene oxide composites, exhibit lower tuning potential, alternative interface deposition tiers, which consist of nanomaterials, have been used to enhance the binding capacity of bacteria targets, as well as signal transduction (Nath *et al*., 2024; Rahmasari *et al*., 2025).

The detection of pathogens depend on the antibody-antigen interactions. The immobilization of antibodies on sensor surface is done in a manner that it exposed to many target pathogen as possible. When bound, the conformational change or increase of mass is converted to an optical or electrical signal. This can be spoiled in SPR immunosensors by a change in resonance angle, or by the fiber-optic or imaging ellipsometry systems by a change in light intensity or interference pattern (Bae *et al*., 2004; Lin *et al*., 2007). The given strategy provides the possibility of the most specific identification of separate pathogens such as *Listeria, Vibrio cholerae*, and *Salmonella* (Morlay *et al*., 2017; Jyoung *et al*., 2006). Electrochemical biosensors work in another principle. In this case, the electrochemical change that is caused by binding of the pathogen or target biomolecule is the change in current, voltage, or impedance, which is then detected and used to measure the analyte (Bergwerff & Knapen, 2006). These sensors are very compatible with miniaturized and portable systems of detection, giving them on-site analysis with minimum sample administration. In general, the overall mechanism of biosensors in detecting and quantifying foodborne

pathogens is a synergistic combination of specific molecular recognition, efficient signal transduction, and accurate data processing. Advances in SPR technology, nanomaterials, photoluminescent enhancement, and multiplexed platforms play leading roles in the rapid, sensitive, and real-time detection of multiple pathogens simultaneously. These mechanisms are critical for improving food safety monitoring, reducing detection times, and providing actionable data to prevent the spread of contamination in food products (Chen *et al*., 2025; Qu *et al*., 2020; Topor *et al*., 2023).

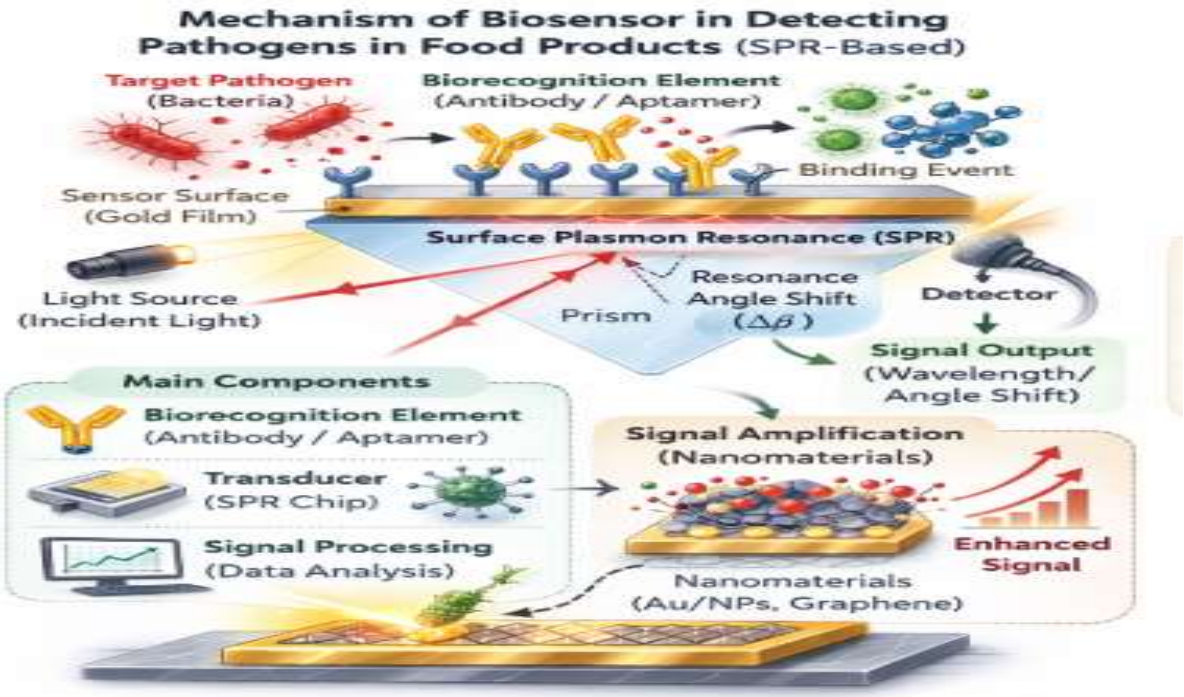

Figure 1: Mechanism of Biosensor in Detecting and Quantifying Pathogens in Food Products
Benefits of Using Biosensors in the Detection and Quantification of Pathogens in Food Products.

