

Received: 20.7.2023

Revised: 17.8.2023

Accepted: 22.8.2023

Published: 12.9.2023

Potravinárstvo Slovak Journal of Food Sciences

vol. 17, 2023, p. 728-747

<https://doi.org/10.5219/1903>

ISSN: 1337-0960 online

www.potravinarstvo.com

© 2023 Authors, CC BY-NC-ND 4.0

Advancements in nano bio sensors for food quality and safety assurance – a review

Zhainagul Kakimova, Duman Orynbekov, Klara Zharykbasova, Aitbek Kakimov, Yerlan Zharykbasov, Gulmira Mirasheva, Sandugash Toleubekova, Alibek Muratbayev, Godswill Ntsefong

ABSTRACT

Nano-biosensors are rising as a promising technology for ensuring the protection and high-quality of meals merchandise. They offer excessive sensitivity, selectivity, and speedy reaction, making them ideal for detecting contaminants, pathogens, and first-rate signs in meals samples. This up to date evaluate affords a complete evaluation of recent improvements in nano-biosensor technology for meals great and safety warranty. The evaluate covers the essential standards and kinds of nano-biosensors typically utilized in meals evaluation, exploring various nanomaterials and their unique homes and sensing talents. It also discusses mixing nanomaterials with biological reputation elements, antibodies, enzymes, and DNA aptamers to enhance sensor performance. The software of nano-biosensors in detecting chemical contaminants, which includes pesticides, heavy metals, and mycotoxins, is drastically protected. Nanomaterials allow ultrasensitive detection of these contaminants, even at trace stages, ensuring the protection and compliance of meal products. The review also explores the usage of nano-biosensors for rapid identification and quantification of foodborne pathogens, such as microorganisms, viruses, and parasites, allowing on-web page pathogen detection and timely interventions to prevent outbreaks. Additionally, the review highlights the tracking of meals satisfactory signs of using nano-biosensors, including freshness, spoilage, and dietary composition. Accurate assessment of those parameters offers treasured information to manage and predict shelf-life. Overall, the advancements in nano-biosensor generation maintain high-quality promise for ensuring the integrity of meals products, defensive public fitness, and assembly regulatory standards.

Keywords: nano-biosensors, food safety, food quality, contaminants, pathogens, nanomaterials

INTRODUCTION

Nanobiosensors are a promising tool for enhancing meals quality and safety assurance. These sensors use nanomaterials and biological recognition elements to locate and analyze food samples' specific biological or chemical components. They offer numerous blessings over traditional strategies, including rapid response, high sensitivity, and miniaturization. Nanomaterials have been utilized in various programs, including food production, processing, packaging, labeling, transporting, tracing, and maintaining excellent food products. They have also been used to broaden green optical sensors to discover hint pollution stages from various sources. Additionally, nanomaterials have increased nanobiosensors for food safety, enabling rapid and touchy detection of food-borne pathogens. Using nanocomposite materials in meal packaging has also made for a better great food product, with enhanced antimicrobial, mechanical, thermal, and barrier properties against external factors that could affect the food packaging system [1], [2], [3], [4], [5].

