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A Review of Nanosensors for Ensuring Food Safety

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Abstract

Food analysis presents significant challenges due to the complexity and heterogeneity of food matrices. Detecting trace levels of chemicals and microbiological substances often requires sophisticated, costly analytical techniques, typically conducted in specialized laboratories by skilled personnel. This creates a strong demand for innovative analytical technologies that can offer rapid and cost-effective detection of contaminants in the field, on production lines, and with minimal sample preparation-ideally usable by individuals without extensive scientific training. Recent advancements in nanotechnology, which leverages the unique properties of materials at the nanoscale, have opened new avenues for both qualitative and quantitative detection of gases, small molecules, biopolymers, and even living microbes. One promising approach involves the use of Nanosensors-chemical or mechanical sensors specifically designed for food and water quality assessment. These sensors can effectively identify chemical species, enhancing food quality and extending shelf life through biosensor-enabled packaging systems. Nanosensors facilitate faster and more accurate detection of microbes, toxins, and adulterants, while nanoparticles can also identify biodegradable components such as vitamins and antioxidants. This review examines the emerging applications of nanotechnology-based sensors for analyzing food shelf life, including monitoring freshness, ensuring food safety, and detecting spoilage. Key categories of nanomaterials for these sensors include inorganic, organic, and carbon allotropes. A significant focus is placed on inorganic nanomaterials such as gold, silver, titanium dioxide, quantum dots, and zinc oxide nanoparticles. These materials possess notable properties-such as biocompatibility, non-toxicity, photochemical activity, large surface area, and favorable electronic characteristics-making those promising candidates for sensor development in the food sector. Studies have highlighted the vital role of nanosensors in the food industry as effective tools for identification and detection, underscoring their potential impact on food safety and quality control.

Keywords: Nanosensors, gold nanoparticle, silver nanoparticle, titanium dioxide nanoparticle.

Introduction

Sensors are devices designed to detect physical quantities and convert them into signals that can be easily interpreted by observers. They play a crucial role in monitoring the internal environment of food products, continuously sensing their properties and providing real-time data. Nanotechnology has also found applications in grain quality control through the use of nanosensors. These sensors can respond to environmental changes during storage, such as temperature fluctuations, oxygen levels, humidity, degradation products, and microbial contamination. They can also detect the presence of fungi or insects in stored grains. Furthermore, nanosensors for monitoring grain quality have been developed using polymer nanoparticles that react to volatile compounds and other analyte in stored foods. This capability allows for the detection of specific causes and types of decomposition. As a result, nanosensors are gaining attention and becoming increasingly important in the food industry, serving as efficient tools for identifying gases, microbes, and toxic substances in packaged foods. Nano biosensors have been testified for detecting pathogens in processing plants or alerting clients, protocols, and providers on the safety position of food. It has been also employed for the existence of impurities, mycotoxins, and microbes in food. Allergens have also been detected via biosensors tools with the assistance of nanoparticles and the report is about to commercialize. These tools can also detect the history of time, expiration date, and temperature. Some examples include gold nano particle incorporated enzymes for microbes' detection, gas sensing related to condition of food products: nanofibril of perylene-based fluorophores indicates fish and meat spoilage by detecting gaseous amines. The use of smart sensors benefits consumers by enhancing the identification of food quality, while producers gain from faster distribution and authentication of their products. "Active packaging" and "smart packing" have become popular trends, leveraging nanomaterial-based sensors to monitor food quality effectively. Nanosensors are highly advanced yet precise and sensitive systems capable of detecting one or more specific physical or chemical phenomena based on a particular signal. These sensors operate on a nanometre scale and even react to the presence of several atoms in a single gas, which offer significant enhancements in speed, selectivity, and sensitivity in comparison with conventional chemical and biological techniques. The application of different nanomaterials in the construction of biosensors can promote their sensitivity and other properties. In general, Nano sensors are fabricated by combining a receptor and a transducer. Any organic or inorganic substance can play the role of receptor and interact with the analyte or its derivatives. However, the role of the transducer is to convert the response to the determinable signal. This signal comes in various forms, including electrical, electrochemical, and optical signals. Nanosensors are evaluated with several main characteristics. "Selectivity" is a vital characteristic of the sensors that indicates to what extent the system can separate the analyte from the other materials in the sample. In other words, the higher selectivity enabled sensors can detect and measure the analyte with the least disturbance from the other materials within the sample. The next important characteristic is "sensitivity." High sensitivity means that with the slightest variations in the analyte concentration, a significant change in the sensor output signal is observed. "Repeatability" is another essential characteristic defined by the word precision. The high precision indicates that the results of the repeated measurements are close together. Accuracy indicates that the measurement results are close to the actual value.