Biosensors have become an important analytical instrument in the detection and through to quantification of foodborne pathogens and contaminants in food products.

i. The high sensitivity and specificity is one of their greatest benefits as it enables the correct identification of the pathogens with very low concentrations. As an illustration, Zhang *et al*. (2025) designed a combined three-channel ultrasensitive biosensor with a phage multi-functional probe that was capable of detecting live and dead *Listeria monocytogenes*. Such sensitivity and specificity is above a number of traditional microbiological methods, which usually involve protracted culture time and substantial preparation of the sample. Equally, Pasquardini *et al*. (2023) showed that immuno-SPR biosensors would effectively detect *Brucella abortus*, which emphasized the ability of the biosensors to address specific pathogens in compound food samples.

ii. Quick detection of biosensors is another advantage which is very important in monitoring the safety of food in real-time. Microbiological tests may require 24-72 hours and biosensors, e.g., surface-enhanced Raman spectroscopy (SERS), can deliver results within minutes or hours (Zhang *et al*., 2022). Perishable food products, especially in the context of the rapid detection because timely response can eliminate outbreak and financial losses. On-site analysis can also be provided by the use of biosensors in continuous monitoring systems, which eliminates the reliance on the central laboratory facilities (Wang *et al*., 2025). This type of real time monitoring can be useful in a factory food processing facility since contamination is easily detected early and action can be taken to rectify the situation promptly.

iii. Biosensors are also beneficial because they are used in terms of their versatility in detection strategies. The biosensors of the contemporary world utilize numerous recognition components such as antibodies, nucleic acids, enzymes, and phage proteins, and all these elements can be customized to identify bacteria, viruses, or toxins (Zhao *et al*., 2025). An example is the inhibition and detection of *Salmonella typhimurium* and *Listeria monocytogenes* with a graphene-doped photocatalyst, which stated how the biosensor platform could be combined with nano-materials to allow a better detection level (Yan *et al*., 2025). Equally, Cao *et al*. (2018) demonstrated that gold nanoparticles, which are functionalized, could be used to enhance the detection of small-molecule metabolites in the food indicating the versatility of biosensors to detect microbial and chemical hazards in food.

iv. Non-destructive and label-free analysis is another significant advantage of the technique that does not compromise the sample of food. Such

methods as localized surface plasmon resonance (LSPR) or surface plasmon resonance (SPR) allow detecting pathogens directly without fluorescent or radioactive labeling (Lin *et al.*, 2025; Prajna and Sinha, 2024). This also makes sample preparation easier besides avoiding interference by food components. Furthermore, label-free detection is capable of giving real-time kinetic information that scientists and food safety experts can use to study the dynamics between the pathogens and the recognition factors in the food matrix which is useful in determining the behaviour of pathogens in food.

v. Biosensors are also miniaturized and portable thus can be used in fields. The combination of nanomaterials and microfluidic systems has made it possible to have miniature devices that can be used to multiplex detect. Wang *et al.* (2025) focused on the application of multiplexed optical sensors driven by nanomaterials to simultaneously detect multiple food pathogens with a high degree of improvement in the analytical throughput. Such devices are compact and can be easily moved, which is why they are known to be ideal when the purpose is to monitor the environment in farms, food processing plants, and retail stores, extending their monitoring capabilities to the outside of the conventional laboratories.

vi. Another benefit is the combination of biosensors and digital technologies with data analytics. Nowadays, the state-of-the-art biosensors interface with smartphone-facilitated applications and computational frameworks to provide automated readouts, which can be quickly interpreted and decisions made (Zhang *et al.*, 2025). This is especially useful with food production on a large scale, where constant monitoring of products produces large datasets that need to be processed efficiently. Biosensors in combination with machine learning algorithms can support predictive monitoring and risk assessment to enable proactive food safety management, not reactive.

vii. Lastly, biosensors proved to be cost effective in the long run. Despite the high initial cost of establishing biosensor system, the capability of making precise, quick and real time detection makes them cheaper in terms of the cost of large scale laboratory work, recalls and epidemics in food and beverages. They also make traditional microbiological tests less intensive in terms of labour, which enables the food safety operators to work on prevention as opposed to reactive testing.

viii.

