INNOVATIVE BIOSENSOR TECHNOLOGY FOR REAL-TIME DETECTION OF PATHOGENIC BACTERIA IN FOOD SUPPLY CHAINS

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Abstract

Microbiological foodborne diseases pose significant difficulties to public health and the food sector, involving prompt and precise detection techniques to avoid foodborne diseases and guarantee food safety. Traditional individual biosensing methods often have constraints regarding their sensitivity, specificity, and response time. Implementing biosensors has been recognized as an innovative method for quickly identifying foodborne diseases in food products. A biosensor is a system that combines a biological detection material with chemical or physical transducers to convert chemical, biological, or biochemical information into detectable electrically transmitted impulses. This review presents an examination of the benefits, difficulties, and future possibilities of multimodal biosensing for foodborne diseases, highlighting its revolutionary capacity for ensuring food safety and improving public health. Finally, the primary objective of this study is to make a valuable contribution to the advancement of novel approaches in addressing foodborne diseases and guaranteeing the authenticity of the food supply chain.

Key words: foodborne diseases, biosensors, food safety, food supply.

Understanding the problem

Foodborne diseases have increased in frequency and now they pose a significant hazard to worldwide public health, impacting around 600 million individuals annually. Foodborne pathogens induce thousands of diseases, being considered important risks to human health and economy due to their detrimental health impacts (Faour-Klingbeil D. *et al,* 2020; Moi I.M. *et al,* 2022). The World Health Organization (WHO) reports that about 30% of foodborne fatalities occur in children under five years old. Foodborne bacteria, the etiological agents of foodborne diseases, can induce symptoms ranging from mild to severe, including diarrhea, or debilitating illnesses like meningitis (Scallan Walter E.J. *et al,* 2020; Elbehiry, A. *et al,* 2023).

Food poisoning may lead to malnutrition, serious gastrointestinal disorders, and potentially cancer. To successfully manage the challenge of toxicity in food products, it is essential to create rapid and precise instruments for detecting harmful substances in food. Sun drying and heating were likely the initial procedures employed, followed by polymerase chain reactions and instrumental analysis, which are two of the most prevalent traditional techniques for detecting food toxins (Tarannum N. *et al,* 2024). These procedures are laborious, costly, and time-consuming, rendering them impractical for business applications that require rapid and on-site screening of a significant number of samples (Wang L.Y.Z. *et al,* 2019).

The surveillance of bacterial contamination in the food chain encompasses several analytical techniques and the application of advanced automated tools designed for the detection of foodborne contaminants (Silvestri E.E. *et al,* 2017). Nonetheless, certain challenges and constraints exist in the application of these conventional methods. Furthermore, diagnostic instruments must evaluate feasibility and provide flexibility to detect specific pathogens responsible for the occurrence of foodborne diseases (Ali A.A. *et al,* 2020). In this context, nanotechnology, specifically nanosensors, can be employed in the food industry to detect toxicity in food during packing and storage. There is an increasing demand for nanotechnologies due to the development of remarkable potential and innovative applications across various sectors, including the food businesses (Tarannum N. *et al,* 2024).

Nanotechnology-based sensors and other technologies are employed to detect harmful microparticles, including microplastics and bacteria, found in various materials used by consumers. Nanomaterials are defined as substances possessing at least one dimension less than 100 nanometers. Owing to their very small dimensions, they display unique chemical and

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physical features. Nanoparticles can enhance the physical, mechanical, and biological attributes of food packaging by improving its quality, flexibility, grade, and sustainability (Ashfaq A.N. *et al,* 2022).