Different Types of Nanosensors

Optical Nanosensors

One of the key sensory parameters for detecting analytes is light, particularly through the perception of colors within the visible spectrum. This detection can be significantly enhanced using nanoparticles, especially metal nanoparticles like gold, silver, copper, nickel, palladium, and iron, which exhibit unique electronic and plasmonic properties. These nanosized particles have size-dependent characteristics, such as a high surface area-to-volume ratio, localized surface plasmon resonance, and super-paramagnetism, which differ markedly from larger particles. Optical nanosensors leverage these properties, particularly the noticeable color changes that occur as the size of metallic nanoparticles increases beyond 5 nm. Gold and silver nanoparticles, particularly spherical gold nanoparticles (GNPs), are commonly used. GNPs can be synthesized easily through the chemical reduction of gold ions using sodium citrate, which acts as both a reducing and capping agent, preventing aggregation and facilitating functionalization with biomolecules. By functionalizing GNPs with bioreceptors like aptamers or antibodies, pathogens in food and water can be detected. The agglomeration of nanoparticles upon interaction with bacteria leads to a red shift in coloration, which can be visually assessed for higher concentrations or quantified using a spectrophotometer. For the detection of pathogens in fresh food sources like milk and meat, there is an urgent need for quick screening methods by local vendors and food processing companies. Visual aids, such as small paper-based colorimeter sensors, offer a practical solution for monitoring and mitigating the risks of bacterial contamination in packaged foods.

Electrochemical Nanosensors

Electrochemical sensors detect changes in electrical current, potential, conductance, or impedance at the interface between the electrode and the sample. Their sensitivity, simplicity, speed, cost-effectiveness, and compatibility with portable devices have made them the fastest-growing class of sensors. Electrochemical nanosensors perform well with colored and turbid samples and can utilize disposable electrodes, minimizing sample preparation and cross-contamination while reducing costs. Similar to optical nanosensors, electrochemical variants can analyze a wide range of analyte using various recognition elements and have been tested across diverse food matrices. Recent research has concentrated on

1. Developing nanotechnology-enhanced electrodes,
2. Designing new nanomaterial tracers for signal amplification, and
3. Integrating miniaturized sensors into handheld devices.

Additionally, there is interest in novel recognition elements, such as molecularly imprinted polymers (MIPs) and aptamers, along with new transducing elements like nanoporous membranes that can detect single analyte by measuring current changes. Among the various inorganic nanomaterials used in food nanotechnology for developing sensors, titanium dioxide, silver nanoparticles, gold nanoparticles, zinc oxide, quantum dots, and magnetic nanoparticles are prominent for shelf-life detection and quality monitoring of food products.

Titanium Oxide-based Sensors

Titanium dioxide (TiO_2) is a transition metal oxide that exists in three phase structures: anatase, rutile, and brookite. It is an inexpensive, non-toxic, and inert material with antimicrobial properties. The nanoform of TiO_2 boasts biocompatibility, high UV absorbance, excellent photochemical activity, and a large surface area, making it suitable for various applications. TiO_2-based sensors are effective for detecting volatile chemicals and biological substances. These sensors have been employed in gas sensors, chemical oxygen demand sensors, and biosensors. TiO_2 nanoparticles are widely utilized across multiple sectors, including agriculture, medical devices, food industry, and wastewater treatment. Recent developments include a titanium dioxide-polyaniline/silk fibroin microfiber sensor designed to evaluate the freshness of pork meat, which uses in situ polymerization to create a sensing film. Another gas sensor, based on a Polypyrrole/TiO_2 nanocomposite, evaluates the shelf life of products like mango, egg, and fish by measuring trace gases such as ammonia and trimethylamine, demonstrating high sensitivity and stability. Furthermore, TiO_2-based sensors can detect synthetic colorants in food, such as sunset yellow and tartrazine, which are associated with health concerns. Utilizing graphene and mesoporous TiO_2, electrochemical sensors can determine these colorants at low concentrations, making them effective for monitoring food products like ice cream and soft drinks.