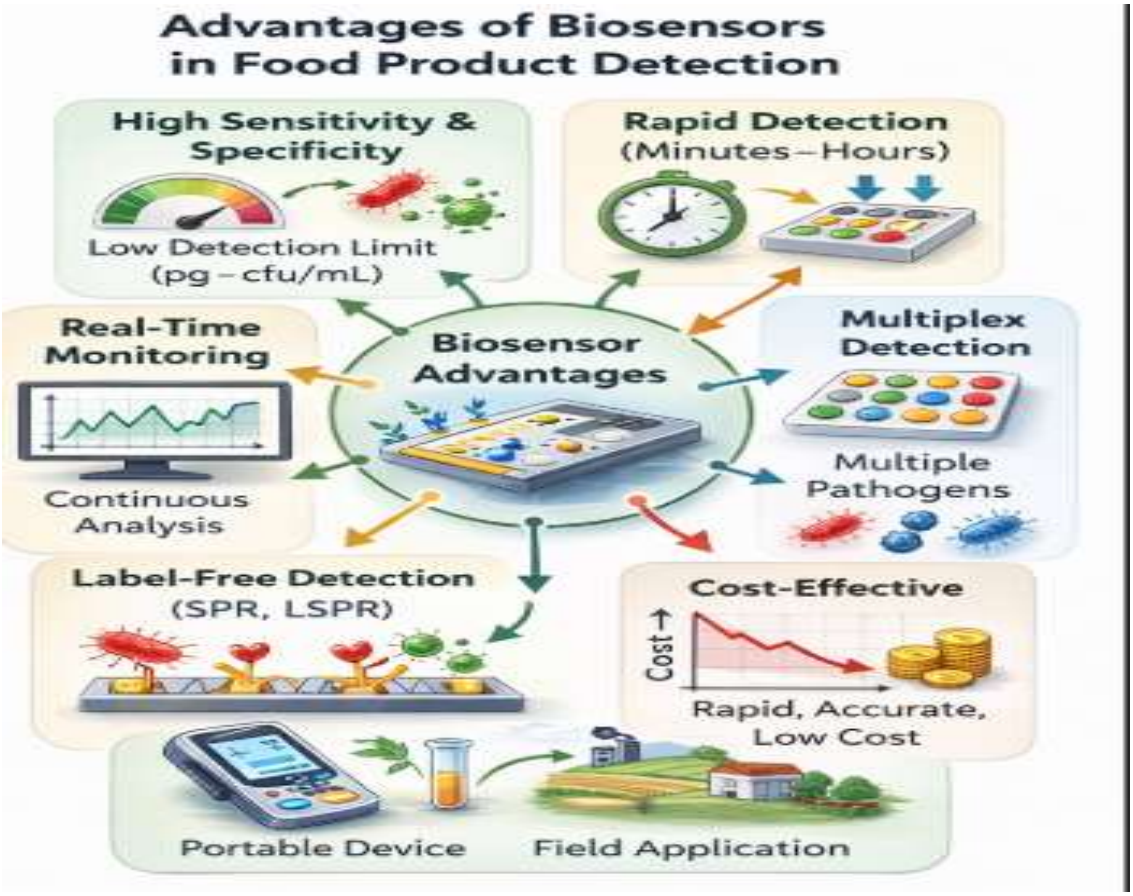

Figure 2: Benefits of Biosensors in Detecting and Quantifying Pathogens in Food Products

Challenges and Limitations of Using Biosensors in the detection and Quantification of Pathogens in Food Products

In spite of the numerous benefits, biosensors also have a number of challenges and limitations when applied in practice.

i. Complex food matrices are one of the key limitations as they can cause interference with the sensor and confound the accuracy and reliability of sensors. Fats, proteins and polysaccharides, among others, may inhibit pathogen detection and binding resulting in false positives and negatives (Tchatchiashvili *et al.*, 2025). As an example, one may consider the fact that the sensitivity of SPR and LSPR-based sensors may be impaired in dairy or meat products and require a meticulous preparation of the samples and optimization of sensor surfaces.

ii. The other important challenge is the separation between live and dead cells. The effectual determination of viable pathogens is extremely important in assessing hazards to food safety. Despite the materials presented by Zhang *et al.* (2022) and Zhao *et al.* (2025) which combine SERS with computational models to differentiate between live and dead *Salmonella* cells, the complexity and cost of the proposed methods prevent their universal use. In a similar manner, not every conventional type of fluorescent dye such as SYTO9 / PI could offer reliable discrimination when working with biofilm or mixed microbial communities (Tchatchiashvili *et al.*, 2025; Hirakata *et al.*, 2023).

