



BIOSENSORS IN VARIOUS FOOD APPLICATIONS- A SYSTEMATIC REVIEW

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Abstract:

Biosensors are replacing the traditional quality checking and safety measure methods in food industry. Their robust applications in various sectors, specifically in food sector have been an advantage in supplying fresh food from farm to fork. These increased the food supply chain business to mitigate export needs and have shown proven results by detecting food borne pathogens and other contaminants during storage, processing until it reaches consumer. Combining the sensor technology to biological molecules detection has great importance in assessment of authenticity of foods in the adulteration market. An attempt was made to construct a systematic review on biosensors in various food applications which might throw light in understanding and developing specific methods for rapid quality assurance of food until it reaches the consumer.

Key Words: Biosensors, Food, spoilage, microbial, analyte.

Introduction:

In recent scenarios, food industries are functioning as a complex global sector involving various businesses in delivering food from “farm to fork” with different segments of production, processing, supply, distribution, preservation and packaging of innumerable food items. In the view of the facts that, as there are significant challenges arising in the raw materials sector, including contamination risks, inadequate traceability, and financial constraints which are a threat to food quality and safety measures. While in case of processing, poor hygiene practices, cross contamination, and lack of employee training call forth/causing foodborne illnesses, whereas in the packaging sector, numerous risks including contamination, inadequate labelling, and insufficient sealing, are leading for foods recalls. Therefore, these challenges are affecting the food quality, safety and consumer health.

In order to overcome these challenges, biosensors are used widely in food sectors as they are receptor-transducer devices that change a biological response into an electrical signal. The electronic component of these devices detects, records and transmits information regarding physiological changes or the presence of various chemical or biological materials in the environment of the food matrix. Biosensors can detect changes in measuring, low concentrations of specific pathogens, or

toxic chemicals and detect analytes. Biosensors in the food industry play a crucial role in enhancing food safety, quality control and monitoring.

Types of Biosensors in food industry

Type of Biosensor	Mechanism	Analyte	Application	Reference
Based on Processing				
Electrochemical	Electrochemical DNA biosensor	<i>Hepatitis A virus</i>	Food safety monitoring(e.g., Detection of HAV in contaminated shellfish or produce)	Manzano et.al 2018
Optical	2-member fluorescence sensor array	Detects volatiles in meat	Real-time meat freshness monitoring	Yu & co-workers 2024
Immunosensor	Electrochemical immunosensor	Aflatoxin B1	Detection of Aflatoxin B, in food samples	Wang et al., 2025
Piezoelectric	Used to detect specific biological molecules or pathogens that might be present in food (sensitive to stress).	<i>Salmonella</i> , <i>Escherichia coli</i> Ochratoxins	Detection of pathogens and mycotoxins	Bodkhe et al. 2025
Based on raw materials				
Immunosensors	Use antibodies to selectively bind to the target analyte	Organophosphate pesticides Cadmium	Detection using antibodies in quantification of cadmium levels in food samples.	Bhat et al. 2025
Electrochemical Biosensors	Detecting microorganisms, toxins, or nutrients.	Peanut proteins Volatile organic compounds.	Screen printed carbon electrodes (SPCEs) enables the simultaneous determination of these allergens in food matrices.	Rodriguez-Herrera et al. 2021
Optical Biosensors	Detecting gases such as ethylene for ripeness or spoilage indicators through light base methods.	<i>Campylobacter</i> Glucose, Amino acids	Fluorescence resonance energy transfer (FRET) between glucose binding proteins and amino acid binding proteins achieving detection limits in the micro molar range.	Niu et al.2024
Piezoelectric	Detecting bacterial contamination or moisture levels	Fumonisin Arsenic	Detection of fumonisins in food matrices. Arsenic detection functionalizing the sensor surface with specific receptors or aptamers that bind arsenic.	Fernandez Abedul et al. 2015
Enzyme based Biosensors	Enzymes to catalyse reactions with specific substrates, enabling the detection of contaminants or nutrients	Organophosphate pesticides Biogenic amines	On-site detection of pesticide contamination Quick and sensitive detection of spoilage	Vargas-Bernal et al. 2012.
Based on packaging & storage				
Colorimetric biosensors	Visual indication of the conduction of the food inside the package, such as freshness or microbial contamination.	Temperature probe pH probe Ethylene	Microbial contamination detection Ethylene detection	Zheng et al. 2023.
Immunosensors	For detecting pathogens such as <i>Salmonella</i> , <i>E.coli</i> or <i>Listeria</i> .	Biogenic amines such as histamine, tyramine and putrescine.	Biogenic amines Biotoxins	Vasconcelos et al.2021
Enzyme based	Biosensors that detect microbial enzymes or byproducts like lactic acid,	<i>Campylobacter</i> CO ₂	Detection of microbial enzymes and by products.	Carducci et al.2024.

