Smart Food Quality Control via Integration of Nanotechnology and Biosensing

Matin Mohamadinezhad[1*] - Zahra Yousefian-Jazi[2] - Mani Mohamadinezhad[3]
[1] M.Sc. in Food Science and Engineering, Department of Food Science and Technology, College of Agriculture, Isfahan University of Technology, Isfahan, Iran
[2] M.Sc. in Organic Chemistry, Department of Chemistry, Isfahan University of Technology, Isfahan, Iran
[3] B.Sc. in Applied Chemistry, Department of Chemistry, University of Isfahan, Isfahan, Iran

ABSTRACT

Ensuring food safety and quality is a global priority, yet conventional detection methods often fall short in speed, sensitivity, and adaptability. This review highlights the transformative role of nanotechnology in biosensor development, offering innovative solutions for real-time, high-precision monitoring across the food supply chain. It explores the fundamental components and mechanisms of biosensors, emphasizing how nanomaterials—through enhanced surface reactivity, signal amplification, and structural stability—significantly improve sensitivity, selectivity, and durability. The article categorizes nanobiosensors based on detection mechanisms (electrochemical, optical, and mass-based) and biorecognition strategies (enzymatic, immunochemical, and microbial). Practical applications are discussed, including pathogen detection using metal nanoparticles, toxin and allergen sensing via carbon quantum dots, freshness evaluation through colorimetric nanostructures, and fermentation control using electrochemical nanobiosensors. These advancements underscore the potential of nanobiosensors to revolutionize food safety monitoring and quality assurance.

Keywords:* *Nanobiosensors, Food safety, Nanotechnology, Quality Assessment

1. *INTRODUCTION*

1.1 Importance of Food Safety and Quality

Food safety and quality are among the most influential factors affecting public health in human societies. According to international reports, the consumption of unsafe food leads to millions of illnesses and hundreds of thousands of deaths worldwide each year [1]. Therefore, ensuring access to safe food not only saves lives but also promotes individual and societal well-being.

Food safety is a comprehensive concept that begins at the earliest stages of production and extends through to final consumption— a concept that encompasses the entire food supply chain "from farm to fork." Implementing safety and quality systems across all stages of the food chain—including production, processing, packaging, storage, and distribution—plays a critical role in safeguarding consumer health.

In this context, Good Hygiene Practices (GHP) and Good Manufacturing Practices (GMP) help ensure food safety by improving sanitary conditions throughout various processes. Additionally, quality assurance systems ensure that food products conform to specified characteristics, through the definition of standardized criteria [2].

1.2 The Need for Advanced Detection Methods

Food safety is a vital pillar of public health and a key factor in maintaining consumer trust in the food supply chain. However, conventional detection methods are often slow, costly, and heavily reliant on laboratory-based equipment. These limitations hinder the ability to perform rapid and effective monitoring under real-world production and distribution conditions. In response, emerging technologies such as artificial intelligence (AI), nanotechnology, and biosensors have introduced transformative capabilities in contaminant detection. Key advancements include:

- Machine learning, powered by AI, enhances the analysis of complex food data, improves imaging techniques, and—through integration with the Internet of Things (IoT) and blockchain—enables precise and intelligent traceability.
- Nanotechnology, utilizing NPs and nanozymes, facilitates ultra-sensitive and rapid detection of contaminants.
- Biosensors, employing enzymes, immunosensors, and DNA-based aptamers, offer high specificity in identifying toxins, pathogens, and harmful chemical compounds.
- Next-generation biosensors, including electrochemical, optical, and paper-based formats, have expanded practical applications in industrial and commercial settings.
- Hybrid concepts, such as smart nanobiosensors, IoT-enabled active packaging, and autonomous response systems, allow real-time monitoring and rapid reaction to food safety threats [3].

1.3 Emergence of Nanotechnology and the Evolution of Biosensors

As discussed in the previous section, conventional detection methods face significant limitations, making it essential to explore alternative approaches for rapid monitoring in real-world conditions. One such alternative is the biosensor, which has undergone substantial improvements in selectivity, repeatability, stability, sensitivity, and linearity due to recent innovations in design. A particularly noteworthy advancement is the incorporation of nanoscale materials into biosensor construction, resulting in the development of nanobiosensors, a rapidly evolving field. These nanomaterials impart unique properties that not only overcome challenges related to sensitivity and detection limits but also enhance the stabilization of biological molecules, thereby improving the efficiency of biochemical reactions [4].

