Journal of Nutrition and Human Health Advances

Open Access

REVIEW ARTICLE

Volume 2 - Issue 5

Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection

Okunbi Favour Onasokhare [1], Okeke Calistus Obinna [2], Ahinful Isaac Anku [3], Moses Adondua Abah [4, 5]*, Micheal Oladosu Abimbola [5, 6] and Ochuele Dominic Agida [4,5]

[1] Department of Biological Sciences, College of Basic and Applied Sciences, Mountain Top University, Ibafo, Ogun State, Nigeria

[2]Department of Food Engineering, Faculty of Technology, Ile-Ife, Osun State.

[3]Department of Physical Science, Eastern New Mexico university, USA.

[4]Department of Biochemistry, Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria.

[5]ResearchHub Nexus Institute, Nigeria.

[6]Department of Chemical Sciences, Faculty of Science, Anchor University, Ayobo, Lagos State, Nigeria.

***Corresponding author:** Moses Adondua Abah, Department of Biochemistry, Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria.

Received: 18 June, 2026 | **Accepted:** 10 July, 2026 | **Published:** 05 September,2026

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, *J. Nutrition and Human Health Advances,* 2(5): dx.doi.org/JNHHA/PP.0013

Abstract :

Foodborne pathogens remain a major global public health concern, contributing significantly to food contamination, disease outbreaks, and economic losses across food supply chains. Conventional detection methods, including culture-based, biochemical, and molecular techniques, often suffer from limitations such as long processing times, complex sample preparation, and inadequate sensitivity for rapid on-site monitoring. In recent years, nanotechnology has emerged as a transformative approach in food safety diagnostics due to its unique physicochemical properties, high surface-area-to-volume ratio, enhanced sensitivity, and rapid detection capabilities. This review critically examines the applications of nanotechnology in foodborne pathogen detection, with emphasis on nanosensors and functional nanomaterials employed in modern food safety systems. Various nanomaterials, including metallic nanoparticles, carbon-based nanostructures, quantum dots, and magnetic nanoparticles, are discussed in relation to their sensing mechanisms, selectivity, and analytical performance. The review further explores different nanosensor platforms, such as electrochemical, optical, fluorescent, colorimetric, and magnetic nanosensors, highlighting their applications in dairy products, meat, seafood, fresh produce, and packaged foods. In addition, recent advances in smart packaging, portable detection devices, lab-on-a-chip technologies, and AI-assisted nanosensing systems are evaluated as emerging tools for real-time monitoring and rapid pathogen identification. Despite remarkable progress, challenges associated with nanomaterial toxicity, regulatory approval, scalability, reproducibility, and commercialization remain significant barriers to widespread adoption. Overall, nanotechnology-based detection systems demonstrate substantial potential to improve food safety monitoring through rapid, sensitive, and reliable pathogen detection, thereby supporting the development of safer and more sustainable food systems worldwide.

Keywords: nanotechnology; food safety; foodborne pathogens; nanosensors; nanomaterials and pathogen detection

1.Introduction

Food safety is a major global public health concern due to the persistent burden of foodborne diseases caused by pathogenic microorganisms and toxins. Each year, contaminated food causes millions of illnesses, hospitalizations, and deaths, disproportionately affecting low- and middle-income countries with weak monitoring systems (World Health Organization, 2024). Common pathogens such as *Escherichia coli*, *Salmonella spp*., and Listeria monocytogenes are frequently linked to outbreaks in raw, processed, and ready-to-eat foods. Globalized supply chains, changing diets, and climate-related disruptions have further increased contamination risks across production and distribution systems (Velusamy *et al.,* 2010). Therefore, there is a pressing need for rapid, sensitive, and reliable detection methods to prevent outbreaks and ensure food quality before consumption. The economic burden associated with foodborne diseases also places significant strain on healthcare systems and food industries globally, necessitating preventive technological interventions and policy planning strategies globally.

Conventional detection methods, including culture-based techniques, PCR, and immunological assays, are widely used due to their reliability and validation. However, they are often slow, labor-intensive, and require specialized laboratory infrastructure, limiting real-time or on-site application (Singh *et al.,* 2013; Justino *et al.,* 2016). Culture methods may take several days, while molecular and immunological assays require skilled personnel and controlled conditions (Velusamy et al., 2010). Food matrices such as meat and dairy may also interfere with detection accuracy, causing reduced sensitivity and false negatives (Inbaraj and Chen, 2016). These limitations highlight the need for rapid, cost-effective, and portable diagnostic tools. Biosensor-based technologies have thus emerged as promising alternatives offering faster response, higher sensitivity, and potential for miniaturization (Inbaraj and Chen, 2016; Justino *et al.*, 2016).

Nanotechnology has significantly advanced food safety diagnostics by enabling highly sensitive biosensors with improved analytical performance. Nanomaterials possess unique properties such as high surface-area-to-volume ratio, tunable optical behavior, and excellent conductivity, enhancing signal detection (Khan, 2018). Materials including gold nanoparticles, carbon nanotubes, graphene derivatives, and magnetic nanoparticles are widely used in pathogen sensing platforms (Inbaraj and Chen, 2016). Electrochemical nanosensors are particularly notable for their sensitivity, rapid response, and portability (Bobrinetskiy *et al.,* 2021). Additionally, bacteriophage-based and nanoparticle-assisted systems provide high specificity even at low pathogen concentrations (Singh *et al.*, 2013). Recent developments integrate optical, fluorescent, and electrochemical mechanisms for multiplexed, real-time food contaminant detection (Jangid et al., 2025). Furthermore, integration of nanotechnology with microfluidic platforms and artificial intelligence-driven data analysis is increasingly being explored to enhance detection accuracy, automation, and real-time decision-making in food safety monitoring systems and field deployment applications.

Despite progress, nanotechnology-based pathogen detection faces several challenges. Interactions between nanomaterials and complex food matrices can reduce accuracy and reproducibility (Jangid *et al.*, 2025). Concerns regarding nanotoxicity, environmental impact, scalability, and regulatory approval remain significant barriers to commercialization (Khan, 2018). Additionally, variability in sensor performance, stability issues, and lack of standardized protocols limit widespread adoption (Bobrinetskiy *et al.*, 2021). Addressing these challenges requires interdisciplinary collaboration among scientists, engineers, and regulators to ensure safe and effective implementation in real-world food systems.

