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Review Article

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Unveiling the Nano World: Expanding Food Safety Monitoring Through Nano-biosensor Technology

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Abstract

The potential of nano-biosensor technology for improving food safety monitoring is investigated in this research. Nano-biosensors have several advantages, including rapid detection, high sensitivity, real-time monitoring, and adaptability in detecting food borne risks. They have been used successfully in food testing to detect pathogens, allergies, poisons, and chemical pollutants. However, issues with nanoparticle leakage and migration, as well as potential toxicity, have been resolved. Future developments are predicted to be driven by advancements in nanomaterials and integration with technology such as artificial intelligence. While nano-biosensors have the potential to revolutionize food safety monitoring, a thorough awareness of dangers is required for appropriate application. Continued advancements in nano-biosensor development will almost certainly result in even more effective platforms, ensuring safer food consumption and public health.

Keywords

Rapid detection, High sensitivity, Adaptability, Food testing, Advancements

Introduction

Nanoparticles are the building blocks of nanotechnology. Their versatility, unique properties, dynamic size, and a large surface area relative to their compact volume have made them useful in a wide range of applications, particularly necessitated in the modern world made of incorporations of nanotechnology. It is a particle having a nominal diameter of less than 100 nm and such physio chemical features that precludes any semblance to sub-micron/micron particles. Nanotubes, nano-beads, nano rods, and nano wires are examples of nanometer-scale structures known as nanomaterials. Bactericides, nano fungicides, nano fertilizers, and biosensors are generated in the food and agricultural industries employing nanometer-sized synthetic and biological chemicals derived from classic physical and chemical processes as well as current green synthesis [1]. The use of biosensors has become more important in drug research, biomedicine, food safety standards, defense, security, and environmental monitoring. This resulted in the development of precise and efficient analytical equipment that used a biological sensing element as a biosensor [2].

The term "biosensor" refers to a powerful and novel analytical equipment with a biological sensing element that has a wide range of applications including drug discovery, diagnostics, biomedicine, food safety and processing, environmental monitoring, defense, and security. Clark and Lyons [3] invented the first biosensor for assessment of assessment in biological samples. This biosensor employed an electrochemical detection technique for either oxygen or hydrogen peroxide [2].

A nano-biosensor is a type of biosensor that employs nanomaterials such as nanoparticles and nano-structures. Nano-biosensors are more reliable and sensitive in bio sensing than conventional sensors due to the unique properties of nanomaterials, such as good conductivity and physio chemical, electrochemical, optical, magnetic, and mechanical properties, by amplifying signals and providing new signal transduction mechanisms, quantum dots, nanotube, nano wires, magnetic and other nanoparticles improve sensitivity and lower detection limits for food contaminants, pesticides, food borne pathogens, toxins, and plant metabolites [4] every year, food infected with pathogenic germs kills 420,000 people and sickens 600 million people worldwide. According to the World Health Organization (WHO), food borne infections account for approximately 30% of fatalities among children under the age of five [5].

Recognized microbial culture analysis can aid in the identification of bacteria, although the method is time-consuming and occasionally yields ambiguous results. Compared to standard methods, nanotechnology-based methods can be used to eradicate pathogenic bacteria. This method is extremely sensitive and shows undoubtedly its ability to detect bacteria in composite food matrices.

Nano-biosensors: An Overview

Nano-biosensors comprise a biological molecule capable of detecting analyte/target molecules when bound to a receptor molecule and a transducer that converts the recognition event into readable signals capable of detecting analyte molecules, understanding complex and dynamic biological events has been aided by the creation of large surface area nanoparticles and their incorporation into biosensors [6].

Electrochemical, optical, and piezoelectric biosensors are the most suited and widely used. They all work on the same principle: they recognize the stimulus produced by the interaction of the analyte and the biosensor element and convert it into a detectable signal (Table 1 and figure 1) [7].

Types of biosensors

Enzyme based biosensors

A freshness assessment approach based on biogenic amines is commonly employed in food analysis, there have been numerous papers on both multi-enzyme and single-system techniques. Typically, such tests are performed to investigate sauerkraut, salmon, and other comparable items [8, 9], use of enzyme-based nano-biosensors for the analysis of biologic amines ,which are important indicators for food freshness, these biosensors are applied to analyze food products like sauerkraut and fish enzyme based biosensors are used as the bio recognition elements as a bio-recognition elements to selectively detect and quantify specific biogenic amines [9].