iii. Other concerns include stability and reproducibility of biosensors. Biological recognition elements (antibodies or enzymes, etc.) in sensors can denature, degrade, or lose their functionality over time (Pasquardini *et al.*, 2023).

iv. Other environmental influences such as temperature, pH and ionic strength can also influence sensor performance especially in field or on-site use. To overcome this, there is growing research on nanomaterial-based and synthetic recognition elements to enhance stability, but resulting in increased cost of producing the recognition elements (Lin *et al.*, 2025; Hang *et al.*, 2024).

v. Biosensor platforms require an expensive and technically challenging initial cost and may also restrict their implementation in constrained resource environments. Such advanced methods as SERS, LSPR, and integrated biosensors that use multiple signals all demand specific instrumentation and technical competence which might not be readily available in small food processing plants or in the developing regions (Yu *et al.*, 2024; Wang *et al.*, 2025). In addition, the combination of biosensors and computational analysis though beneficial, presents another field of complexity that is likely to stall the uptake of these systems without relevant training.

vi. Limited multiplexing capability remains a challenge. Even though there are biosensors of high sophistication that can detect several pathogens at the same time (Zhang *et al.*, 2025; Wang *et al.*, 2025). It is still not easy to target a specific pathogen in a complex sample with a high level of sensitivity and selectivity. Cross sensitivity and interference have the ability to diminish analytical accuracy, and hence there is need to ensure critical sensor design and validation.

vii. Data interpretation and management is another limitation. Monitoring systems generate large volumes of data, which need prolific software to analyze, interpret, and store in real-time. Poor management of data may cause delays in the process of making decisions or sensor readings to be misunderstood, decreasing the usefulness of the biosensor system in practice (Wang *et al.*, 2025).

viii. Finally, the problem of regulatory and standardization is also a major hurdle. The biosensor implementation in food safety measurements is limited because of the absence of standard principles and regulatory principles used to verify and approve them (Pasquardini *et al.*, 2023). This may hinder commercialization and reduce acceptance of innovative biosensors technologies by the food businesses and health departments.

Case Study on Biosensor in Pathogen Detection and Quantification in Food

Foodborne illnesses have remained a massive health challenge in the world and early detection and quantification of pathogenic organisms in food items are still critical in ensuring that people remain safe. Microbiological techniques, which are considered to be reliable but time consuming, are not always practical in making real time decisions as part of food production and distribution chain. As a reaction to such constraints, biosensors have emerged as promising analytical tools, with its ability to detect at rapid speeds, sensitivity and in situ. In the recent literature, it is shown that biosensors were successfully used in food pathogen monitoring, which shows their effectiveness, versatility, and possibility to change food safety practices.

i. Among them is the creation of immuno-surface plasmon resonance (SPR) biosensors to perform *Brucella abortus* detection, described by Pasquardini *et al.* (2023). In the study, *Brucella*-specific antibodies was attached to the sensor surface, allowing fastening of bacterial cells to the sensor surface as direct food samples in the study. Real time SPR measurements were used to monitor changes in the refractive index at antigen-antibody interactions, and could therefore be detected rapidly and without the use of labelling. The biosensor was highly sensitive and selective as the results were comparable to the conventional immunoassays, but the measurements required only minutes instead of hours or days. The study has nevertheless also indicated some difficulties encountered by using complex food matrices like dairy products (where fats and proteins may provide unwanted non-specific signals) in which case optimized sample preparation and passivation of surfaces must be used to reduce the interference. It highlights the ability of SPR-based biosensors to provide consistent analytical output and provides an insight into the practical implications in order to implement the biosensors in a food system setting.

ii. Equally, Zhang *et al*. (2025) made a phage-enhanced biosensor, which would select live and dead *Listeria monocytogenes* simultaneously. This system employed bacteriophage probes with high specificity to viable bacterial cells, and integrated fluorescent and electrochemical readouts, so as to offer a consensus readout. The biosensor decreased the probability of false positivity due to non-viable bacteria because it used three separate signals to make a more precise judgment about the risk of microbes in food. Notably, the technique could directly be used on complex matrices like meat and leafy greens with no prior pre-enrichment processes. The multifunctional design shows the tendency to develop biosensors that merge the biological specificity with engineered signal amplification that present strength and resistance in non-homogeneous food samples.