Silver Nanoparticles-based Sensors

Silver nanoparticles (AgNPs) exhibit a range of beneficial properties, including antiviral, antibacterial, anti-inflammatory, antiangiogenic, antitumor, and antioxidative effects. They are widely used across various sectors such as textiles, environmental applications (water disinfection), catalysis, food packaging, and healthcare. AgNPs have been employed in sensors for detecting harmful substances, including melamine in raw milk and sodium ions in fish sauce. These sensors utilize oxidation/reduction reactions, offering high sensitivity and stability. AgNPs-based sensors have been developed to monitor meat spoilage, including a plasmonic membrane that changes color in response to ammonia gas released during spoilage. AgNPs are effective in identifying synthetic colorants in food, such as sunset yellow and tartrazine, which can pose health risks. They have also been used to detect specific dyes and prohibited food colorants, employing techniques like surface-enhanced Raman scattering. AgNPs can detect chloramphenicol in food and monitor vitamin B1 levels in various samples, including water and food products. Their interaction with analytes can produce significant color changes that facilitate detection. Overall, AgNPs are emerging as versatile tools in food safety and quality monitoring, demonstrating significant potential for enhancing food safety practices.

Gold Nanoparticle-based Sensors

Gold nanoparticles (AuNPs) possess a variety of advantageous properties, including chemical inertness, biological compatibility, high stability, non-cytotoxicity, strong plasmonic characteristics, and excellent electrical and heat conductivity. These properties make AuNPs valuable in biosensors, where their color change upon aggregation or disaggregation is a key detection mechanism. AuNPs have been utilized in the detection of hazardous substances such as aflatoxin B1 in wheat flour and various food products like yogurt and soft drinks. For example, a surface plasmon resonance biosensor using AuNPs demonstrated high recovery rates in detecting aflatoxins. AuNPs are conjugated with DNA, antibodies, and aptamers for detecting pathogens. They have been employed in various applications, including the detection of Salmonella in milk and Staphylococcal Enterotoxin B in foods. One study reported a detection limit of 50 CFU for Salmonella using an isothermal recombinase polymerase amplification method with AuNPs. Gold nanoparticles are integrated into sensors to monitor food freshness. For instance, a recent study developed a colorimetric sensor to detect hypoxanthine, a decay product in meat, which resulted in a visible color change corresponding to the freshness level. AuNPs have been applied in sensors to detect synthetic colorants like sunset yellow and tartrazine, with high sensitivity and low detection limits. They are also used to identify toxic food dyes such as metanil yellow and fast green, demonstrating enhanced signal responses. Multiple electrochemical biosensors based on AuNPs have been developed for various applications, including detecting histamine and tyramine in food products, as well as aflatoxin M1 in milk. These sensors often exhibit high sensitivity and specificity. Gold nanoparticles have been employed in visual sensors to indicate the presence of contaminants, such as melamine, where color changes upon aggregation signal the detection of this compound.

Quantum Dots-based Sensors

Quantum dots (QDs) are fluorescent nanoparticles that exhibit unique optical properties, making them valuable in various sensing applications. These include semiconductor quantum dots (SQDs), carbon quantum dots (CQDs), and graphene quantum dots (GQDs), each with specific characteristics that allow for effective interaction with analytes. QDs exhibit fluorescence that changes based on interactions with surrounding molecules. This property is utilized for detecting and measuring various analytes. QDs, typically 1 to 10 nanometers, consist of a semiconductor core and a shell with a larger energy gap, allowing for interactions with biological molecules like proteins. A β-cyclodextrin-modified CdSe/ZnS QD sensor was developed for determining vanillin in milk and sugar. GQDs have been used to detect phenols in olive oil and as optical sensors for glucose and pesticides. Carbon dot aptamer complexes were created for quantifying Salmonella typhimurium in eggshells and tap water, achieving a limit of detection (LOD) of 50 cfu/mL. Carbon dots combined with AuNPs and aptamers achieved a LOD of 5 pg/mL for Aflatoxin B1, with recovery rates between 92% and 105% in actual samples such as corn and peanuts. An immune sensor developed by Gan *et al.* utilized IO NPs on graphene oxide and CdTe QDs, detecting aflatoxin M1 with an impressive LOD of 0.3 pg/L.

Magnetic Nanoparticles

Magnetic nanoparticles (MNPs) are typically independent particles with sizes up to 100 nm that exhibit unique magnetic properties, differing significantly from their bulk counterparts. Key magnetic elements include iron, nickel, and cobalt, though some non-magnetic materials can gain magnetic properties at the nanoscale due to increased surface area and the presence of broken bonds. MNPs are employed in the detection of food contaminants and pathogens. Sensors have also been developed for detecting quercetin in tea, dimethoate in cabbage, kanamycin in pork, and aflatoxin M1 in milk. Wang *et al.* developed antibody-coated magnetic beads that detected Bacillus anthracis spores in food, achieving a detection limit of 6×10^4 spores/g in milk powder without requiring sample pre-treatment. Suaifan *et al.* established a biosensor using magnetic beads for detecting E. coli O157 with detection limits as low as 12 cfu/mL in broth and 30–300 cfu/mL in food matrices.