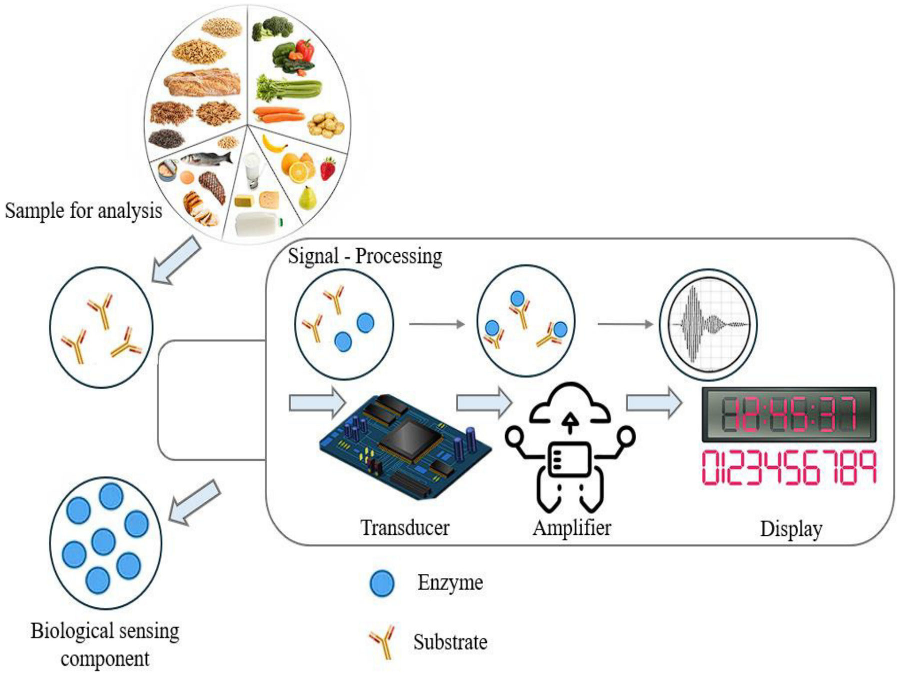

Figure 1 **- Diagram of biosensor operation, indicating recognition element – analyte contact and signal transduction (adapted from Nath S., 2024)**

Introduction to Biosensor Technology

A biosensor is an analytical instrument that quantitatively or semi-quantitatively measures, having a sensing element of biological origin that is either integrated with or closely associated with a physico-chemical transducer. A chemical sensor is an instrument that converts biochemical information, from the concentration of a particular element to comprehensive composition analysis, into an output which is analytically valuable *(figure 1)* (Thakur, M.S. *et al,* 2012). Chemical sensors typically have two fundamental components linked in the series: a chemical identification system (receptor) and a physicochemical transducer. Biosensors are chemical sensors that employ a biological process for recognition, interacting with a photoelectric device. A device that employs specialized biochemical processes facilitated by isolated enzymes, immune systems, tissues, organelles, or entire cells to identify chemical molecules, typically through electrical, thermal, or luminescent signals (Nic M. *et al,* 2006).

The sensor layer, integrated with appropriate transducers such as carbon nanotubes, graphene, or nanoparticles, produces quantifiable signals from these biorecognition processes. Diverse signal detecting methodologies, including as impedimetric, amperometric, and voltametric procedures, enable biosensors to provide responses that are proportionate to the number of specific analytes. This approach is applicable for the pre-treatment procedures and identification of microorganisms in different food products (Zhang L. *et al,* 2024).

Biosensors are instruments that identify diseases through the utilization of biological recognition features such as antigens, enzymes, or sequences of DNA. They can detect and quantify the presence of pathogenic germs in real time. Several types of biosensors exist, such as electrochemical and optical sensors (Castillo-Henríquez L. *et al,* 2020). Electrochemical sensors identify alterations in electrical signals in the presence of a pathogen, whereas optical biosensors utilize variations in light patterns, such as fluorescence, that indicate the contamination. The advantages of such devices are manifold - rapidity, sensibility, and accuracy (Naresh, V. *et al,* 2021).

Due to their minuscule scale, nanomaterials provide a significantly broader surface for reactions. This enhances the biosensor's sensitivity, enabling the detection of very small amounts of pollutants or pathogens. Nanomaterial biosensors are frequently coated with biological detection components such as antigens, enzymes, or DNA that exhibit high affinity for the biological target (bacteria, toxins, etc.). After binding the target substance to the sensor, the characteristics of the nanomaterial (such as electrical conductivity, color, or fluorescence) undergo alteration. The biosensor's transducer identifies these alterations, converting the physical or chemical reaction into a signal that can be measured. This signal is subsequently analyzed and exhibited, enabling users to promptly ascertain contamination levels in real time (Malik S. *et al,* 2023; Fu Y. *et al,* 2024). *Identification of pathogens (e.g. E. coli or Salmonella spp.) in food products such as meat, dairy products, and vegetables:* a biosensor embedded with gold nanoparticles is engineered to selectively attach to the DNA of bacteria or protein molecules. When the pathogen is detected in a food sample, such as meat, the bacterial particles adhere to the surface of the sensor. This alters the characteristics of the nanoparticles, such as their electric or optic signals. Thus, these alterations are subsequently identified and analyzed, signifying the pathogen's presence in real-time (Xu L. *et al,* 2021). *Identification of pesticide residues on agricultural products, facilitating food safety and adherence to health standards*: nanosensors derived from graphene are capable of detecting pesticide residues. The sensor is equipped with enzymes that bind with pesticide compounds. The interaction between the pesticide and the surface of graphene alters the sensor's electrical conductivity. This alteration is subsequently assessed and quantified, yielding prompt feedback on the concentrations of pesticides detected. In a supply chain, business companies can employ these types of biosensors to rapidly assess batches of products before shipment to verify compliance with safety regulations (Srinivasan S. *et al*, 2024; Pan Y. *et al*, 2024).