Electrode based biosensors

Research focuses on electrode-based biosensors, especially screen-printed biosensors, exploring different techniques for immobilizing the bio-sensing component. The basic configurations of biosensors are also explored using screen printing technology, one of the main problems is the ingestion of marine toxins of low molecular weight from both terrestrial foods and seafood, leading to various forms of poisoning. These tox-

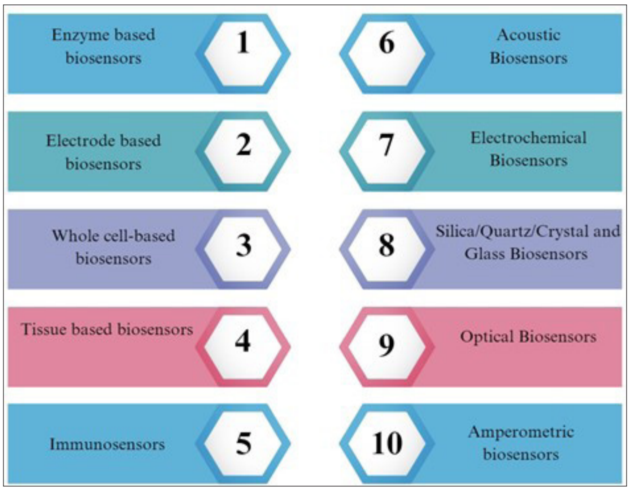

Figure 1: Several types of biosensors.

Table 1: Type of nano-biosensors and their mechanism.

Type of biosensor	Mechanism	Application
Optical biosensors	Optical biosensor mechanism relies on the detection of changes in specific light wavelengths.	Using this method, highly sensitive and portable. Cytochrome P450 enzyme biosensors were produced.
Biosensors fabricated from silicate-based and crystalline materials	Optical transparency facilitates stimulation and illumination passage that enhances biocompatibility for functionalization and cell safety (though not consistently).	Cancer therapy, bio-imaging, and bio-sensing.
Biosensors contrived from fluorescent nano particles, quantum dots	Semiconductor quantum dots exhibit size- and composition-dependent fluorescence properties, making them well-suited for highly sensitive and multi-target imaging using a single excitation wavelength.	Quantum dots water solubility makes them ideal for biological applications such as imaging, sensing, and bio molecular conjugation.
Microbial biosensors	Microbial sensors employ synthetic biology and genetic/protein engineering techniques.	Bioremediation. Newly developed microbial fuel-based biosensors can monitor biochemical oxygen demand and toxicity in the environment. Detection of pesticides and heavy metals.

ins include domoic acid, okadaic acid, tetrodotoxin, and breve toxin. To address this issue, the study explores the development of general disposable immune sensors using a screen-printed sensor. These immune sensors aim to detect trace amounts of marine toxins efficiently and accurately in food samples and achieve detection limits in parts per billion [10].

Whole-cell-based biosensors

Researchers have been studying the use of genetically modified yeast or bacterial cells harboring the luc or lux gene operon for several years. Green fluorescent protein and other luminous proteins are expressed in these transformed cells, many articles cover the basics of this approach, focusing on topics like hydrocarbon stress, pollution, and other signaling systems like alkaline phosphatase, insect luciferase, bacterial luciferase, b-galactosidase, and green fluorescent protein. Biosensors can be customized to detect specific analytes or signal a general stress response, such as gene toxicity or toxicity detection, by using specific cell types and genetic engineering procedures. The literature contains numerous examples of biosensors, including those based on the fusion of the lux operon with fatty acid production and those sensitive to various stressors such as membrane, DNA, or oxidative damage [9].

Tissue/whole organism-based biosensor

Biosensors based on antibodies and receptors have received a lot of attention. One example is the detection of 2,4-dinitrophenol as a model dioxin analyte utilizing a quartz crystal micro balance as a transducer, with a detection limit of 0.01 ng/ml. Another study looked at how organic solvents affected a similar biosensor setup. Furthermore, a simazine-specific potentiometric biosensor was created and effectively applied to the measurement of various food products such as milk, cucumbers, tomatoes, and wheat extracts. Another novel approach was the invention of an isoproterenol flow-through immune sensor, which was used in the examination of agricultural foods and the investigation of well water [9].