Zinc Oxide-based Nanoparticles

The zinc oxide NPs generally have diameters less than 100 nm, whereas, the NPs have high catalytic activity and high surface area. The several synthesis processes include hydrothermal methods, laser ablation, electrochemical depositions, chemical vapor deposition, solgel method, thermal decomposition, anodization, co-precipitation, ultrasound, etc. ZnO NPs are extensively used in developing a sensor for sensing food properties during storage. Zinc oxide and its nanoforms are used in detecting odours of seafood, vapor sensing properties for monitoring quality during storage, biogenic amine detection, and trace detection of sunset yellow in soft drinks. The thick film sensor based on tin oxide and zinc oxide is used as a vapor sensor that can be used to monitor the quality of potato tubers and dry cured ham during storage. The aluminium doped zinc oxide thin film developed by the sputtering technique is used as a smell sensor for seafood such as Salmon, oyster, squid, sea bream, and sardine, which produces trimethylamine gas during fish degradation.

Challenges

Most of the nanosensor research results are obtained in laboratories under controlled conditions, which may be different from those real conditions. In the food industry, the sensors should be capable of working under extreme temperatures, pressures, pH, ionic strength, and other changing parameters. In the real world, sensors must operate in the presence of multiple microorganisms and other substances, which could interfere with the sensor measurements. In addition to the significant cost of the devices, at least until the popularization of the technology, high infrastructure costs are expected. In fact, the technological advancement in the nanoindustries will probably change the fabrication process of the entire packaging industry, which is even greater when biotechnological efforts should be included (eg, production of nanobiosensors). Critical issues of sampling may occur in both internal and external nanosensors. The scale of the sensors is extremely small compared to the product, or condition, it is measuring. This implies that the sensor measures only a small part of the food or environment. Autonomous wireless sensors networks arranged in various sites are often mentioned as possible solutions to this problem.

Future Outlook

While research has highlighted the advantages of using nanomaterials for food monitoring, quality, and freshness, studies on their toxicity, fate, transport, and degradation are still in the early stages. To fully harness their potential, more comprehensive studies and thorough life cycle analyses of nanomaterials in food and the environment are essential. First, we need to develop methods to effectively characterize and measure the properties of nanomaterials and their biotransformation in food. Conventional techniques often fall short due to high costs, limited sample throughput, and the complexity of food matrices. Second, further studies are required to assess the toxicity of nanomaterials, whether they are added as food ingredients or are in contact with food through packaging. Third, addressing cost, biocompatibility, and scalability is crucial for successful implementation. Future efforts should focus on ensuring the long-term stability and storage of sensing elements under adverse conditions, as well as validating the technology. Additionally, developers must consider industry and consumer acceptance, including the willingness to pay. Concerns about the migration of nanomaterials from packaging into food and the environment also need thorough investigation. These issues should be integral to the development process. Moreover, the lack of a regulatory framework for nanotechnologies in food has contributed to consumer hesitance regarding nano-enabled products. Establishing standards for the classification and characterization of nano-products, along with appropriate labelling, is necessary to meet consumer demands and address regulatory challenges, ultimately facilitating commercial adoption. These topics are actively discussed at large-scale conferences and forums. The Institute of Food Technologists regularly addresses these issues and hosts topical sessions on the implementation of nanotechnologies in food, with expectations for increased activity in the future. In summary, while nanotechnology offers innovative solutions to enhance food quality, production, protection, and analysis, concerns regarding toxicity and environmental impact must be addressed. Ongoing efforts are vital to ensure the safe application of nanotechnology in the food sector and to understand its potential implications.

Conclusion

Nanomaterials possess unique sensory properties that enable nanosensor to detect microorganisms, toxins, and adulterants much faster and more effectively than traditional sensors. These nanoparticles are also valuable for identifying degradable food components, such as vitamins and antioxidants. Other applications include individual pack quality indicators and smart packaging materials. An overview of these applications highlights the role of nanotechnology-based sensors in detecting spoilage and adulteration in food products. These sensors are extensively used in shelf-life analysis, focusing on freshness monitoring, spoilage detection (including volatile gases and amines), and safety measures to ensure food is safe for consumption. The use of specific nanomaterials enhances sensitivity, reproducibility, and selectivity-key traits for effective sensing. To meet future demand, large-scale production of these sensors will be necessary, alongside intensified research to ensure the safe and healthy delivery of food to consumers. Future developments in nanosensors should aim to improve their ability to detect complex matrices, reduce costs, and enhance portability. Economic considerations will also be crucial for the commercialization and scalability of these sensors within the food industry, as well as for regulatory organizations tasked with monitoring food quality and safety.

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