2. Fundamentals and Principles of Biosensors

2.1 Core Components of Biosensors

Typically, biosensors consist of two primary components: a biorecognition element and a transducer. These sensors are classified into various categories based on the type of bioreceptor and transduction mechanism employed. Biorecognition elements include compounds capable of specifically identifying target molecules, such as antibodies, enzymes, aptamers, nucleic acids, and molecularly imprinted polymers. The transducer is responsible for converting the biological response into a measurable signal and through mechanisms such as optical, electrochemical, mass-sensitive, electrical, or thermal mechanisms [5].

2.2 Mechanism and Performance Indicators

Biosensors are analytical tools designed to detect specific analytes through selective interactions facilitated by biorecognition elements. These interactions induce physical or chemical changes that are subsequently converted into quantifiable signals by the transducer. While the fundamental operating principle of biosensors remains consistent, the choice of bioreceptor and transducer varies depending on the analytical requirements [6].

Like other technologies, biosensor systems have evolved over time, leading to significant improvements in key performance indicators such as sensitivity, selectivity, detection limit, reliability, validity, and response time, which have, in turn, contributed to enhanced functionality and broader applicability [7].

3. Overview of Nanotechnology in Biosensors

3.1 Definition and Classification of Nanomaterials

In 1959, during the annual meeting of the American Physical Society, Richard Feynman delivered a seminal lecture titled "There's Plenty of Room at the Bottom," which drew significant attention to the concept of nanotechnology—despite the term "nano" not yet being coined. More than five decades later, in 2011, the European Commission defined a nanomaterial as "a natural, incidental, or manufactured material containing particles in an unbound state or as an aggregate or agglomerate, where 50% or more of the particles in the number size distribution have one or more external dimensions in the size range of 1 to 100 nanometers" [8].

Beyond precise definitions, nanomaterials can be classified based on their origin, dimensionality, and constituent materials. Additionally, classification based on intrinsic toxicity levels has also been proposed [9].

3.2 Advantages of Nanoscale Materials in Sensors

Nanobiosensors offer numerous advantages over sensors constructed from bulk materials, including enhanced sensitivity and specificity, a high surface-to-volume ratio, and novel functional properties. For instance, the application of nanophotonics can significantly improve sensitivity and selective detection.

Ultimately, these features contribute to reduced cost and response time, making nanobiosensors suitable for high-throughput applications [10].

3.3 Effects on Sensitivity, Selectivity, and Stability

The incorporation of NPs into biosensors has been shown to significantly enhance their sensitivity, selectivity, and stability through various mechanisms.

Impact on Sensitivity

- Signal Amplification: NPs provide a large surface area and catalytic activity that amplify the sensor signal, enabling the detection of analytes at extremely low concentrations and improving the limit of detection [11, 12].
- Increased Surface Reaction Sites: The high surface-to-volume ratio of NPs offers more binding sites for target molecules, increasing the likelihood of interaction and thereby enhancing sensitivity [10].

Impact on Selectivity

- Catalytic and Reactive Properties: Functionalizing sensors with specific NPs (e.g., noble metals) is a strategy to enables targeted catalytic reactions that preferentially interact with specific analytes, leading to improving selectivity [13, 12].
- Material and Structural Tuning: The size, distribution, and chemical composition of NPs can be engineered to selectively direct the sensor response toward specific substances while minimizing interference from others [14, 12].

Impact on Stability

- Enhanced Structural Stability: NPs can improve the mechanical and chemical stability of the sensor's active layers, helping maintain performance during repeated use or prolonged exposure to analytes, which is crucial for practical applications [11].
- Reversible Catalytic Behavior: Certain NPs coatings enable reversible reactions, allowing the sensor to be reset for repeated measurements without degradation, thus contributing to long-term stability [12].

4. Overview of Nanotechnology in Biosensors

4.1 Definition and Classification of Nanomaterials

The design and development of robust enzymatic nanobiosensors require insight into nanofabrication and bioconjugation techniques. Bioconjugation is an enabling technology that reduces costs and enhances biosensor performance, operating based on the interaction between functional surface groups of enzymes and nanomaterials. Common bioconjugation strategies include physical methods (adsorption, entrapment), covalent methods (covalent bonding, cross-linking), and bioaffinity approaches [15].

In 2014, Pal and colleagues successfully detected choline at a concentration as low as 0.0005 µM in milk samples using a zinc oxide nanorod film. In this study, choline oxidase and peroxidase enzymes were simultaneously immobilized covalently on the transducer surface, resulting in high stability and nearly 99% recovery in real samples [16].