This review provides a comprehensive overview of nanotechnology-based approaches for foodborne pathogen detection, focusing on nanosensors and nanomaterials. It examines biosensing principles and the role of nanomaterials in improving sensitivity, specificity, and response time. It also evaluates electrochemical, optical, and bacteriophage-based nanosensors across food matrices such as dairy, meat, seafood, and produce. Emerging innovations, including portable devices and real-time monitoring systems, are discussed. Finally, the review highlights advantages,

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

limitations, research gaps, and future directions for developing rapid, reliable, and commercially viable food safety technologies that enhance global public health protection. Particular emphasis is placed on translational challenges and the need for scalable manufacturing approaches to facilitate commercial adoption of these emerging diagnostic technologies in global food systems. Standardization of validation protocols and regulatory frameworks remains essential to ensure reliability, reproducibility, and safety of nanotechnology-based diagnostic devices across diverse application contexts overall effectiveness.

Fundamentals of Nanotechnology in Foodborne Pathogen Detection

Nanotechnology has emerged as a transformative approach in food safety diagnostics by enabling the development of highly sensitive and rapid detection systems for foodborne pathogens. At the core of this advancement is the ability to manipulate materials at the nanoscale (1–100 nm), where unique physicochemical properties such as increased surface area, quantum effects, and enhanced reactivity significantly improve sensing performance (Poeta *et al.,* 2023). These properties allow nanomaterials to interact efficiently with biological molecules, thereby enhancing the detection of pathogens at very low concentrations in complex food matrices.

Principles of Nanoscale Sensing and Biosensing

Nanoscale biosensing is based on the integration of a biological recognition element (such as antibodies, nucleic acids, enzymes, or bacteriophages) with a nanomaterial-based transducer that converts biological interactions into measurable signals. The high surface-to-volume ratio of nanomaterials increases the density of immobilized bioreceptors, thereby improving sensitivity and lowering detection limits (Shruti *et al.,* 2024). In addition, nanoscale effects such as localized surface plasmon resonance (LSPR) and quantum confinement enhance optical and electrical signal responses, enabling real-time detection of pathogens with high accuracy (Rizzotto *et al.,* 2023).

Electrochemical, optical, and piezoelectric nanosensors are among the most widely studied platforms. Electrochemical nanosensors measure changes in current, voltage, or impedance upon pathogen binding, while optical nanosensors rely on changes in fluorescence, absorbance, or scattering properties. These mechanisms allow rapid and label-free detection, making them highly suitable for food safety applications (Subramaniam and Velu, 2024).

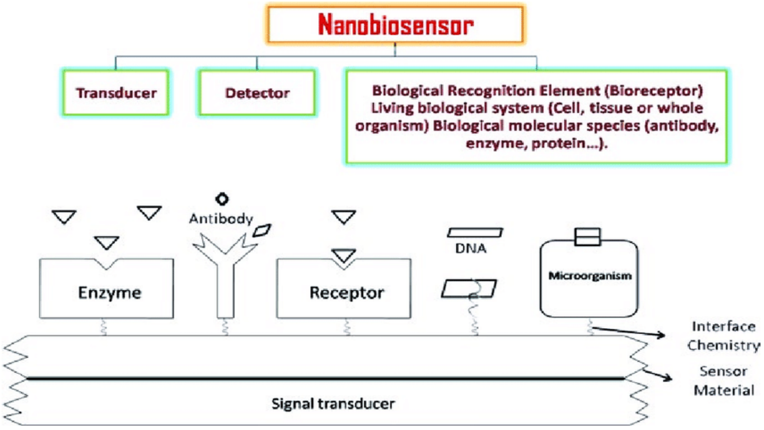

Figure 1. Principle of nanobiosensors. It illustrates the basic working principle of nanobiosensors used in foodborne pathogen detection. The system typically consists of a biorecognition element, such as antibodies, enzymes, or nucleic acids, integrated with nanomaterials that enhance signal sensitivity and detection efficiency. When target pathogens interact with the sensing surface, measurable electrical, optical, or colorimetric signals are generated for rapid and accurate analysis.

Source: Singh (2019)

Interaction of Nanomaterials with Biological Targets

The interaction between nanomaterials and biological

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

targets is fundamental to pathogen detection. Nanoparticles can bind directly to microbial cell walls, nucleic acids, or proteins through electrostatic interactions, covalent bonding, or receptor–ligand recognition. For example, gold nanoparticles can be functionalized with antibodies or DNA probes to selectively bind Escherichia coli or Salmonella spp., producing measurable optical or electrochemical signals (Poeta *et al.*, 2023).

Additionally, nanomaterials can enhance signal amplification by facilitating electron transfer or acting as catalytic labels. Magnetic nanoparticles are particularly useful for target isolation and sample pre-concentration, improving detection efficiency in complex food matrices such as milk, meat, and vegetables (Shruti *et al.,* 2024). These interactions significantly improve sensitivity, specificity, and response time compared to conventional detection systems.

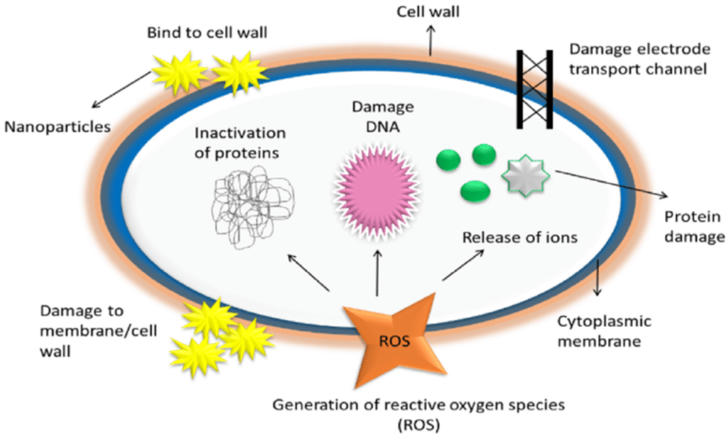

Figure 2. Schematic representation of nanoparticle interaction on microbial cells. It shows the interaction of nanoparticles with microbial cells, including attachment to the cell surface, membrane disruption, and intracellular interference. These interactions enhance microbial detection and contribute to improved sensitivity in nanotechnology-based biosensing systems.