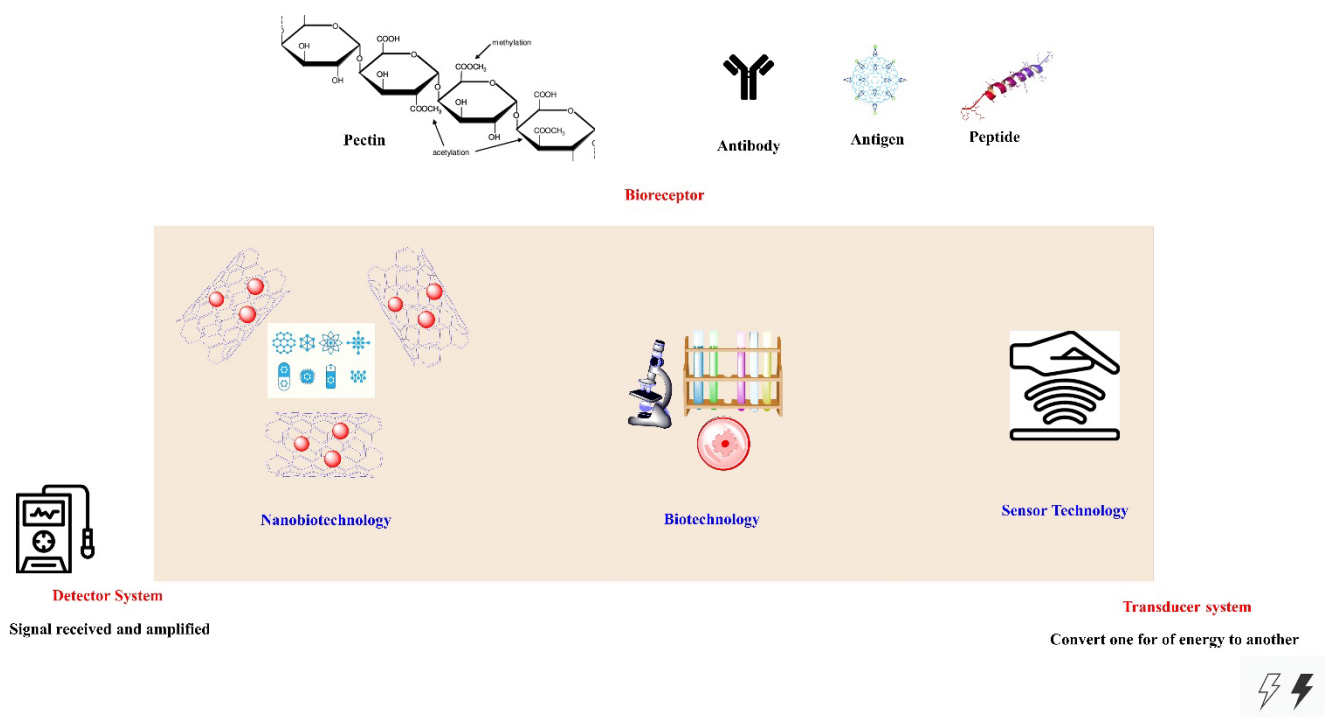


Figure 1 Scheme of different applications of nanobiosensors.

Food quality and safety assurance are essential elements of the food industry, ensuring that our food is safe, nutritious and free from contamination. Traditional approaches to food quality and safety assessment often require time-consuming and labour-intensive processes, which can delay the identification of potential hazards and compromise consumer health. In order to overcome these challenges on, researchers and scientists have turned to nanotechnology, especially nano biosensors, as a promising solution. Nano biosensors combine nanomaterials with biological sensors to detect and analyze specific biological or chemical compounds in food samples. These sensors offer several advantages over conventional methods, making them an attractive tool for improving food quality and safety [2], [6], [7].

One of the main advantages of nano biosensors is their fast reaction time. Traditional methods typically require extensive sample preparation and analysis time, which can take several hours or even days. In contrast, nano biosensors offer real-time monitoring and detection, providing almost immediate results. This allows quick decisions and interventions to prevent further contamination or food waste. Nano biosensors also exhibit high sensitivity, enabling the detection of trace contaminants or pathogens in food samples. Their ability to detect and quantify specific substances at trace levels is critical in identifying potential hazards and ensuring compliance with regulatory standards. Upon reaching high sensitivity, nano biosensors can reduce false positives, negative and false positives, to give accurate and reliable results [8], [9], [10].