4.2 Immunochemical Nanobiosensors

Immunosensors include electrochemical, microgravimetric, optical, and calorimetric formats. They offer advantages such as high sensitivity, selectivity, rapid response, and cost-effectiveness. Notably, antibody-based biosensors have surpassed traditional methods in the detection and analysis of various compounds [17].

Owing to these advantages, immunochemical nanobiosensors play a critical role in food safety by enabling rapid, sensitive, and selective detection of contaminants such as pathogens, toxins, allergens, pesticides, and heavy metals. For example, studies have demonstrated the successful identification of aflatoxin strains B1, B2, G1, G2, and tetrodotoxin [17].

4.3 Cell-Based and Microbial Nanobiosensors

Cell-based and microbial nanobiosensors are devices that use entire microbial cells—often combined with nanomaterials—to detect specific biochemical or environmental signals. Their responsiveness, operational stability, and long-term usability depend on the stabilization method, which can be physical or chemical. Microorganisms have been paired with various transducers, including amperometric, potentiometric, conductometric, luminescent, and fluorescent systems, to create biosensing devices. Amperometric microbial biosensors are commonly used to measure biochemical oxygen demand (BOD) in water samples, aiding in the detection of biodegradable organic pollutants.

5. Types of Nanobiosensors Based on Detection Mechanism

5.1 Electrochemical Detection

The measurement of electrical properties for extracting data from biological systems typically involves electrochemical processes, where the electroactive biological component serves as the primary transduction element. Common techniques in this category include amperometry, potentiometry, conductometry, cyclic voltammetry, chronoamperometry, and chronopotentiometry [18].

5.2 Optical Detection

Optical biosensors detect analytes by interacting with biorecognition elements. Two main approaches are employed: label-free and label-based detection. In label-free methods, the signal is generated directly through the interaction between the analyte and the transducer. In contrast, label-based methods utilize a signaling molecule, and the optical signal is produced via fluorescence, colorimetry, or luminescence. Various optical biosensing platforms exist, including surface plasmon resonance (SPR), interferometers, localized surface plasmon resonance (LSPR), optical gratings, resonators, and refractometers. Each optical biosensor must generate a signal that directly correlates with analyte concentration to enable accurate quantification [19].

5.3 Mass-Based Detection

As the name suggests, mass-based biosensors measure minute changes in mass resulting from interactions between the analyte and the biorecognition element. These systems are typically based on piezoelectric crystals, which oscillate at a specific frequency when an electrical signal is applied. The oscillation frequency depends on both the applied signal and the mass of the crystal. When chemical bonding increases the crystal's mass, the frequency shifts accordingly. This change is measured electrically and used to quantify the added mass [20].

6. Applications of Nanobiosensors in the Food Industry

6.1 Pathogen Detection Using Gold, Silver, and Zinc Oxide NPs

Food contaminated with pathogenic microorganisms poses a serious threat to public health and may cause debilitating illnesses in consumers. Among various pathogens, Campylobacter species, non-typhoidal Salmonella enterica serotypes, Shiga toxin-producing Escherichia coli strains, and Listeria monocytogenes are among the most recognized [21].

To address this threat, various nanobiosensors have been developed. Studies have shown that nanobiosensors incorporating gold NPs can detect Listeria monocytogenes, Bacillus cereus, Staphylococcus aureus, and Campylobacter jejuni [22]. Silver NPs-based biosensors have demonstrated the ability to identify Staphylococcus aureus and Escherichia coli [23]. Zinc oxide NPs have been successfully employed in biosensors for detecting pathogens such as Listeria monocytogenes, Salmonella Typhimurium, Staphylococcus aureus, Escherichia coli O157:H7, and Campylobacter jejuni [24]. This demonstrates the broad applicability of nanotechnology in pathogen detection.

6.2 Detection of Toxins, Allergens, and Contaminants Using Carbon Quantum Dots

Carbon quantum dots (CQDs) have emerged as versatile fluorescent alternatives widely used as probes in food detection applications. These nanomaterials possess extensive surface areas with functional groups that interact with a broad range of substances, modifying their optical properties. CQD-based biosensors can detect pesticides, nutrients (e.g., glutathione, ascorbic acid), microbial toxins (e.g., ochratoxin A, aflatoxin B1), pathogens (e.g., Salmonella Typhimurium, Escherichia coli), and prohibited food additives [25].