	ethanol, or ammonia associated with spoilage of food.			
Electrochemical sensors	Detect changes in the pH of dairy products, meat or fermented foods.	Ethanol CO ₂ Ethylene	pH monitoring in dairy , meat and fermented foods.	Campuzano et al. 2024

Application of biosensor in various food sectors:

Biosensors have been applied in many areas in the food industry. At every stage of food manufacturing they provide better stability and sensitivity as compared with the traditional methods. Their application in food sectors address critical challenges such as food safety, quality control, traceability and regulatory compliance. From detecting pathogens, allergens and toxins in raw materials to monitoring freshness, spoilage and adulteration in processed products, biosensors are enhancing the efficiency and reliability of food analysis. Additionally, their portability and ease of use make them highly suitable for on-site testing, offering real-time data to support timely decision making. As consumer demand for transparency and safety continues to grow, biosensors are becoming indispensable tools in ensuring food integrity throughout the supply chain from farm to fork.

Food Biosensors applications in raw materials:

These advanced sensing tools enable rapid, sensitive and specific detection of contaminants and quality markers, helping ensure that only safe and high quality raw inputs enter the processing stage. By enabling early detection of contaminants and quality deviations, biosensors help food producers maintain product consistency, reduce waste and meet regulatory requirements. Their integration into raw material screening processes not only enhances food safety but also contributes to overall efficiency and sustainability in the food supply chain. Numerous studies emphasize the role of biosensors in detecting harmful contaminants in raw materials, particularly pathogens and chemical residues.

Biosensors detection of pathogens: Biosensors are significant in detection of pathogens causing microbial contamination. A review by Cossettini et al. 2022 explores various biosensor technologies such as immunosensors, DNA based sensors and enzyme linked sensors that can detect pathogenic microorganisms like *Salmonella*, *Listeria monocytogenes* and *Escherichia coli* in raw meat, dairy and vegetables. Similarly, in agricultural products such as cereals and nuts, biosensors are employed to detect mycotoxins like aflatoxins. DNA and antibody based biosensors have been developed to detect *Salmonella*, *Listeria* and *E.coli*, often achieving results in under an hour as mentioned by Chen et al. 2023. A portable biosensor developed by Zhao et al. 2024 could detect *E.coli* in meat samples with high specificity using electrochemical methods. Biosensors represent a transformative tool in ensuring food safety and quality by enabling early detection of microbial contamination and spoilage. As the technology advances, they hold immense potential for integration into smart food systems, ensuring better consumer protection and reducing food waste. Immunosensors use antibodies to selectively bind to microbial antigens. Applied for detecting *Salmonella*, *Listeria monocytogenes* and *E.coli* in meat, dairy and water. Huang et al 2022 developed a label free immunosensor for *E.coli* strain with a detection time under 30 minutes. A method of detection of pathogens using biosensors was shown in the figure 1.