Acoustic biosensors

The piezoelectric properties of quartz crystals can be affected by mass changes on the surface of the crystal, this phenomenon has been effectively exploited in the development of acoustic biosensors. In practical applications, the surface of the crystal can be modified by adding recognition elements such as antibodies that can selectively bind to the target analyte. This approach makes it possible to identify and analyze specific substances using the principles of acoustic biosensing.

Immunosensors

Immunosensors rely on the interactions between antibodies and antigens, immunological tests typically employ labels such as enzymes, antibodies, or fluorescent markers to detect an immune response. Immunoassays, on the other hand, when combined with biosensor platforms, provide a path to rapid and accurate quantitative assessment of target analytes. This combination of Immunoassays format with biosensor technology allows for fast and accurate analysis, allowing for the efficient identification and quantification of required chemicals [9].

Electrochemical biosensors

These biosensors detect the presence of electroactive substances consumed or produced by biological components including cells and enzymes. The signals generated can be sent using a variety of methods, which are loosely classified as amperometry biosensors and potentiometric biosensors. These technologies enable biosensors to efficiently convert biological activity into detectable electrical signals, enabling precise detection and analysis of target analytes [11].

Optical/visual biosensors

Changes in a certain wavelength of light are detected by optical/visual biosensors, making them appropriate for biomedical and environmental monitoring. To increase the performance of these biosensors, advances centered on simplicity and high sensitivity are required. One interesting option is to incorporate nanoparticles made of materials such as gold, silica, quartz, glass, or carbon into micro fabrication processes, thereby creating a novel bio-sensing tool. This method has been used successfully to create very sensitive and portable cytochrome P450 enzyme biosensors. Fiber-optic chemical biosensors have also found use in biomedicine, drug development, and bio-sensing. Hydro gels are now employed as an immobilization material for element detection, with benefits including element capture, improved analyte detection, controlled release, and DNA protection, in addition, the optical transparency of the hydro gels facilitates convenient visual detection [7].

Silica/quartz/crystal and glass biosensors

Because of their remarkable qualities, recent breakthroughs in biosensor research have resulted in the use of silica, quartz, crystal, and glass materials. Silicon nanoparticles have enormous promise for technological advancement in biosensor applications, owing to their biocompatibility, abundance, and exceptional electrical, optical, and mechanical capabilities. Furthermore, silicon nanoparticles have the advantage of being non-toxic, which is a vital criterion for biomedical and biological applications [2].

Amperometric biosensors

The use of amperometric biosensors for signal transduction has been extensively documented, particularly through an electrochemical approach. These biosensors have been widely reported and have gained considerable popularity in the field. They are available in both a web format, which allows multiple measurements, and in "single use" disposable formats, commercially available sensors are valuable tools for monitoring various target analytes [8, 9].

Advantages of Nano-biosensor Technology in Food Safety Monitoring

In recent years, much has been invested in the development and research of biosensors to detect food pathogens. The sensitivity of the biosensor depends on the characteristics of the transducer and the bio-detection element. Biosensor technology has the potential to increase sensitivity and specificity, accelerate detection, enable high-throughput analysis, and can be used to monitor critical control points in food production [8].

Highly efficient

They can work even at the atomic scale with very high efficiency reaction time [10, 12].

Enhanced sensitivity

Food products are safe because food pollutants and pathogens can be detected by nano-biosensors at incredibly low concentrations [13, 14].

Rapid detection

They yield speedier results, enabling more rapid quality control and lowering the possibility that tainted or defective food would be consumed by customers [13, 14].

Portability

Field testing and real-time food quality monitoring are made possible by the use of miniature nano-biosensors [13, 14].

Specificity

By focusing on certain chemicals, nano-biosensors can reduce false positive findings and enhance the precision of food testing [13, 14].

Cost-effectiveness

Nano-biosensors might be more economical for routine food testing due to their small size and lower reagent requirements [13, 14].

Applications

Recently, nanotechnology-based control and prevention measures have been developed to ensure food safety and quality, and some of them are still under development. Food spoilage falls into three main categories: toxins, microbial sources, and chemicals. Clinical reports have identified a total of 160 food allergies. Around 90% of patients are allergic to one of eight major allergens: egg, milk, shellfish, fish, peanuts, tree nuts, soybeans, and wheat. WHO recognizes the majority of dietary allergies. Despite the fact that more than 160 foods can cause allergic responses in people with food allergies, these eight major food allergens are the most common and should be labelled separately on food packages. Therefore, careful monitoring of foods for such nanotechnology-induced interference can help overcome the pitfalls faced by conventional food contaminant detection methods [15].