Source: Ashfaq *et al.* (2022)

Major Foodborne Pathogens of Concern

Foodborne diseases are primarily caused by bacterial pathogens such as Salmonella spp., Escherichia coli (particularly O157:H7), Listeria monocytogenes, and Campylobacter jejuni. These microorganisms are responsible for a significant proportion of global foodborne illness outbreaks and are commonly associated with contaminated meat, dairy products, seafood, and fresh produce (World Health Organization, 2024).

Viruses such as norovirus and hepatitis A virus, as well as certain parasites like Toxoplasma gondii, also contribute to foodborne infections, although bacterial pathogens remain the primary focus of nanosensor-based detection systems due to their prevalence and public health impact (Rizzotto *et al.*, 2023). The ability to detect these pathogens at early stages is critical for preventing large-scale outbreaks and reducing foodborne disease burden.

Nanomaterials Employed in Pathogen Detection

Nanomaterials have become central to modern foodborne pathogen detection due to their exceptional physicochemical properties, including high surface-area-to-volume ratio, tunable optical behavior, strong catalytic activity, and enhanced electrical conductivity. These properties enable improved sensitivity, faster response times, and lower detection limits compared to conventional analytical systems. Recent advances in nanotechnology have enabled the design of multifunctional biosensors capable of detecting pathogens such as Salmonella spp., Escherichia coli, and Listeria monocytogenes at very low concentrations in complex food matrices (Zheng *et al.*, 2023; Shruti *et al.,* 2024).

Metallic Nanoparticles (Gold, Silver, Platinum)

Metallic nanoparticles, particularly gold (AuNPs), silver (AgNPs), and platinum nanoparticles (PtNPs), are widely used in biosensing applications due to their strong surface plasmon resonance and excellent biocompatibility. Gold nanoparticles are especially prominent in colorimetric

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

and optical biosensors, where aggregation-induced color changes enable rapid visual detection of pathogens (Park and You, 2024). Silver nanoparticles exhibit strong antimicrobial activity and enhanced signal amplification, making them suitable for dual-function detection systems. Platinum nanoparticles, though less commonly used, provide excellent catalytic activity for electrochemical sensing platforms. Recent studies highlight that noble metal nanoparticles improve signal transduction efficiency and allow label-free detection of foodborne bacteria in real time (Zheng *et al.,* 2023). Their ability to be easily functionalized with antibodies, DNA probes, or aptamers further enhances selectivity and detection accuracy.

Carbon-Based Nanomaterials (Graphene, Carbon Nanotubes)

Carbon-based nanomaterials such as graphene, graphene oxide, reduced graphene oxide, and carbon nanotubes (CNTs) have gained significant attention due to their high electrical conductivity, mechanical strength, and large surface area. These properties make them highly effective in electrochemical biosensors for pathogen detection. Graphene-based platforms enable rapid electron transfer and highly sensitive signal detection, while CNTs enhance electrode conductivity and support biomolecule immobilization (Chen *et al.*, 2024). In food safety applications, graphene derivatives have been used to detect bacterial contamination in dairy products, meat, and water samples with improved sensitivity and reduced detection time (Shruti *et al.,* 2024). Additionally, carbon nanomaterials support multiplexed detection systems due to their ability to interact with multiple biomolecular targets simultaneously.

Quantum Dots and Fluorescent Nanomaterials

Quantum dots (QDs) are semiconductor nanocrystals that exhibit size-dependent fluorescence properties, high photostability, and strong signal brightness. These characteristics make them ideal for optical biosensing applications in food pathogen detection. QDs can be conjugated with antibodies or nucleic acid probes to detect specific bacterial strains through fluorescence emission changes. Fluorescent nanomaterials, including carbon dots and upconversion nanoparticles, have also been widely explored for their ability to provide real-time and highly sensitive detection signals (Yuan *et al.,* 2023). Compared to traditional organic dyes, quantum dots offer superior stability and resistance to photobleaching, making them suitable for long-term monitoring of food safety conditions. Their multiplexing capability also allows simultaneous detection of multiple pathogens in a single assay (Chen *et al.,* 2024).

Magnetic Nanoparticles and Nanocomposites

Magnetic nanoparticles, particularly iron oxide (Fe_3O_4) nanoparticles, are widely used in pathogen detection due to their ability to be manipulated by external magnetic fields. This property enables efficient separation, pre-concentration, and purification of target microorganisms from complex food matrices before detection. Magnetic nanoparticle-based biosensors enhance sensitivity by isolating pathogens from interfering substances in food samples, thereby improving detection accuracy (Adampourezare *et al.,* 2023). Recent developments also include magnetic nanocomposites, which combine magnetic cores with conductive or optical materials to improve signal amplification and detection efficiency. These hybrid systems are increasingly used in electrochemical and immunosensing platforms for rapid foodborne pathogen detection (Zheng *et al.,* 2023).

Table 1. Functional classification of nanomaterials in foodborne pathogen detection

Nanomaterials	Representative Materials	Role in Pathogen Detection
Metallic nanoparticles	Gold (AuNPs), Silver (AgNPs), Platinum (PtNPs)	Enable rapid optical/colorimetric readouts and enhanced electrochemical signal transduction for sensitive pathogen detection in food samples
Carbon-based nanomaterials	Graphene, graphene oxide, carbon nanotubes (CNTs)	Enhance biosensor sensitivity by promoting efficient electron transfer and stable bioreceptor immobilization in

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

		complex food matrices
Quantum dots and fluorescent nanomaterials	CdSe QDs, carbon dots, upconversion nanoparticles	Support ultra-sensitive fluorescence sensing and multiplex detection of foodborne pathogens in heterogeneous food systems
Magnetic nanoparticles	Fe_3O_4, $CoFe_2O_4$ nanoparticles	Enable selective isolation and pre-concentration of pathogens from food matrices, improving downstream detection accuracy
Nanocomposites	Hybrid systems (Au–graphene, CNT–Fe_3O_4, polymer-based hybrids)	Integrate optical, electrochemical, and magnetic functions to improve robustness, sensitivity, and real-time detection performance

Nanosensor Platforms for Food Safety Applications

Nanosensor platforms have emerged as advanced analytical tools for rapid and sensitive detection of foodborne pathogens and contaminants. These systems integrate nanomaterials with biological recognition elements such as antibodies, enzymes, aptamers, and nucleic acids to convert biological interactions into measurable electrical, optical, or magnetic signals. Compared with conventional microbiological methods, nanosensors provide faster detection, improved sensitivity, portability, and lower detection limits for real-time food safety monitoring applications (Wang *et al.,* 2023; Tarannum *et al.,* 2024).