iii. The use of machine learning with the surface-enhanced Raman spectroscopy (SERS) also illustrates the promising perspective of biosensors in diagnostics of pathogens. Zhang *et al*. (2022) presented a quick process of categorizing live and dead *Salmonella* cells by using a combination of SERS-generated molecular fingerprints with a convolutional neural network (CNN). The CNN model was able to classify spectral data effectively wherein viable and non-viable bacteria were differentiated in the backdrop of background signals of food components. The system demonstrated accuracy rates above 90 % when applied to contaminated samples of artificially-contaminated food like milk and spinach, demonstrating that artificial intelligence (AI) machine learning (ML) is effective because it can enable biosensors to perform multiple tasks using high-dimensional inputs. The case describes the increased synergy between biosensor technology and artificial intelligence, which offers the opportunity to interpret the subtle spectral variation that would be difficult to solve otherwise.

iv. In addition, Wang *et al*. (2025) also mentioned the suitability of multiplexed optical sensors with nanomaterials to detect more than one pathogen in food at a time. These sensors increased the optical signals by using plasmonic nanoparticles and metasurfaces and could detect *E. coli*, *Listeria*, and *Salmonella* bacteria simultaneously in complex food matrices. The potential to measure multiple targets in low concentrations in a variety of food products is an indication of the practicability and scalability of contemporary biosensor platforms in solving the problem of co-contamination that typically permeates all foods systems in natural environments. These multiplexed systems highlight the importance of engineered nanostructures to optimize its sensitivity and selectivity in order to make the food safety monitoring a rapid decision-making process.

Taking together, these case studies demonstrate some common trends in the modern application of the biosensors. A real time, label free detection, as is the case in SPR and SERS systems, can give instant feedback of analysis that is important in timely interventions. Multimodal systems which incorporate integrated fluorescence and electrochemical system and optical signal improvements are also stronger and less false positive especially in distinguishing between live and dead pathogens. The usefulness of biosensors is also further enhanced by machine learning and data analytics which are able to interpret complex signals accurately, and the improvements of nanomaterials which enhance sensitivity, selectivity and multiplexed detection. Nevertheless, there are still some challenges, such as the effects of more complicated food matrices, which can pose a challenge to signal interpretation and need thorough surface engineering and sample preparation.

Table 2: Recent Case Studies on Biosensor Applications in Food Pathogen Detection

Author (Year)	Pathogen	Biosensor Technique	Sample Type	Key Outcome
Pasquardini *et al*. (2023)	*Brucella abortus*	Immuno-SPR	Dairy/meat samples	Rapid, label-free detection with high specificity
Zhang *et al*. (2025)	*Listeria monocytogenes*	Phage-based three-signal biosensor	Meat, leafy greens	Simultaneous live/dead detection with ultrasensitivity
Zhang *et al*. (2022)	*Salmonella* spp.	SERS + CNN	Milk, spinach	Accurate live/dead classification using AI-assisted spectroscopy
Yan *et al*. (2025)	*Salmonella* & *Listeria*	Graphene-doped nanomaterial platform	Coconut juice	Enhanced detection and inhibition via nanomaterials
Wang *et al*. (2025)	Multiple pathogens	Multiplexed optical nanomaterial sensor	Juice, meat, dairy	Simultaneous multi-pathogen detection at low concentrations

CONCLUSION

The use of biosensors in the determination and detection of pathogens in food products represents a significant advancement in food safety management. Based on the case studies analyzed one can say that biosensors offer higher speed, sensitive and accurate detection properties that offer superior speed and operational efficiency compared with conventional microbiological methods. The versatility and strength of such technologies is achieved by the fact that they can identify viable pathogens, separate live from dead cells, and analyze multiple samples simultaneously. In addition, these new capabilities of biosensors contributed to the reduction of their size: incorporation of nanomaterials and machine learning has enhanced the sensor capabilities to work in food matrices and give data useful in food safety decision-making. There is room for improvements notwithstanding, issues of food component interference, optimization of surface engineering, and the affordability and scalability are also aspects of consideration which are vital to the massive adoption. There is need for collaboration between the researchers, technology developers, and food producers to optimize the work of biosensors, make them more stable to work with matrices, and create standard operating procedures and ensure food safety thereby saving public health from foodborne diseases

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