Identification of toxins (e.g., aflatoxins) in cereals, nuts, or herbs and spices: nanomaterial biosensors are employed to identify minimal quantities of aflatoxins in the food chain. Quantum dots, which are semiconductor nanoparticles, are employed in fluorescence biosensors for the detection of harmful substances. These sensors are covered with antibodies that specifically attach to aflatoxins. Thus, aflatoxins from a food product adhere to the quantum dot surface, modifying the sensor's fluorescence characteristics. The alteration in fluorescence is recognized, yielding a rapid and precise assessment of the toxin level. Grain facilities for storage use these types of sensors to test corn or nuts for aflatoxin contamination prior to processing or exportation (Yan C. *et al,* 2020; Yadav N. *et al,* 2021).

Monitoring heavy metals, including residues of lead or mercury, in food and water to guarantee food safety by preventing hazardous concentrations of metals in products: silver nanoparticles are frequently utilized in biosensors for the detection of metals like lead or mercury. These nanoparticles exhibit high sensitivity to metal ions. The binding of lead or mercury ions to the silver nanoparticles in the sensor results in a quantifiable alteration in the optical or electrochemical properties, signifying the presence of heavy metals in the sample. A biosensor can be submerged in a sample of water or a beverage such as juice, to detect heavy metal contamination during the production or the packing process (Ivanišević I. *et al,* 2021; Anchidin - Norocel L. *et al,* 2024).

Assessing the freshness of food products to identify spoiling gases, including free ammonia or hydrogen sulfide, that are emitted during degradation: carbon nanotube-based sensors may be incorporated into innovative packaging. They identify gases generated by bacterial action during decomposition. The interaction of gases with carbon nanotubes alters the sensor's electrical characteristics, resulting in a visual signal, such as a color change, or the transmission of an electrical signal for monitoring purposes. Consequently, packed meat or fish may be embedded with these sensors to notify retailers or consumers of spoilage, therefore guaranteeing fresher food in the marketplace (Erna K.H. *et al,* 2021; Chiu I. *et al,* 2023).

AI-Enhanced Biosensors

A notable innovation is the incorporation of artificial intelligence (AI). AI-enhanced biosensors integrate the rapidity and sensitivity of conventional biosensors with the computational capabilities of artificial intelligence. These systems can evaluate extensive data sets in real time, offering precise predictive capabilities and reducing false positives/responses. AI-enhanced biosensors in the food industry combine sophisticated sensor technology and machine learning algorithms to deliver rapid and precise detection of food spoilage, contaminants, and the level of quality. By recreating human sensory systems like taste and olfaction and analyzing intricate data sets, these sensors guarantee food safety and quality control from production to consumption (Zhang L. *et al,* 2023; Chen Y. *et al*, 2024). AI-enhanced biosensors are ideal for application in milk processing facilities. Consequently, they can assess vapor and liquid samples to identify potential bacterial contamination or food degradation more rapidly than conventional methods. Consequently, AI contributes in discovering and recognizing spoiling patterns that may differ between samples, thereby mitigating food loss. The electronic nose and tongue are engineered to replicate human senses through sensor networks that identify various scents, flavors, or chemical substances in food products. Moreover, the sensor data undergoes processing through sophisticated algorithms that differentiate between fresh and rotten samples by comparing them with established data patterns (Zhang L. *et al,* 2023). AI-enhanced electronic noses may be employed in the wine industry to oversee fermentation and detect potential spoilage at an early stage. An electronic tongue may identify off-flavors in beverages or assess the balance of certain compounds, such as sugar or acidity levels (Figure 2).