Electrochemical Nanosensors

Electrochemical nanosensors are among the most extensively studied biosensing platforms for food safety applications because of their high sensitivity, rapid response, and compatibility with miniaturized devices. These systems detect changes in electrical properties such as current, impedance, or voltage generated during interactions between pathogens and nanomaterial-modified electrodes. Nanomaterials including graphene, carbon nanotubes, metallic nanoparticles, and conductive polymers improve electron transfer efficiency and signal amplification, thereby enhancing analytical performance (Rizzotto *et al.,* 2023). Recent advances in electrochemical biosensors have enabled rapid and selective detection of foodborne pathogens such as Escherichia coli, Salmonella spp., and Listeria monocytogenes in complex food matrices with significantly reduced assay time and low detection limits (Wang *et al.,* 2023). Furthermore, the development of lab-on-a-chip electrochemical biosensors has improved portability and facilitated on-site food pathogen detection (Zolti *et al.*, 2023). Electrochemical aptasensors and genosensors have also demonstrated enhanced specificity and stability through aptamer-based molecular recognition strategies (Nazari-Vanani and Negahdary, 2024).

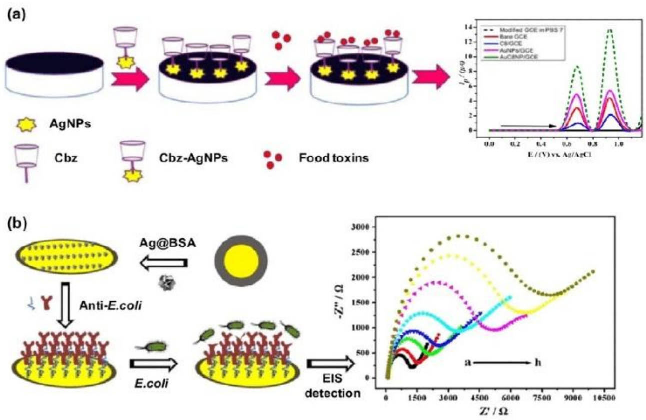

Figure 3. Silver nanoparticle based cbz for detection of food pollutant by electrochemical sensors. It depicts the application

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

of silver nanoparticle-based electrochemical sensors for the detection of food pollutants. The incorporation of silver nanoparticles enhances electrical conductivity, signal amplification, and detection sensitivity, enabling rapid and accurate pollutant analysis in food samples.

Source: Tarannum *et al.* (2024)

Optical and Fluorescence-Based Nanosensors

Optical and fluorescence-based nanosensors detect pathogens through measurable changes in fluorescence intensity, absorbance, Raman scattering, or refractive index. These systems commonly employ quantum dots, noble metal nanoclusters, carbon dots, and plasmonic nanoparticles because of their excellent optical properties, high photostability, and tunable emission characteristics (Pan, 2024). Fluorescence-based nanosensors enable highly sensitive and multiplex detection of microbial contaminants in food systems, while surface-enhanced Raman scattering (SERS) platforms amplify optical signals for trace-level pathogen analysis (Pang *et al.*, 2024). The integration of nanomaterials with optical biosensing technologies has therefore enhanced the sensitivity and accuracy of food contaminant detection systems (Tarannum *et al.,* 2024).

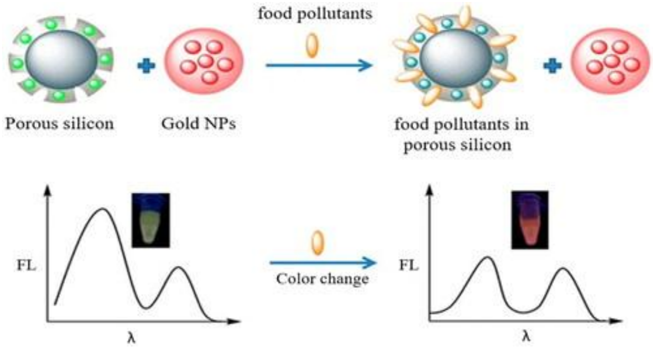

Figure 4. Nanoparticle based fluorescence sensors (‘turn-off’) fluorescence quenching, (‘turn-on’) fluorescence amplification, and (FRET) fluorescence resonance energy transfer for detection of food pollutants.

Source: Tarannum *et al.* (2024)

Colorimetric and Plasmonic Nanosensors

Colorimetric nanosensors provide rapid visual detection of pathogens through observable color changes induced by nanoparticle aggregation or localized surface plasmon resonance effects. Gold and silver nanoparticles are widely employed because of their distinct plasmonic properties and ease of surface functionalization. These sensors are advantageous for field and point-of-care applications because they require minimal instrumentation and allow rapid interpretation of results. Plasmonic nanostructures significantly improve biosensing sensitivity by enhancing optical signal transduction during pathogen-binding events (Anker *et al.,* 2008). Recent developments in nanomaterial-based colorimetric sensing systems have further improved rapid food contaminant detection and real-time monitoring capabilities (Tarannum *et al.*, 2024).