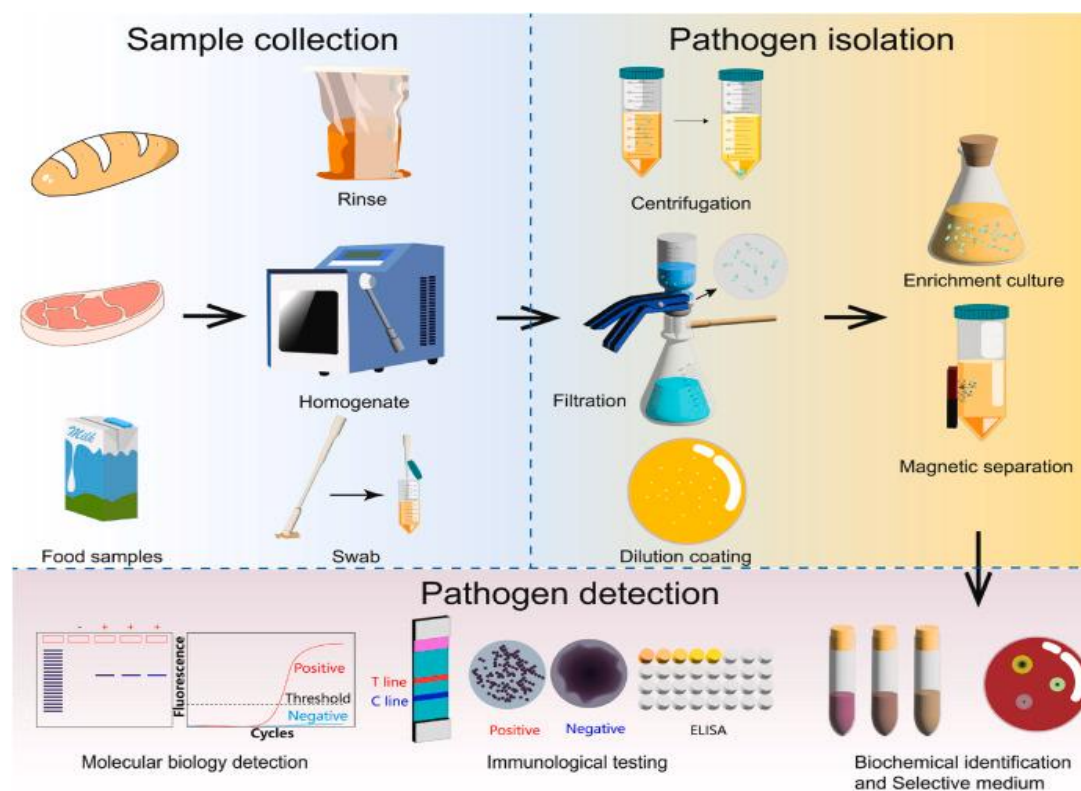


Figure 1: Method of detection of pathogens using biosensors

Source: Ye et al. 2025

Biosensors in detection of pesticide and herbicide residues: Biosensors are good monitors of pesticide residues in raw fruits and vegetables. Traditional chemical analysis methods are often time consuming and require laboratory facilities, whereas biosensors offer on-site, real-time detection with minimal sample preparation. Research by Wu et al. 2023 investigated about biosensors for detecting pesticide residues in agricultural raw materials like fruits and vegetables. They discuss different types of biosensors such as surface plasmon resonance (SPR) and electrochemical sensors, noting their sensitivity and specificity in detecting low levels of pesticides which are crucial for meeting regulatory standards. Biosensors using acetylcholinesterase inhibition have been effective in detecting pesticide residues in vegetables and grains as mentioned in Ravindran et al. 2023.

Biosensors are having wide scope, specifically in food industry for monitoring of freshness and ripeness of raw food in order to minimise the wastage, has gained a great importance in maintaining quality of food.

Biosensors in monitoring of freshness and ripeness:

In order to evaluate freshness, biosensors act as an indicators in monitoring raw fish and meat for biogenic amines or pH changes assessment, in monitoring of somatic cell count or antibiotic residues in raw milk to compliance with safety standards. Ethylene biosensors and volatile organic compounds monitoring biosensors are used for monitoring of freshness and ripeness of foods.

Biosensors in ethylene monitoring: These are innovative tools in food industry contributing significantly to freshness monitoring by detecting and quantifying ethylene gas, thereby waste reducing and efficient supply chain management. Janssen et al. 2014 incorporated ethylene biosensors for monitoring fruit ripeness which was commercialized for smart packaging solutions. Sreeram et al. 2024 have developed electrochemical sensors utilizing multiple walled carbon nanotubes, which exhibit superior sensitivity and selectivity compared to earlier models. These sensors are effective for non-destructive analysis of fruit ripening stages. Use of biosensors for ethylene detection was showed by Xu et al. 2024. Integration of biosensors into storage and transportation systems to ensure the produce is processed at its peak ripeness, enhancing both flavour and nutritional content can be achieved.