Furthermore, the miniaturization of nano biosensors allows them to be integrated into portable handheld devices. This portable unit allows for easy on-site testing and monitoring across the entire food supply chain, from fields to pans. Farmers, food manufacturers, and distributors can use these devices for real-time analysis, spoilage detection, and detection of harmful substances. Nanomaterials have been widely used in a variety of applications in the food industry. For example, processing, manufacturing, labelling, transportation and inspection of food products to ensure the quality and safety of foods are used to obtain the environment of mature consciences the development of the enabled pollution is enhanced and protected. Specialized nano(bio)sensors have been developed to ensure food safety. These sensors allow rapid and sensitive detection of food-borne pathogens, such as *Salmonella*, *Escherichia coli* (*E. coli*), and *Listeria monocytogenes*. Their high sensitivity enables rapid detection, allowing for early intervention to prevent the spread of infection and reduce the risk of foodborne illness [2], [3], [10], [11], [12].

The use of new nanocomposite materials in food packaging has also contributed significantly to the quality of the food. Nano composite materials have desirable properties, such as high antimicrobial properties, mechanical strength, thermal stability, and barrier properties to prevent migration in food packaging systems and these properties can help extend the shelf life of perishable foods, reduce food waste and reduce the need for chemical preservatives [3], [13], [14], [15].

This review aims to provide a comprehensive understanding of the progress of nano biosensors for food quality and safety assurance. By highlighting the capabilities of these sensors and discussing their applications, limitations and prospects, it seeks to contribute to the growing knowledge base in this fascinating area and to stimulate further research and innovation to promote nanobiosensors for food technology.

Challenges in Shelf-Life Monitoring

Accurate and predictive analysis of the shelf life of food products is essential to ensure safety and quality throughout storage and distribution. However, there are many challenges to this task. One of the major challenges is the complexity of food systems, which have different components and characteristics. Factors such as moisture, pH, fat content, and the presence of additives or preservatives can significantly impact storage time. Understanding the interconnections and dynamics of these complex matrices is essential to monitor shelf life accurately. Another challenge is the inherent variability in the material properties. Food products can exhibit variations in microbial loads, enzymatic activity and chemical reactivity due to factors such as raw materials, processing methods and storage conditions. These variations make it difficult to establish statistics fixed retention period [3], [15], [16].

Microbial spoilage and decomposition are important challenges in storage time management. Microorganisms play an important role in food packaging, affecting storage and safety. Accurate identification and detection of microbial organisms is essential for effective management. Furthermore, microbial adaptation and evolution can lead to the emergence of new strains or pathogens, further complicating monitoring efforts. Time and cost are additional challenges in determining shelf life. Traditional methods typically require time-consuming and expensive procedures such as sensory testing, microbiological testing, and chemical analysis. These methods may not be suitable for real-time monitoring, making it difficult to respond quickly to product quality or safety changes. The lack of standardized methods for predicting the shelf life of foods is another challenge. Each production stage may require specific procedures, making it difficult to establish standardized quality control guidelines and procedures [2], [16], [17].

Furthermore, interactions between packaging and food products can affect shelf life. Process efficiency and stability can be affected by factors such as air permeability, moisture permeability, and the presence of volatiles. Understanding and managing these interactions is essential to maintaining shelf life accuracy. Addressing these challenges requires developing and adopting advanced technologies such as nano biosensors. By integrating this technology into food packaging design, it is possible to improve the accuracy, efficiency and reliability of inspection practices through the limitations of traditional methods, controlling limitations of traditional methods using nanobiosensors also provide real-time precision monitoring capabilities, timely intervention and enhanced quality control. They provide valuable insights into changes in the food chain, enabling better decision-making and reducing food waste [3], [11], [13], [14], [15], [16].