6.3 Freshness Evaluation Using Colorimetric Nanostructures

Colorimetric nanostructures are increasingly recognized as effective tools for assessing food freshness by detecting volatile organic compounds and secondary metabolic byproducts released during spoilage. Yu et al. (2023) developed a colorimetric sensor array based on silver NPs embedded in agar. These arrays exhibited distinct color changes that corresponded to the freshness stages of chilled chicken meat stored at 4°C. The sensor's color transitions were found to correlated with biochemical freshness indicators such as total volatile basic nitrogen (TVB-N), allowing consumers to visually assess meat quality without opening the packaging [26].

6.4 Fermentation Process Control Using Nanobiosensors

Fermentation processes in the food and biotechnology industries are inherently complex, involving multiple critical variables that are challenging to monitor in real time. Historically, the saccharification stage during fermentation was controlled using the traditional Fehling method. Since this technique relies on the titration of reducing sugars, its results often lacked sufficient precision. However, following the introduction of glucose biosensors in 1975, the fermentation industry has benefited significantly. Today, glucose biosensors are widely employed in sugar production and fermentation workshops to monitor glucose levels through bioenzymatic methods [27].

In recent years, nanobiosensors incorporating nanomaterials such as multi-walled carbon nanotubes and specialized enzymes have enabled more precise and faster monitoring of key metabolites during fermentation. For instance, electrochemical sensors based on multi-walled carbon nanotubes and oxidase enzymes—such as glucose oxidase and alcohol dehydrogenase—have been developed for real-time monitoring of alcoholic fermentation in beverage production. These sensors, with enzymes immobilized in polymeric matrices such as chitosan or polyvinyl alcohol, function as active electrodes and precisely track changes in glucose, ethanol, or lactic acid concentrations [28].

7. Conclusion

Food safety and quality are among the most pressing concerns in public health and food security today. Given the limitations of conventional contaminant detection methods—including lengthy procedures, high cost, and reliance on laboratory equipment—there is an urgent need to develop innovative and reliable tools. In this context, nanobiosensors, leveraging nanomaterials and biological recognition elements, have significantly enhanced the performance of biosensing systems.

These sensors offer improved sensitivity, selectivity, stability, and miniaturization capabilities, facilitatingrapid and specific detection of harmful compounds under real-world conditions of food production, storage, and distribution. The diversity in nanobiosensor design—based on biorecognition elements (enzymes, antibodies, cells) and detection mechanisms (electrochemical, optical, mass-based)—has expanded their applications across various sectors of the food industry. Key applications include pathogen detection, toxin and contaminant analysis, freshness evaluation, and fermentation process control.

Moreover, the use of nanomaterials such as metallic NPs, carbon quantum dots, and carbon nanotubes has conferred unique advantages to these sensors, enhancing their performance in complex and industrial environments. With recent advancements, nanobiosensors present a promising outlook for the development of smart, portable, and cost-effective systems for food safety monitoring. These technologies have the potential to play a pivotal role in protecting consumer health, reinforcing public trust in the food supply chain, and raising safety standards across the food industry.

REFERENCES

[1] Fung, F., Wang, H. S., & Menon, S. (2018). Food safety in the 21st century. Biomedical journal, 41(2), 88-95.

[2] Varghese, S. M., Parisi, S., Singla, R. K., & Begum, A. A. (2022). Trends in food chemistry, nutrition and technology in Indian sub-continent. Berlin/Heidelberg, Germany: Springer.

[3] Pandhi, S., Kumari, N., Jain, A., & Sharma, V. (2025). Emerging technologies in food safety: AI-powered, nano-enabled, and biosensor-based strategies for rapid contaminant detection. Food Analytical Methods, 1–15.

[4] Bhattarai, P., & Hameed, S. (2020). Basics of biosensors and nanobiosensors. In Nanobiosensors: From design to applications (pp. 1–22).

[5] Ozkan, S. A., Uslu, B., & Sezgintürk, M. K. (Eds.). (2022). Biosensors: Fundamentals, Emerging Technologies, and Applications. CRC Press.

[6] Karunakaran, C., Rajkumar, R., & Bhargava, K. (2015). Introduction to biosensors. In Biosensors and bioelectronics (pp. 1-68). Elsevier.

[7] Ahmed, S., Shaikh, N., Pathak, N., Sonawane, A., Pandey, V., & Maratkar, S. (2019). An overview of sensitivity and selectivity of biosensors for environmental applications. In Tools, Techniques and Protocols for Monitoring Environmental Contaminants (pp. 53–73).

[8] Dolez, P. I. (2015). Nanomaterials definitions, classifications, and applications. In *Nanoengineering* (pp. 3–40). Elsevier.