Biosensors for monitoring volatile organic compounds (VOCs): Volatile organic compounds (VOCs) are carbon based chemicals that easily evaporate at room temperature. They are emitted from various sources including food (during spoilage), plants, industrial processes and packaging materials. VOCs found in food sector include ethanol, acetone, ethylene and aldehydes. Kundu & Ghosh, 2024 utilized Density Functional Theory (DFT) and Non-equilibrium Green's Function (NEGF) methods to model chemoresistive gas sensors based on two dimensional silicone nanosheets. Fluorine passivated silicone demonstrated superior sensitivity towards six VOCs commonly emitted by food products including acetone, ethanol and toluene. This suggests potential for more effective VOC detection in food quality assessment. Raza et al. 2025 discussed about biosensors designed to detect specific VOCs produced by raw materials like fish or fruits as they approach spoilage.

Biosensors in nutri analysis and quality assessment: Biosensors are increasingly being used to assess the nutritional content of raw materials by measuring proteins, fats, sugars and other important nutrients. Biosensor technologies capable of detecting sugar and starch levels in raw plant materials like cereals and fruits was examined by Rakha et al. 2024 which can help processors understand and control ingredient sweetness and overall flavour balance. Zhang et al. 2023 showed that glucose biosensors particularly based on glucose oxidase have been widely applied to detect sugar levels in beverages and dairy products. Effectiveness in monitoring triglycerides and fatty acid content in processed foods using lipase based biosensors was studied by Sharma et al. 2022. Biosensors involving amino acid oxidase or urease enable real time nutritional monitoring for protein content as given by Wang et al.2019. In raw meat and plant based materials, protein and lipid content were detected and ensured consistency in the nutritional profile of their products in the context of alternative meat or protein rich foods were mentioned in Aslan et al.2025.

Biosensors in detecting adulteration: Biosensors offer a rapid, sensitive and cost effective alternative for identifying food fraud and verifying product authenticity. These devices are increasingly used to detect adulterants, mislabelling and counterfeiting in food commodities. These are used to verify authenticity of raw materials, addressing the growing concern of food fraud in dairy products, edible oils and spices. Enzyme based biosensors using urease, peroxidase and amylase can selectively detect these adulterants in milk and dairy products studied by Sharma et al.2021. Electrochemical biosensors developed by An et al. 2022 detects melamine, a nitrogen based adulterant in milk. DNA biosensors and FTIR coupled biosensors can identify the genetic or chemical fingerprint of the oil's origin from adulteration as shown in Kalaitzis & El-Zein, 2016 in which using these biosensors the method for olive oil adulteration with other oils like soybean or sunflower oil was detected. Capacitive biosensors using molecularly imprinted polymers (MIPs) have demonstrated success in detecting adulteration in coconut and mustard oils. Research by Gonzalez et al. 2021 reviews biosensor technologies used to detect adulterants in high value raw materials like olive oil, saffron or honey. They highlight the use of enzyme based sensors that can detect the presence of cheaper adulterants or non-authentic ingredients ensuring consumers receive the products of their expectations.

Biosensors in authenticity verification: DNA biosensors of species specific help verify meat origin which is crucial for religious or ethical dietary needs as studied by Nehal et al. 2021. Distinguishing between wild caught and farmed fish can be done with specific proteins and hormones targeted immunosensors based monoclonal antibodies. Bharathi et al. 2018 studies the adulteration of turmeric with lead chromate or paprika with synthetic dyes like Sudan red, which was detected using colorimetric and enzyme based biosensors. DNA biosensors and NIR based sensor systems help in verifying authenticity of saffron. Wang et al., 2022 showed that amperometric biosensors and MIP based systems help in identification of artificial colorants, stones and starches added to grains and pulses. Gao et al. 2021 focused on application of immunobiosensors to verify the presence of cow's milk or it has been diluted or mixed with non-dairy ingredients. Glucose oxidase targeting biosensors detect artificial sugars as given by Mishra et al. 2022. For detecting honey purity Raman biosensors are emerging which work through sugar profile analysis for authentication.

Biosensors applications in food processing:

Biosensors for food spoilage monitoring: Conventional methods used for *Vibrio parahaemolyticus* monitoring in seafood based on microbiological counts are time consuming, laborious and they cannot identify virulence genes. So a duplex electrochemical biosensor for the detection of the *tdh* and *trh* genes of *V.parahaemolyticus* in oysters was developed by Campas et al. 2023. These are able to detect as low as 1 CFU of *V.paramhaemolyticus* in oyster homogenate as shown in figure 2.