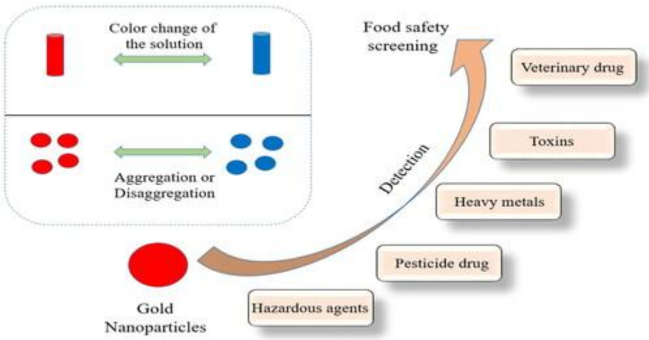

Figure 5. Nanoparticle based colorimetric sensors for food safety screening test significantly shifting the absorption band to red and changing the colour to blue. It demonstrates the working mechanism of nanoparticle-based colorimetric sensors

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

used in food safety screening. Interaction with target contaminants causes a shift in the absorption band from red to blue, producing a visible color change that enables rapid and simple detection.

Source: Tarannum *et al.* (2024)

Magnetic and Immuno-Nanosensors

Magnetic nanosensors utilize magnetic nanoparticles, particularly iron oxide nanoparticles, to isolate and concentrate pathogens from complex food matrices before detection. This pre-concentration process minimizes matrix interference and improves analytical sensitivity. Immuno-nanosensors combine antibodies or aptamers with nanomaterials to achieve selective recognition of target microorganisms. Hybrid magnetic–electrochemical systems have demonstrated enhanced specificity and rapid detection efficiency for foodborne pathogens in contaminated food products (Nazari-Vanani and Negahdary, 2024). The incorporation of multifunctional nanomaterials into biosensing platforms has also improved sensor stability, selectivity, and overall diagnostic performance in food safety applications (Tarannum *et al.,* 2024).

Applications in Food Safety Monitoring

Nanotechnology-based biosensors and nanosensing platforms have gained considerable attention in food safety monitoring because of their rapid response, high sensitivity, portability, and ability to operate in complex food matrices. These systems have been increasingly applied across diverse food categories, including dairy products, meat, seafood, fresh produce, and ready-to-eat foods, while also supporting the development of intelligent packaging and portable detection devices for real-time food quality assessment.

Detection in Dairy Products

Dairy products are highly susceptible to microbial contamination because of their rich nutrient composition and moisture content. Foodborne pathogens such as Listeria monocytogenes, Escherichia coli, and Salmonella spp. are commonly associated with milk, cheese, and yogurt products. Nanobiosensors based on electrochemical, fluorescence, and optical detection mechanisms have demonstrated rapid and highly sensitive detection of microbial contaminants in dairy matrices. Noble metal nanocluster-based optical nanosensors and electrochemical biosensors have shown improved sensitivity and lower detection limits for identifying pathogenic bacteria in milk products, thereby reducing analysis time compared with conventional microbiological methods (Wang *et al.,* 2023; Pang *et al*., 2024). Portable nanosensing systems have also improved on-site monitoring of dairy safety during processing and storage.

Detection in Meat and Poultry

Meat and poultry products are major reservoirs for foodborne pathogens due to contamination during slaughtering, handling, transportation, and storage. Nanotechnology-based detection systems have significantly improved rapid screening of pathogens such as Campylobacter, Salmonella, and Listeria in raw and processed meat products. Electrochemical nanosensors integrated with aptamers and nanomaterial-modified electrodes provide enhanced selectivity and rapid pathogen identification in meat samples (Nazari-Vanani and Negahdary, 2024). In addition, smart nanosensors incorporated into packaging systems enable continuous monitoring of spoilage gases, microbial growth, and freshness indicators during storage and distribution (Heo and Lim, 2024).

Detection in Seafood and Water Samples

Seafood and water samples are highly vulnerable to microbial contamination and toxin accumulation because of environmental exposure and poor storage conditions. Nanomaterial-based optical and electrochemical biosensors have been widely applied for rapid detection of pathogenic microorganisms and contaminants in seafood products. Surface-enhanced Raman scattering (SERS) nanosensors and fluorescence-based systems have demonstrated high sensitivity for detecting bacterial contamination and spoilage indicators in fish and shellfish products (Pan, 2024; Pang *et al.,* 2024). Portable nanosensor platforms have further improved water quality monitoring through rapid on-site detection of microbial pathogens and hazardous contaminants in aquatic environments.

Detection in Fruits, Vegetables, and Ready-to-Eat Foods

Fresh fruits, vegetables, and ready-to-eat foods are increasingly associated with foodborne disease outbreaks due to contamination during harvesting, processing, packaging, and retail handling. Nanosensor technologies

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

have enabled rapid identification of pathogens, pesticide residues, and spoilage biomarkers in fresh produce. Optical nanosensors, colorimetric biosensors, and electrochemical sensing platforms provide sensitive detection of contaminants in minimally processed foods while reducing sample preparation requirements (Tarannum *et al.*, 2024). The integration of nanotechnology into food packaging materials has also improved microbial monitoring and shelf-life assessment in ready-to-eat products (Herrera-Rivera *et al.,* 2024).

Smart Packaging and Real-Time Monitoring Systems

Smart packaging systems represent one of the most significant applications of nanosensor technology in food safety. These systems integrate nanosensors, gas indicators, biosensors, and intelligent monitoring devices into food packaging materials to provide real-time information about food quality, freshness, and microbial contamination. Intelligent packaging technologies can detect changes in oxygen concentration, carbon dioxide levels, pH, temperature, and volatile spoilage compounds during storage (Chiu *et al.,* 2024). Recent developments in nano-enabled smart packaging have improved shelf-life monitoring, traceability, and contamination detection in packaged foods (Bhatlawande *et al.,* 2024). Gas sensors and spoilage indicators incorporated into packaging films, labels, and sachets further support rapid assessment of food deterioration and microbial growth (Heo and Lim, 2024).

Portable and Point-of-Care Detection Devices

Portable and point-of-care nanosensing devices have transformed food safety diagnostics by enabling rapid, on-site detection of pathogens without the need for sophisticated laboratory infrastructure. Lab-on-a-chip biosensors, smartphone-integrated nanosensors, paper-based analytical devices, and portable electrochemical systems provide real-time detection of food contaminants in field conditions. These technologies are particularly valuable in food processing facilities, supply chains, and resource-limited environments because they reduce assay time, operational cost, and dependence on centralized laboratories (Zolti *et al.*, 2023). Battery-free and autonomous smart sensing systems have further enhanced real-time monitoring capabilities through wireless sensing and integrated food quality assessment technologies (Douaki *et al.*, 2025).