[9] Pietroiusti, A., & Magrini, A. (2014). Engineered nanoparticles at the workplace: current knowledge about workers' risk. *Occupational Medicine*, 64(5), 319–330.

[10] Darwish, M. A., Abd-Elaziem, W., Elsheikh, A., & Zayed, A. A. (2024). Advancements in nanomaterials for nanosensors: a comprehensive review. Nanoscale Advances, 6(16), 4015-4046.

[11] Jalalvand, A. R., & Karami, M. M. (2025). Roles of nanotechnology in electrochemical sensors for medical diagnostic purposes: A review. *Sensing and Bio-Sensing Research*, 100733.

[12] Bulemo, P. M., Kim, D. H., Shin, H., Cho, H. J., Koo, W. T., Choi, S. J., ... & Kim, I. D. (2025). Selectivity in chemiresistive gas sensors: Strategies and challenges. *Chemical Reviews*, 125(8), 4111–4183.

[13] Kwon, Y. M., Son, Y., Lee, D. H., Lim, M. H., Han, J. K., Jang, M., ... & Song, W. (2025). Enhancing selectivity and sensitivity in gas sensors through noble metal-decorated ZnO and machine learning. *Applied Surface Science*, 693, 162750.

[14] Saruhan, B., Fomekong, R. L., & Nahirniak, S. (2023). High-sensitivity and selectivity gas sensors with nanoparticles, nanostructures, and thin films. *Chemosensors*, 11(2), 81.

[15] Verma, M. L. (2017). Nanobiotechnology advances in enzymatic biosensors for the agri-food industry. *Environmental Chemistry Letters*, 15(4), 555–560.

[16] Pal, S., Sharma, M. K., Danielsson, B., Willander, M., Chatterjee, R., & Bhand, S. (2014). A miniaturized nanobiosensor for choline analysis. *Biosensors and Bioelectronics*, 54, 558–564.

[17] Kumar, H., Dhalaria, R., Guleria, S., Cimler, R., Prerna, P., Dhanjal, D. S., ... & Kuča, K. (2024). Immunosensors in food, health, environment, and agriculture: A review. *Environmental Chemistry Letters*, 22(5), 2573–2605.

[18] Grieshaber, D., MacKenzie, R., Vörös, J., & Reimhult, E. (2008). Electrochemical biosensors—sensor principles and architectures. *Sensors*, 8(3), 1400–1458.

[19] Mudenkattil, S., Girigoswami, A., Jayaprakash, T., & Girigoswami, K. (2022). Development of nanobiosensors for human immunodeficiency virus detection: A mini review. *Exploration of Medicine*, 3(5), 479–493.

[20] Huang, X., Zhu, Y., & Kianfar, E. (2021). Nano biosensors: Properties, applications and electrochemical techniques. *Journal of Materials Research and Technology*, 12, 1649–1672.

[21] Heredia, N., & García, S. (2018). Animals as sources of food-borne pathogens: A review. *Animal Nutrition*, 4(3), 250–255.

[22] Hua, Z., Yu, T., Liu, D., & Xianyu, Y. (2021). Recent advances in gold nanoparticles-based biosensors for food safety detection. *Biosensors and Bioelectronics*, 179, 113076.

[23] Zorraquín-Peña, I., Cueva, C., Bartolomé, B., & Moreno-Arribas, M. V. (2020). Silver nanoparticles against foodborne bacteria: Effects at intestinal level and health limitations.

Microorganisms, 8(1), 132.

[24] Zhao, C., Xu, S., Wei, J., Xie, S., Wei, J., Han, J., ... & Zhu, Y. (2022). Enhanced response for foodborne pathogens detection by Au nanoparticles decorated ZnO nanosheets gas sensor. *Biosensors*, 12(10), 803.

[25] Das, P., Nath, P. C., Pandey, V. K., Singh, R., Rustagi, S., Shaikh, A. M., & Kovács, B. (2025). Carbon quantum dots as emerging biosensors for food safety and environmental applications: Advances and challenges. *Applied Food Research*, 101255.

[26] Yu, J., Huang, M., Tian, H., & Xu, X. (2023). Silver nanoparticle sensor array-based meat freshness inspection system. *Foods*, 12(20), 3814.

[27] Manish, A. (2022). Applications of biosensors: A short review. *International Journal of Clinical Biochemistry and Research*, 9, 283–285.

[28] Monge, M., & Moreno-Arribas, M. V. (2016). Applications of nanotechnology in wine production and quality and safety control. In *Wine safety, consumer preference, and human health* (pp. 51–69). Cham: Springer International Publishing.