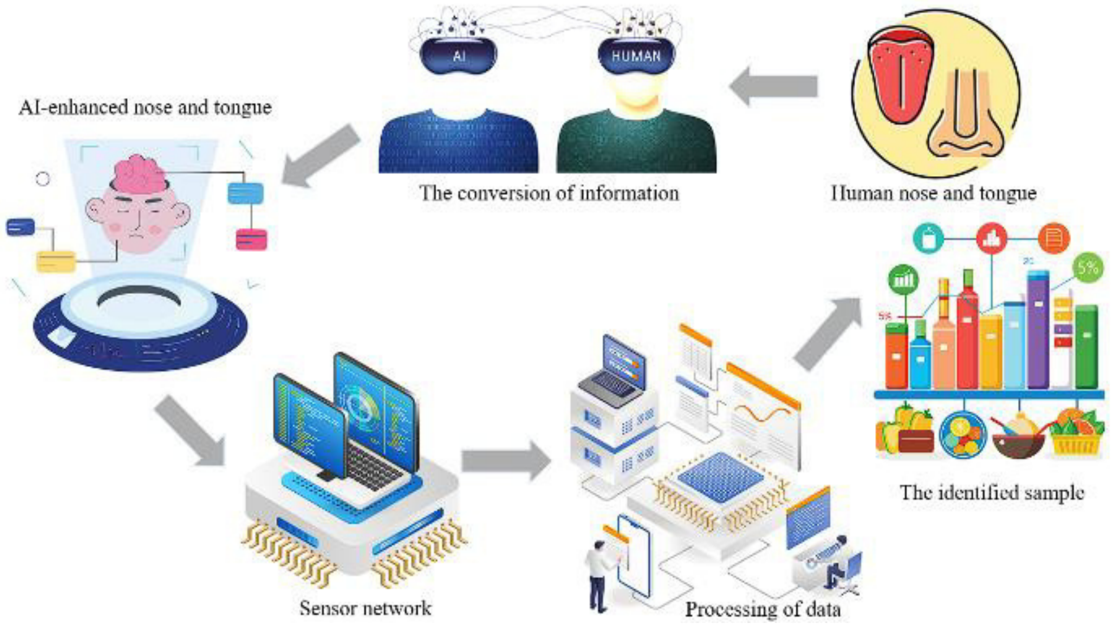

Figure 2 - **Food industry use of AI and biosensors. Comparison of gustatory and olfactory systems (adapted from Zhang et al, 2024)**

Artificial intelligence techniques, like Principal Component Analysis (PCA) and machine learning algorithms, can enhance the sensor's capacity to evaluate extensive data sets and recognize significant patterns within them. This facilitates a significantly faster and more precise classification of a food sample, ascertaining whether the food is spoiled or fresh (L.M. & De Saja, J.A., 2016; Munekata, P. E. *et al,* 2022).

In the food industry, AI-enhanced biosensors can be employed to identify pesticides in fruits and vegetables. They can assess product samples on-site to ascertain the presence of pesticide residues that may pose a risk to human health. AI algorithms possess the capacity to analyze complex data to distinguish between safe and hazardous chemical levels, hence ensuring adherence to food safety requirements (Zhao G. *et al,* 2015). Similarly to carbon nanotube-based sensors AI-enhanced electronic noses and tongues may identify spoilage gases, including ammonia and hydrogen sulfide, released by decomposing food. AI-enhanced sensors can be incorporated into packaging to notify retailers or consumers when food is decreasing in freshness. Another use may involve smart packaging with AI-enhanced biosensors. These can be included in intelligent packaging to assess the freshness of food. Packaged meat might incorporate sensors that identify spoiling gases and generate a visual signal, such as a color change on the packaging, to alert the consumer that the item is no longer safe for consumption (Singh R. *et al,* 2023).

Multimodal Biosensing

Multimodal biosensing integrates many technologies, including optical and electrochemical methods, within a single platform, beyond single-use biosensors. This combination facilitates a more comprehensive detection of contamination, as various signals can be simultaneously evaluated. Multimodal biosensors integrate various detection techniques (optical, electrochemical, or piezoelectric) to identify a diverse array of contaminants within a single sample. Consequently, by employing many detection techniques, multimodal biosensors may simultaneously identify several contaminants with enhanced precision (Ullah N. *et al,* 2023).

In seafood processing facilities, multimodal biosensors could simultaneously identify several risks, including heavy metals (mercury in fish), different pathogens (*Vibrio* in shellfish), and pesticide residues (in farmed shrimps). These sensors may conduct a comprehensive assessment of the interested food products by integrating label-free and label-based detection methods, alongside employing both electrical and optical signals. Multimodal biosensors use AI and machine learning algorithms to analyze and interpret intricate data. Consequently, AI can rapidly recognize certain patterns within the data and acquire knowledge through machine learning, hence identifying novel contamination patterns (Zhang L. *et al,* 2023). An example of this is the intelligent food packaging system that may incorporate multimodal biosensors to detect contamination and spoiling in real time. AI algorithms can analyze data from various sensors, including those that identify gases emitted during spoilage, pesticide residues, and heavy metals, and alert consumers through a smartphone application if the product is deemed unsafe for human consumption. The use of AI for analyzing intricate sensor data enhances the system's adaptability in identifying new contaminants or changing concentrations of recognized chemicals (Sonwani E. *et al,* 2022; Popescu S.M. *et al,* 2024).

Despite the considerable advantages of biosensors, including rapidity, sensitivity, and real-time monitoring abilities numerous problems remain. Initially, calibration is required to ensure functionality with various intricate food matrices. Moreover, biosensors have not been extensively implemented in all sectors of the food industry, and standardization is essential to guarantee accuracy and reliability among various biosensor technologies (Kaushal J. B. *et al,* 2023).

CONCLUSION

Biosensors represent a novel solution for the real-time detection of pathogens within food supply chains. These technologies have the capacity to revolutionize contamination detection and prevention across the food supply chain, hence providing safer food products for consumers. The future step in this field is to promote research and the eventual implementation of these modern and accessible techniques within the food industry to maximize the advantages of this technology.

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