Table 2. Applications of nanosensor platforms in food safety monitoring

Food Category	**Common target**	**Nanosensor Platform**	**Monitoring function**
Dairy products	Listeria monocytogenes, Escherichia coli, Salmonella spp.	Electrochemical and optical nanosensors	Detection of microbial contamination in milk and dairy products
Meat and poultry	Campylobacter spp., Salmonella spp., Listeria spp.	Electrochemical aptasensors and smart packaging sensors	Monitoring of pathogen contamination and spoilage
Seafood and water samples	Vibrio species, microbial toxins	Fluorescence-based and SERS nanosensors	Detection of microbial contaminants and spoilage indicators
Fruits and vegetables	Pathogenic bacteria, pesticide residues	Colorimetric and optical nanosensors	Detection of contaminants on fresh produce
Ready-to-eat foods	Microbial contaminants and spoilage organisms	Electrochemical and immuno-nanosensors	Monitoring of microbial safety in processed foods
Smart packaging	Spoilage gases, pH changes, microbial metabolites	Embedded nanosensors and gas sensors	Real-time monitoring of food freshness and storage

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

systems			conditions
Portable detection devices	Foodborne pathogens and contaminants	Lab-on-a-chip and smartphone-based nanosensors	On-site and rapid food safety analysis

Advantages, Limitations, and Safety Concerns

Nanotechnology-based biosensors have improved food safety monitoring through rapid detection, high analytical sensitivity, and low detection limits compared with conventional microbiological methods. The unique electrical, optical, and catalytic properties of nanomaterials enhance signal amplification and improve detection efficiency for foodborne pathogens in complex food matrices (Wang *et al.*, 2023). In addition, nanosensor platforms support multiplex detection and real-time monitoring of multiple contaminants simultaneously, while portable and smart packaging systems enable continuous assessment of food freshness and microbial spoilage during storage and transportation (Zolti *et al.*, 2023; Heo and Lim, 2024).

Despite these advantages, several technical and safety concerns limit large-scale application. Certain nanomaterials may exhibit cytotoxicity, oxidative stress induction, and environmental persistence, raising concerns regarding their potential impact on human health and ecosystems (Yaqoob *et al.,* 2020). Sensor stability, reproducibility, and scalability also remain significant challenges because variations in nanomaterial synthesis and surface functionalization can affect analytical performance and consistency (Rizzotto *et al.,* 2023). Furthermore, commercialization of nanosensor technologies is constrained by high production costs, limited standardization protocols, and the absence of harmonized regulatory frameworks for nanomaterial-based food safety systems (Tarannum *et al.*, 2024). Continued interdisciplinary research and regulatory development are therefore necessary to ensure the safe and reliable integration of nanotechnology into food safety monitoring applications.

Emerging Trends and Future Perspectives

Recent advances in nanosensor technology are driving the development of intelligent and highly integrated food safety monitoring systems. Artificial intelligence (AI)-assisted biosensors and smartphone-integrated nanosensing platforms are increasingly being explored for rapid signal interpretation, automated pathogen analysis, and real-time food quality assessment. The incorporation of AI algorithms into biosensing systems improves analytical accuracy, data processing efficiency, and predictive monitoring of foodborne contaminants, while smartphone-based devices enhance portability and field applicability for point-of-care food diagnostics (Banicod *et al.,* 2025). Furthermore, intelligent biosensing platforms integrating advanced nanomaterials and automated sensing technologies are expected to improve future foodborne pathogen surveillance and healthcare applications (Assudani *et al.,* 2026). Lab-on-a-chip and microfluidic technologies are also transforming food safety diagnostics by enabling miniaturized, automated, and multiplex pathogen detection systems. These platforms integrate sample preparation, separation, and biosensing processes into compact devices with reduced reagent consumption and shorter detection time. Recent microfluidic biosensors have demonstrated improved sensitivity and rapid detection of foodborne pathogenic bacteria in complex food matrices, making them promising tools for real-time and on-site food safety monitoring (Zhang *et al.,* 2025). In addition, biosensors for detecting food contaminants continue to evolve toward portable, user-friendly, and high-throughput analytical systems for industrial applications (Inês and Cosme, 2025).

Sustainability has also become an important focus in nanotechnology research, leading to increasing interest in biodegradable and eco-friendly nanomaterials for food packaging and sensing applications. Biodegradable nanomaterials derived from renewable polymers such as starch, cellulose, and chitosan offer improved biocompatibility and reduced environmental impact compared with conventional metallic nanoparticles (Mishra *et al.,* 2024). Nevertheless, metallic and metal-decorated nanomaterials continue to attract attention because of their enhanced catalytic, optical, and antimicrobial properties in biosensing applications (Yaqoob *et al*., 2020). Another emerging innovation is the integration of CRISPR/Cas systems with nanobiosensors for highly selective and rapid detection

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

of foodborne pathogens. CRISPR-based biosensors combined with electrochemical and fluorescence transduction mechanisms have demonstrated exceptional specificity, sensitivity, and rapid nucleic acid detection capabilities in food safety diagnostics (Xie *et al*., 2024). Future industrial and commercial adoption of nanosensor technologies will depend on improvements in cost-effectiveness, large-scale manufacturing, sensor stability, and regulatory standardization. Advances in smart sensing systems, portable analytical devices, and intelligent packaging technologies are expected to accelerate commercialization and strengthen real-time food safety monitoring across global food supply chains.

Conclusion

Nanotechnology has emerged as a transformative approach in food safety monitoring through the development of highly sensitive, rapid, and portable biosensing systems for detecting foodborne pathogens and contaminants. The integration of advanced nanomaterials with electrochemical, optical, magnetic, and fluorescence-based sensing platforms has significantly improved analytical performance, enabling real-time monitoring across diverse food matrices including dairy products, meat, seafood, fresh produce, and ready-to-eat foods. Emerging innovations such as smart packaging systems, lab-on-a-chip devices, AI-assisted biosensors, and CRISPR-based nanosensing technologies further demonstrate the growing potential of nano-enabled diagnostics in modern food safety management.