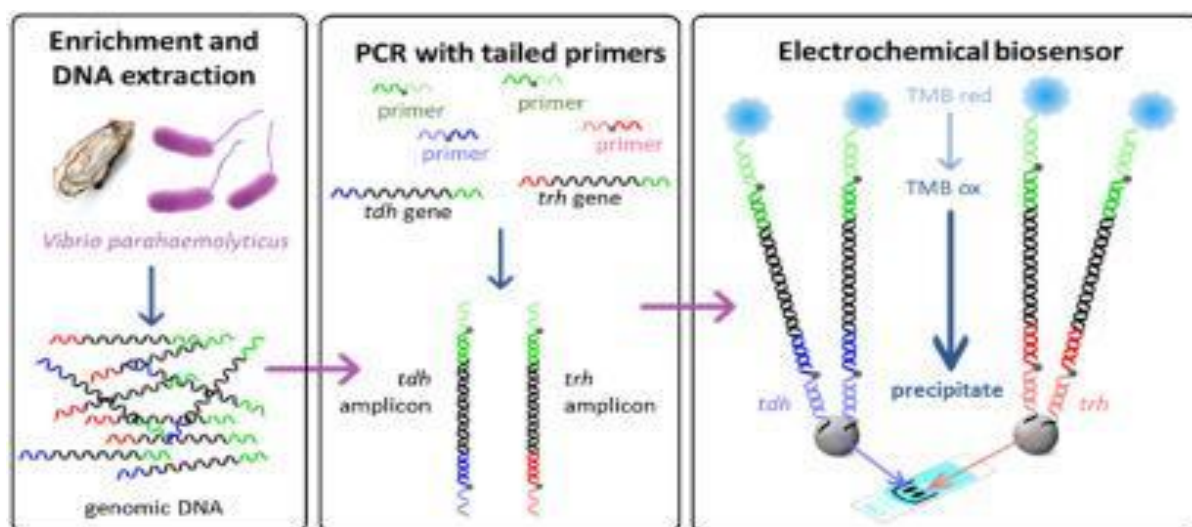


Figure 2: Method of detection of *V.parahaemolyticus* using biosensors

Source: Campas et al. 2023.

Nanotech based detection of contaminants: For detection of *E.coli*, Raj et al.2021 used gold nanocomposites to develop a simple, label free and highly sensitive immunosensor based on electrochemical detection. This biosensor established a high selectivity and sensitivity with a low detection limit of 10 CFU/mL and detected *E.coli* within 30 minutes. Nano enabled biosensors are based on gold particles and carbon nanotubes that have significant enhancement in sensitivity for detecting heavy metals like lead, arsenic and mercury as mentioned in Kaur et al.2024.

Biosensors applications in storage and packaging:

VOCs detection in real-time provides a valuable tool for quality control before these ingredients undergo further processing. Gas biosensors detecting volatile amines like putrescine, cadaverine which were used to indicate meat and fish spoilage as studied by Lee et al.2021.

Genosensors also called as DNA biosensors use single stranded DNA probes that hybridize with microbial DNA or RNA. Zhou et al.2022 designed a genosensor to detect *Listeria monocytogenes* in dairy products using fluorescent readout.

Biosensors detecting meat and seafood spoilage with bacteria were studied by Zhang et al.2023 which helped in allowing processors to discard contaminated materials before they undergo costly further processing. Research by Liu et al.2022 highlights use of biosensors to detect fungal contamination in grains ensuring safety of products during storage.

Internet of things and Biosensor integration helps in real time monitoring of raw materials during storage and transportation as studied by Mani et al.2025. This will allow to track temperature, humidity and contamination levels providing instant feedback to processors ensuring compliance with safety and quality standards. Research by Saini et al. 2021 discusses biosensors embedded in packaging materials can detect spoilage or contamination in raw materials giving alert to consumers or suppliers to potential issues and is a smart packaging system which is innovative for improving food safety.

Wang et al.2024 gave a review on biosensors monitoring environmental conditions such as temperature and humidity in storage facilities for preventing microbial growth and spoilage in raw materials like grain, fruits and vegetables when stored. Eyvazi et al.2021 used biosensors to detect

airborne pathogens in warehouses and food storage environments preventing contamination of raw materials before processing.

Conclusion:

The literature confirms that biosensors are transforming food quality and nutritional monitoring. Their versatility combined with advances in nanotechnology and digital integration promises a future or real time in field analysis, however challenges such as long term stability, cost effectiveness and regulatory validation remain to be fully addressed.

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