Nano-sensors have been created to detect food-borne infections, spoilage bacteria, poisons, allergies, pollutants, and highly sensitive food additives in real time. It's remarkable that even a single microbe pathogen in food may be carefully recorded (Figure 2).

Toxin detection

It was stated that a biosensor for *in situ* detection of mycotoxins and their content in food had been developed. Because of their distinct properties such as high sensitivity and selectivity, feasibility, speed, and dependability, they are ideal candidates for quality monitoring in food processing. Noble metal nanoparticles having sharp edges or corners, such as gold, have been frequently used as sensor components. These features, which are most noticeable in octahedral gold colloidosomes and nanoparticles, boost surface area while also providing biocompatibility, mechanical stability, and electron transfer capability. They could also be good candidates for strong inter particle plasmonic coupling. The addition of aptamers boosted the sensor's detecting capability even further, aptamers are DNA/RNA oligonucleotides with high affinity, specificity, targeting variety, increased stability, and minimal toxicity and immunogenicity.

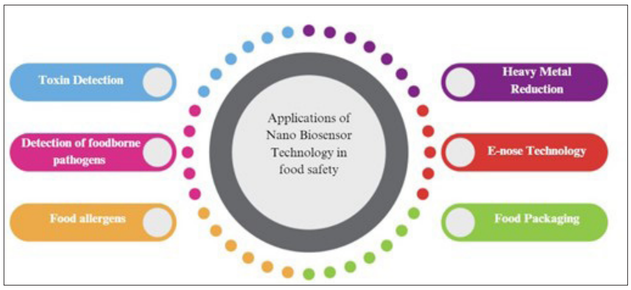

Figure 2: Applications of nano-biosensors in food safety.

A strip-based economical nano-biosensor was designed to assess mycotoxins *in situ* at various phases. As a result, a nanocomposite-based Cd Te quantum dot-carbon nanotube sensor with exceptionally high sensitivity was created to quantify aflatoxin concentration down to a detection limit of 0.3 pg/ml. An acutely sensitive nano-biosensor for the detection of the tyrosinase enzyme produced by poisonous fungi has been extended for the early detection of small amounts of mycotoxins exceeding the European Commission standard of 4 g/kg. A novel electrochemical aptasensor for aflatoxin M1 detection was also disclosed. The detection current is connected to a conformational shift in the hairpin structure of the M1 aptamer, with a detection limit of 0.9 ng/L [15].

Detection of food borne bacterial pathogens

Despite recent advances in food safety, the prevalence of food borne illness remains a serious economic and clinical issue. Food borne diseases are typically caused by organisms or their antigens, such as bacteria, viruses, fungi, and parasites, when contaminated food or water is consumed. A huge number of food contaminants that cause food borne illness have been found and must be eradicated using acceptable scientific approaches to protect consumers. In this discipline, developing an optimal detection method has been a big scientific difficulty. A specific pathogen may be recognized from a food sample or food sample, which would be great. Traditional culture-based techniques often include an enrichment step in which a small number of target cells are encouraged to proliferate to a quantifiable quantity. This, however, necessitates an additional 1-2 days of analysis time. Traditional approaches take a long time because they necessitate substantial substrate preparation, plate inoculation, and colony counting. Furthermore, their limited sensitivity can be a limitation, particularly when it comes to false negative results. Traditional treatments, on the other hand, are typically inexpensive and straightforward. Biochemical and immunological assays have also been used to identify bacterial pathogens for than a century. Nanobiosensors that can be used for food borne pathogens are aptamer based nano-biosensors, such as fluorescent ones. Another example is graphene oxide-modified gold nanoparticles, enhanced with aptamers; for detection of *Escherichia coli* [16].