Despite these advancements, challenges related to nanomaterial toxicity, environmental impact, sensor stability, scalability, and regulatory standardization continue to limit large-scale industrial adoption. Addressing these limitations will require interdisciplinary collaboration, improved safety assessment strategies, and the development of cost-effective and sustainable nanomaterials. Continued progress in intelligent sensing technologies, portable diagnostic devices, and automated monitoring systems is expected to accelerate commercialization and strengthen global food safety surveillance. Overall, nanotechnology-based biosensors hold substantial promise for enhancing rapid pathogen detection, improving food quality assurance, and supporting safer and more sustainable food systems worldwide.

Acknowledgement

We thank all the researchers who contributed to the success of this research work.

Conflict of Interest

The authors declared that there are no conflicts of interest.

Funding

No funding was received for this research work.

Significance of the Study

The significance of this study lies in its comprehensive evaluation of how nanotechnology particularly nanosensors and nanomaterials can revolutionize the detection of foodborne pathogens, thereby greatly enhancing food safety. By highlighting the sensitivity, specificity, and rapid response capabilities of nanoscale devices, this review underscores the potential for early and accurate identification of contaminants in the food supply chain. Such advancements can lead to faster outbreak prevention, reduced public health risks, and improved consumer confidence in food products. Moreover, the study provides valuable insights for researchers, industry stakeholders, and policy makers aiming to implement cutting-edge technologies that ensure food quality and safety in an increasingly complex global food system.

References

1. Adampourezare, M., Hasanzadeh, M., Hoseinpourefeizi, M.-A. and Seidi, F. (2023). Iron/iron oxide-based magneto-electrochemical biosensors for ensuring food safety: Recent progress

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

and challenges. RSC Advances. 13:12760–12780. https://doi.org/10.1039/D2RA07415J

2. Anker, J., Hall, W., Lyandres, O. *et al.* (2008). Biosensing with plasmonic nanosensors. Nature Mater. 7: 442–453. https://doi.org/10.1038/nmat2162
3. Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z. and Younis, K. (2022). Application of nanotechnology in food packaging: Pros and Cons. Journal of Agriculture and Food Research. 7(9):100270. DOI:10.1016/j.jafr.2022.100270
4. Assudani, P. J., P, B., A, A. L., George, G., Avthankar, A., Tiwari, A., Bhaiyya, M. and Kulkarni, M. B. (2026). Biosensing technologies for foodborne pathogen detection and healthcare: principles, emerging materials, and intelligent platforms. Mikrochimica acta, 193(4), 231. https://doi.org/10.1007/s00604-026-07976-x
5. Banicod, R. J. S., Tabassum, N., Jo, D.-M., Javaid, A., Kim, Y.-M. and Khan, F. (2025). Integration of Artificial Intelligence in Biosensors for Enhanced Detection of Foodborne Pathogens. Biosensors. 15(10): 690. https://doi.org/10.3390/bios15100690
6. Bhatlawande, A.R., Ghatge, P.U., Shinde, G.U. *et al.* (2024). Unlocking the future of smart food packaging: biosensors, IoT, and nano materials. Food Sci Biotechnol. 33:1075–1091. https://doi.org/10.1007/s10068-023-01486-9
7. Bobrinetskiy, I., Radovic, M., Rizzotto, F., Vizzini, P., Jaric, S., Pavlovic, Z. *et al*. (2021). Advances in Nanomaterials-Based Electrochemical Biosensors for Foodborne Pathogen Detection. Nanomaterials (Basel, Switzerland). 11(10):2700. https://doi.org/10.3390/nano11102700
8. Chen, MX., Cheng, JH., Ma, J. *et al.* (2024). Advancing Aquatic Food Safety Detection Using Highly Sensitive Graphene Oxide and Reduced Graphene Oxide (GO/r-GO) Fluorescent Sensors. Food Eng Rev. 16: 618–634. https://doi.org/10.1007/s12393-024-09375-5
9. Chiu, I., Ye, H., Aayush, K. and Yang, T. (2024). Intelligent food packaging for smart sensing of food safety. Advances in food and nutrition research. 111: 215–259. https://doi.org/10.1016/bs.afnr.2024.06.006
10. Douaki, A., Ahmed, M., Longo, E., Windisch, G., Riaz, R., Inam, S. *et al.* (2025). Battery-Free, Stretchable, and Autonomous Smart Packaging. Advanced science (Weinheim, Baden-Wurttemberg, Germany). 12(22): e2417539. https://doi.org/10.1002/advs.202417539
11. Heo, W. and Lim, S. (2024). A Review on Gas Indicators and Sensors for Smart Food Packaging. Foods. 13(19): 3047. https://doi.org/10.3390/foods13193047
12. Inbaraj, B. S. and Chen, B. H. (2016). Nanomaterial-based sensors for detection of foodborne bacterial pathogens and toxins as well as pork adulteration in meat products. Journal of food and drug analysis. 24(1): 15–28. https://doi.org/10.1016/j.jfda.2015.05.001
13. Inês, A. and Cosme, F. (2025). Biosensors for Detecting Food Contaminants—An Overview. Processes. 13(2): 380. https://doi.org/10.3390/pr13020380
14. Jangid, H., Panchpuri, M., Dutta, J., Joshi, H. C., Paul, M., Karnwal, A. *et al.* (2025). Nanoparticle-based detection of foodborne pathogens: Addressing matrix challenges, advances, and future perspectives in food safety. Food chemistry: X, 29:102696. https://doi.org/10.1016/j.fochx.2025.102696
15. Justino, C. I. L., Duarte, A. C. and Rocha-Santos, T. A. P. (2016). Critical overview on the application of sensors and biosensors for clinical analysis. Trends in analytical chemistry : TRAC. 85:36–60. https://doi.org/10.1016/j.trac.2016.04.004
16. Khan, M. A. (2018). The Role of Nanotechnology in Food Safety: Current Status and Future Perspective. Journal of Nanoscience and Nanotechnology. 18(12). DOI:10.1166/jnn.2018.16395
17. Mishra, M., Mittal, A , Negi, G. and Singh, P. (2024). Biodegradable Nanomaterials for Sustainable Food Packaging Applications. E3S Web of Conferences. 547. DOI:10.1051/e3sconf/202454701014
18. Nazari-Vanani, R. and Negahdary, M. (2024). Recent advances in electrochemical aptasensors and genosensors for the detection of pathogens. Environmental Research. 243:117850. https://doi.org/10.1016/j.envres.2023.117850
19. Pan, M. (2024). Nanomaterial-Based Optical Detection of Food Contaminants. Foods. 13(4):557. https://doi.org/10.3390/foods13040557
20. Pang, L., Pi, X., Zhao, Q., Man, C., Yang, X. and Jiang, Y. (2024). Optical nanosensors based on noble metal nanoclusters for detecting food contaminants: A review. Comprehensive Reviews in Food Science and Food Safety. 23(1):e13295. https://doi.org/10.1111/1541-4337.13295