Need for Advanced Monitoring Systems

The demand for superior monitoring systems in food packaging and shelf-lifestyles management has grown because of the increasing want for stronger product quality, safety, and efficiency throughout the supply chain. Traditional tracking methods frequently fail to provide real-time data and comprehensive insights into product conditions. Therefore, implementing superior tracking systems, including nano biosensors, is important for numerous key motives. Firstly, advanced tracking systems allow extra correct shelf-life determination. These structures offer actual-time information by constantly tracking essential parameters like temperature, humidity, fuel composition, and microbial hobby, allowing for a more precise shelf life assessment. This is an extensive improvement over conventional techniques that depend upon fixed expiration dates. Secondly, superior tracking structures facilitate prompt intervention and quality control. Real-time monitoring enables the early detection of deviations or adverse conditions, allowing for prompt moves to save you spoilage, maintain product high-quality, and reduce food waste. By figuring out capacity troubles quicker, businesses can take corrective measures to ensure product integrity [11], [13], [14], [16], [18].

Third, these programs contribute to enhancing food safety. Advanced monitoring systems can identify potential sources of contamination, microbial growth, or degraded conditions that could compromise food safety. Early identification of such risks enables appropriate action to prevent the distribution and consumption of unsafe products, thereby protecting consumer health. Another advantage of a comprehensive monitoring system is effective supply chain management. Real-time information about product conditions, such as fluctuations in temperature, helps identify points that can affect product quality or shelf life. This information simplifies logistics planning, reduces losses, and improves inventory management, leading to more efficient and cost-effective supply chains [3].

Additionally, the improved surveillance system contributes to customer confidence and transparency. By incorporating smart labels or QR codes, consumers can receive real-time information on renewal, safety and storage recommendations. This transparency enables consumers to make informed purchasing decisions and builds consumer confidence in the products they purchase. Sustainability and waste reduction are addressed through advanced monitoring systems. By more accurately determining the remaining life of consumer goods, premature disposal of still-safe consumer goods can be reduced, including food waste, consumables role and environmental reduction. These programs help companies comply with regulatory standards. Monitoring companies provide precise timekeeping control and management. Advanced monitoring systems enable product inspection, data recording and proof of compliance with food safety standards to help businesses comply with regulatory requirements [19], [20], [21], [22], [23].

Principles of Nano Biosensors

Nano biosensors are state-of-the-art devices that use the principles of nanotechnology and biotechnology to detect and analyze specific biological, chemical, or physical agents. These sensors work based on several fundamental operating principles. First, nano biosensors incorporate a detector responsible for operating principles selectively interacting with the target probe. This sensing agent can be a biological molecule, such as an enzyme, antibody, nucleic acid, or receptor, or a synthetic material with a specific binding ability. The selectivity of the sensor's specificity and ability to distinguish between the target analyte and other factors. Second, nano biosensors use a transducer, which converts the binding reaction between the detection element and target analyte into a detectable signal. The transducer can be based on physicochemical principles, including electrical, optical, light energy, or piezoelectric effects are included. Converts a biological or chemical discovery process into a quantifiable form that can be detected and analyzed accurately. Nano biosensors typically incorporate amplification techniques to increase the sensitivity and detection capability of the target molecule. These methods can include enzymatic reactions, signal amplification based on nanomaterials, or signal amplification by electronic or optical methods. Amplification techniques increase the signal-to-noise ratio, enabling the analyst to detect even trace amounts [23], [24], [25], [26], [27], [28], [29].

Signals generated by nano biosensors are often read and detected using specialized instruments or devices. This can be electronic devices, optical detectors, imaging systems, or remote sensing methods. The readout system converts the sensor output into meaningful data that can be analyzed and interpreted further. Moreover, nano biosensors are characterized by miniaturization and integration abilities. Using nanoscale materials and manufacturing techniques, these sensors can be made extremely small, allowing them to be incorporated into platforms. They can be incorporated into lab-on-chip devices, wearable sensors, or products that packaging in combinations. This miniaturization enables mobility, adaptability, and integration into complex systems. Concepts of ecological and environmental analysis, importance, and time savings across various industries include those used in various industries, and it lacks the positive role of unique, acceptable and transformative specificity. To analyze implications and emotions, for Shelf-Life decision-making and to provide greater control [22], [30], [31].