Food allergens

Nanomaterial-enhanced devices provide precise, dependable, and very sensitive methods for detecting food allergies. Peanut, gluten, seafood, and sesame allergies can all be detected using nanomaterial technology. We also investigate dust mite allergens that can be detected using nanomaterials, as they are linked to food allergies. Peanut allergy is on the rise in North America, affecting approximately 1% of the population. Ara h 1, the primary peanut allergen, is a 7S globulin with a vicilin-like structure. It is regarded as a significant allergen due to its resistance to digestion and thermal stability in food, the environment, and the intestine. Fortunately, IgE antibodies recognize it, and it can be used as a marker to identify peanuts in foods and products. Gold coating and carbon screen-printed electrodes are used in a nanomaterial biosensor that can detect ara h 1 in foods electrochemical. Monoclonal antibodies labeled with alkaline phosphatase bind to ara h 1 and are subsequently detected by an immunosensor using anodic voltammetry scanning to detect metal precipitation catalyzed by the alkaline phosphatase enzyme. With a detection range of 12.6 to 2000 ng/ml and a lower limit of 3.8 ng/ml, the detection time is 3:50 hours. With a recovery rate of 96.6%, it detects ara h 1 in complex foods such as chocolate and cookies with up to 0.1% peanut content [17].

Deduction of heavy metal pollutants from environment

Heavy metals are a major source of environmental pollution due to their range and non-biodegradability in the environment. Arsenic, lead, mercury, and cadmium are the most toxic heavy metals that can cause various threats to human health. New biosensors incorporating nanotechnology strategies have been developed to detect these heavy metals in various environmental and biological samples [18].

The use of aptamers and whole cells as two important bio-functional nanomaterials is important in the design of bio receptors for heavy metal diagnostic biosensors. The use of hybridized nanomaterials with a specific physicochemical function in the presence of a suitable sensor can improve the detection ability to create an integrated sensor system. Recent studies have shown that carbon nanotube, optical, electrochemical, and field-effect transistor sensors, and alkaline phosphatase cantilever nano-biosensors can be used to detect heavy metals in various environmental samples [19].

The use of nano-structured sensors and nanomaterials improved the detection limit and linear dynamic range, which are important features of improved biosensors for primary toxic metals [20].

Nano-biosensors in E-nose technology

The most common causes of food and food odor are pathogenic microorganisms. The human nose can detect odor over a specific threshold; however, it is not always beneficial for food detection. As a result, rapid odor assessment at an early stage should be most beneficial; in this regard, nano-biosensors with great sensitivity can be utilized to detect these odors. Because nanoparticles have a bigger surface area than macroscopic particles, they absorb gas more effectively on the sensor's surface. The electronic nose (E-nose) is used to detect various types of volatile organic compounds in food to assure good quality, homogeneity, and consistency of raw materials during mixing, cooking, and final product packaging, and storage. Gas sensors made of nanoparticles, such as zinc oxide nano wires, are used to detect gas. Because the amount of ethylene gas found in fruits and vegetables is growing, tungsten oxide-tin oxide nanocomposites have been developed to detect ethylene [4].

Nano-biosensors in food packaging

Food packaging usually aids in the preservation of nutritional value and the extension of shelf life. Smart packaging, on the other hand, provides an additional feature that reveals what temporal and regional variations occur in the contents of the food it contains.

Smart tags use radio frequency identification components and work with a nano-biosensor inserted in a polymer film or polymer matrix. Biosensors for food packaging can operate in the packaged microenvironment's unique physicochemical circumstances. Ammonium molybdate is placed in the nano pores of zeolite, which is used to detect and analyze ethylene in avocado packing, to create zeolite molybdate tablets. When Mo(VI) is reduced to Mo(V), a zeolite-molybdate pill in a ten-day box changes color from yellow to blue [4].

Risks and Challenges

The use of nanocomposites in food packaging poses some concerns as well. Specific procedures for assessing absorption, excretion, metabolism, and digestion, or ADME, *in vivo* have yet to be investigated. Nano-coating has favorably transformed the field of food safety and packaging, and it also poses no possible hazards. To avoid any injury, the quality of materials utilized with nanoparticles must be monitored. This is due to the fact that the nanoparticles employed in the nano-coating, such as silver, zinc, and others, may be antibacterial and poisonous when in touch with the skin, as mentioned in cosmetic products. This is because the nano-sized tiny metal particles employed can easily enter the bloodstream. The consequences can be severe, including DNA damage and free radical generation, and if skin contact can bring such consequences, people would not want it to come into touch with food. We believe this because of the probable brain and nerve damage detected in the offspring of pregnant mice treated with titanium dioxide. Its usage in food safety, quality control, and analysis can be widely commercialized with the development of more robust testing and risk assessment procedures, as well as considerable study into the technology [21].