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

21. Park, S.-H. and You, Y. (2024). Gold Nanoparticle-Based Colorimetric Biosensing for Foodborne Pathogen Detection. Foods. 13(1): 95. https://doi.org/10.3390/foods13010095
22. Poeta, E., Liboà, A., Mistrali, S., Núñez-Carmona, E. and Sberveglieri, V. (2023). Nanotechnology and E-Sensing for Food Chain Quality and Safety. Sensors. 23(20):8429. https://doi.org/10.3390/s23208429
23. Rizzotto, F., Khalife, M., Hou, Y., Chaix, C., Lagarde, F., Scaramozzino, N. and Vidic, J. (2023). Recent Advances in Electrochemical Biosensors for Food Control. Micromachines. 14(7): 1412. https://doi.org/10.3390/mi14071412
24. Rizzotto, F., Khalife, M., Hou, Y., Chaix, C., Lagarde, F., Scaramozzino, N. and Vidic, J. (2023). Recent Advances in Electrochemical Biosensors for Food Control. Micromachines. 14(7): 1412. https://doi.org/10.3390/mi14071412
25. Shruti, A., Bage, N. and Kar, P. (2024). Nanomaterials-based sensors for analysis of food safety. Food Chemistry. 433: 137284. https://doi.org/10.1016/j.foodchem.2023.137284
26. Singh, A., Poshtiban, S. and Evoy, S. (2013). Recent advances in bacteriophage based biosensors for food-borne pathogen detection. Sensors (Basel, Switzerland). 13(2):1763–1786. https://doi.org/10.3390/s130201763
27. Singh, R. P. (2019). Potential of Biogenic Plant-Mediated Iron and Iron Oxide Nanoparticles and Their Utility . Plant Nanobionics. 77-113. DOI:10.1007/978-3-030-16379-2_4
28. Subramaniam, T. and Velu, G. (2024). Critical review on multifunctional nanostructure-based electrochemical immunosensors for foodborne pathogens. ACS Food Science & Technology. 4(10): 2244–2257. https://doi.org/10.1021/acsfoodscitech.3c00624
29. Tarannum, N., Gautam, A., Chauhan, T. and Kumar, D. (2024). Nanomaterial based sensors for detection of food contaminants: a prospect. Sensing Technology. 2(1). https://doi.org/10.1080/28361466.2024.2373196
30. Velusamy, V., Arshak, K., Korostynska, O., Oliwa, K. and Adley, C. (2010). An overview of foodborne pathogen detection: in the perspective of biosensors. Biotechnology advances. 28(2):232–254. https://doi.org/10.1016/j.biotechadv.2009.12.004
31. Wang, B., Wang, H., Lu, X., Zheng, X. and Yang, Z. (2023). Recent Advances in Electrochemical Biosensors for the Detection of Foodborne Pathogens: Current Perspective and Challenges. Foods. 12(14): 2795. https://doi.org/10.3390/foods12142795
32. World Health Organization. (2024). Food safety. https://www.who.int/news-room/fact-sheets/detail/food-safety
33. World Health Organization. (2024). Food safety. https://www.who.int/news-room/fact-sheets/detail/food-safety
34. Xie, S., Yue, Y. and Yang, F. (2024). Recent Advances in CRISPR/Cas System-Based Biosensors for the Detection of Foodborne Pathogenic Microorganisms. Micromachines. 15(11): 1329. https://doi.org/10.3390/mi15111329
35. Yaqoob, A., Ahmad, H., Parveen, T., Ahmad, A., Oves, M., Ismail, I. *et al.* (2020) Recent Advances in Metal Decorated Nanomaterials and Their Various Biological Applications: A Review. Front. Chem. 8:341. doi: 10.3389/fchem.2020.00341
36. Yuan, H., Li, Y., Lv, J., An, Y., Guan, D., Liu, J., Tu, C., Wang, X. and Zhou, H. (2023). Recent Advances in Fluorescent Nanoprobes for Food Safety Detection. Molecules. 28(14):5604. https://doi.org/10.3390/molecules28145604
37. Zhang, J., Ma, C., Du, Y., Huang, J. and Xue, L. (2025). Microfluidic biosensors for rapid detection of foodborne pathogenic bacteria: recent advances and future perspectives. Frontiers in chemistry. 13: 1536928. https://doi.org/10.3389/fchem.2025.1536928
38. Zheng, L., Jin, W., Xiong, K., *et al.* (2023). Nanomaterial-based biosensors for detection of foodborne bacteria: A review. Analyst. 148:5790–5804. https://doi.org/10.1039/D3AN01554H
39. Zolti, O., Suganthan, B. and Ramasamy, R. P. (2023). Lab-on-a-Chip Electrochemical Biosensors for Foodborne Pathogen Detection: A Review of Common Standards and Recent Progress. Biosensors. 13(2):215. https://doi.org/10.3390/bios13020215

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013

Citation: Okunbi Favour Onasokhare , Okeke Calistus Obinna , Ahinful Isaac Anku , Moses Adondua Abah , Micheal Oladosu Abimbola and Ochuele Dominic Agida (2026) Applications of Nanotechnology in Food Safety: A Review of Nanosensors and Nanomaterials for Foodborne Pathogen Detection, J. Nutrition and Human Health Advances, 2(4): dx.doi.org/JNHHA/PP.0013