Introduction to Nano Biosensors

Nano biosensors are advanced devices that combine the principles of nanotechnology and biotechnology to detect and analyze specific biological, chemical, or physical properties of target molecules. These sensors work at the nanoscale, leveraging the unique properties of nanomaterials to enable highly sensitive and selective detection. Nano biosensors have received significant attention and applications in various fields, such as healthcare, environmental monitoring, and food safety. The key components of a nano biosensor are a detector, transducer, and readout system. The sensing agent, typically a biomolecule or synthetic material with the ability to selectively bind to a specific target, selectively interacts with the target probe. This binding process generates a signal that the converter converts into a detectable output such as an electrical, optical, or chemical signal, and the readout system detects and interprets the result, providing valuable information regarding the presence and quantity of the target molecule [32].

As nanotechnology continues to evolve, nano biosensors have the potential to revolutionize food packaging and shelf-life by improving product quality, reducing waste, increasing consumer safety, and maintaining the supply chain. However, challenges related to standardization, integration, and regulatory considerations must be addressed for wider adoption and commercialization of nano biosensors in the food industry [30], [31], [32], [33], [34].

Nano biosensors have several applications in food packaging, including the following:

- Monitoring key parameters: Nano biosensors can be integrated into food packaging materials or devices to monitor critical parameters such as temperature, humidity, gas concentration, and microbial activity in real-time.
- This enables accurate product freshness, quality, and safety determination, enabling timely interventions and informed decision-making throughout the supply chain.
- Detection of pathogens: Nano biosensors can be used to detect pathogens in food packaging, which can help prevent foodborne diseases.
- Shelf-life monitoring: Nano biosensors can be used to monitor the shelf-life of food products by detecting changes in the chemical composition of food, such as the presence of volatile organic compounds (VOCs) that indicate spoilage.
- Quality control: Nano biosensors can be used for quality control in food packaging by detecting contaminants or adulterants present in food products.

Working Mechanisms of Nano Biosensors

Nano biosensors work based on various techniques in which nanomaterials and biological recognition elements are used to detect and analyze target analytes. The working mechanism of a nano biosensor depends on its design and configuration. Some common applications are optical detection, electrochemical detection, piezoelectric detection, magnetic detection, and nanomechanical detection. optical, electrochemical, piezoelectric, magnetic, and nanomechanical detection techniques. Changes in the optical properties of these nanomaterials, such as fluorescence intensity or surface plasmon resonance, occur when the detection element binds to the analyte. On the other hand, electrochemical nano biosensors lead to changes in electrical properties such as conductance or impedance changes used to investigate binding events [35], [36], [37].

Piezoelectric nano biosensors use nanomaterials with piezoelectric properties, causing changes or deformations in mechanical stress due to binding phenomena magnetic nano biosensors use magnetic nanomaterials, where changes in magnetization or magnetic field response indicate that analyte it binds to nano biosensers they measuring structures like mass or resonance frequency to detect binding events, in order to determine bonding phenomena [38].

These working mechanisms show the various approaches nano biosensors use to detect and measure target analytes. By using the distinctive properties of nanomaterials and their interaction with recognition elements, nano biosensors offer high sensitivity and selectivity in detection. They can be customizable for specific analytes and applications, enabling real-time monitoring of essential parameters in food packaging and shelf-life management. Figure 2 displays the mechanism of how nano biosensors working.