There are certain hurdles to overcome before nanotechnology can be employed to create really novel goods and processes in the food business. The major issue is a reliable and effective distribution system that allows people to eat. These systems necessitate sophisticated yet low-cost processing. The leakage and migration of nanoparticles from packing materials into foodstuffs is a serious problem in order to assure food safety. Some nanomaterials brought into a system, either directly or indirectly, may become isolated when users begin to leave the system. Materials behave very differently at the nano-scale, and our grasp of how to analyze this phenomenon is still fairly limited. An in-depth study of nano-scale functionalities and nanomaterial toxicity would substantially improve the practical application and safety requirements of nanotechnology. The potential hazards, toxicity, and environmental concerns associated with nanoparticles must be acknowledged. Nanoparticles have been shown to pass through biological barriers and infiltrate various tissues and organs, nanoparticles can be created using a variety of chemical processes, each of which has the potential to produce hazardous and unfriendly by-products that contribute considerably to environmental contamination. As a result, before manufacturing, packing, and consuming nano-based meals in humans, it is critical to review a comprehensive danger assessment program, regulatory regimes, bio-security, and public concerns. Furthermore, *in vitro*, and *in vivo* studies involving nanoparticle interactions with living organisms are required before antibacterial nanoparticles with environmentally benign features may be widely exploited [22].

Future trends

Nano-biosensors have the potential to revolutionize food safety by providing remarkable detection capabilities in a compact and efficient package, these nano scale sensors will enable real-time and on-site monitoring of food quality and safety parameters, allowing for faster reactions to possible problems. Nano-biosensors will be intended to detect a wide range of contaminants at ultra-low concentrations, including pathogens, toxins, and allergies, improving the overall safety of the food supply chain. Advances in nanotechnology and bioengineering will result in the creation of low-cost, mass-producible nano-biosensors, making them available to a wide range of food industry stakeholders. Furthermore, the incorporation of nano-biosensors into smartphones and other portable devices would allow customers to do quick safety checks on their food purchases, fostering informed decision-making. As nano-biosensor technology advances, it will become a critical tool for regulatory agencies and food manufacturers, allowing them to apply stringent safety measures, prevent food borne illness outbreaks, and establish customer trust. Finally, nano-biosensors have the potential to turn food safety into a proactive and preventive system, protecting public health and well-being.

Nano-biosensors research aims to provide breakthrough technologies that can significantly contribute to the detection and monitoring of biomedical, biochemical, environmental, agricultural, and food sectors. Furthermore, the nano-biosensor's primary goal is to serve people and society. Because of the advancement of nanotechnology, new frontiers for nano-biosensors with dimensions suitable for intracellular use that are submicron-sized depending on the application have opened. Investigating numerous specific effects, such as dimension, quantum size, and surface effect, that are unique to nano-structured materials production and are fundamentally their most appealing feature, should be prioritized [23-26].

Conclusion

The review discusses the numerous advantages of employing nano-biosensor technology in food safety monitoring. These include rapid detection, high sensitivity, real-time monitoring, portability, and potential cost-effectiveness. Additionally, nano-biosensors can be tailored to target specific food borne hazards, making them versatile and adaptable tools for various applications. An extensive examination of the applications of nano-biosensor technology in food safety monitoring is provided. The review highlights the successful use of nano-biosensors in detecting food borne pathogens, allergens, toxins, and chemical contaminants. Furthermore, their application in monitoring food quality, authenticity, and shelf life is discussed, indicating their multifaceted role in ensuring overall food safety. Despite the evident advantages, the review also addressed the risks and challenges associated with nano-biosensor technology. Concerns regarding biosensor stability, reproducibility, and potential toxicity must be thoroughly addressed to ensure the safe deployment of these advanced technologies.

Looking towards the future, the review discusses potential trends that may shape the further development of nano-biosensors for food safety monitoring. Advancements in nanomaterials, integration with other technologies like artificial intelligence, and miniaturization are envisioned as key aspects driving the field forward. In conclusion, nano-biosensor technology shows tremendous promise in transforming food safety monitoring by providing rapid and reliable results. However, a comprehensive understanding of the risks and challenges is imperative to harness the full potential of these technologies responsibly. As the field continues to progress, future developments are expected to lead to even more sophisticated and efficient nano-biosensor platforms, ultimately enhancing food safety and safeguarding public health.

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None.

Conflict of Interest

None.

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