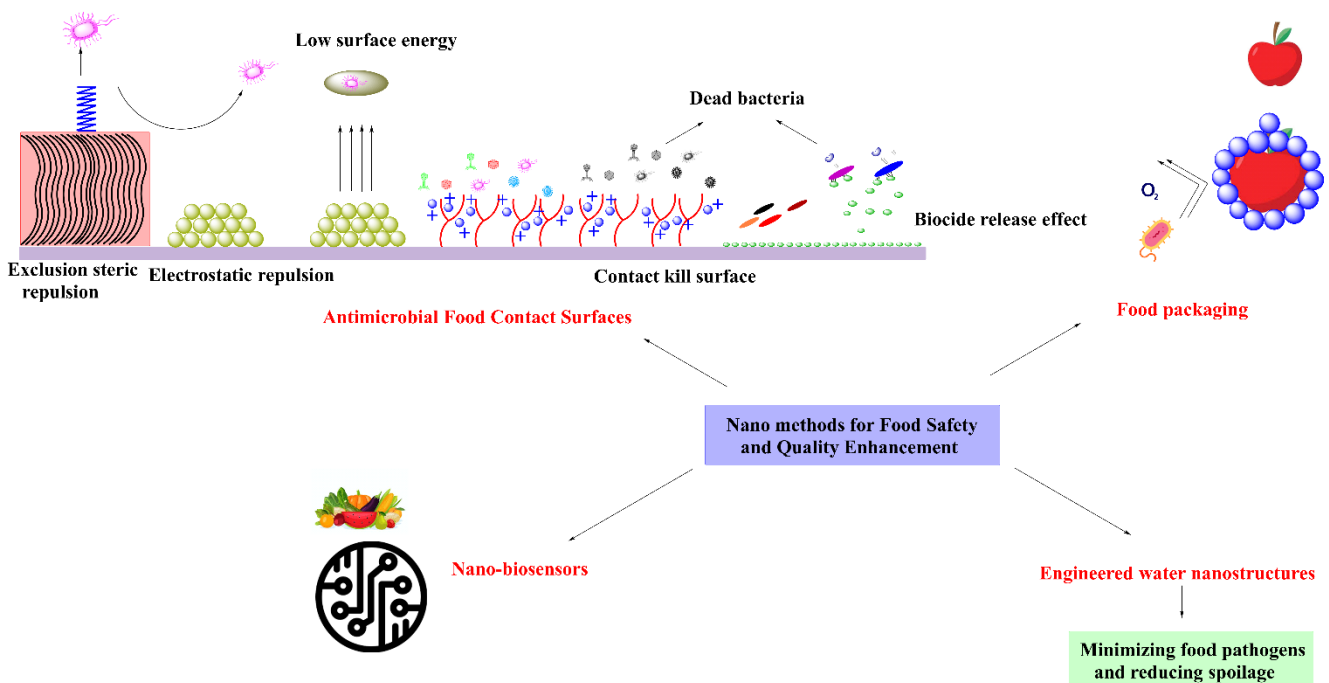


Figure 2 Scheme of nanobiosensors working mechanism.

Types of Nano Biosensors

Nano biosensors include various types of systems, each designed for analyzing specific materials. Some types of nano-biosensors commonly used in various applications, including food packaging and shelf-life monitoring, are nanoparticle-based biosensors, and nano-wire biosensors based on carbon and porous materials. Availability of Raman scattering (SERS) biosensors and nanoimprint biosensors. Nanoparticle-based biosensors use nanoparticles such as quantum dots, gold, or magnetic nanoparticles as transducer components. A detector such as antibodies, enzymes, or DNA probes is used is attached to the surface of the nanoparticles. When the detector binds to the target probe, it induces changes in the optical and electromagnetic properties of the nanoparticles, allowing the analyte to be concentrated and quantified [39], [40], [41], [42].

Nanowire biosensors are nanoscale wires made of silicon or carbon nanotubes. The recognition element is located on the surface of the nanowire, and upon binding to the target analyte, causes a change in electrical conductivity or impedance. These changes are measured, and the concentration of the analyte is determined based on the electrical signal. Carbon-based biosensors use carbon nanotubes, graphene or other carbon-based nanomaterials. These materials exhibit excellent electrical conductivity and a large surface area, making them suitable for sensing applications. The recognition element is embedded in a carbon-based nanomaterial, and the binding event with the target analyte induces changes in electrical conductivity or electrochemical properties, allowing detection and analysis [43], [44], [45].

Nanopore biosensors utilize tiny pores, typically at the nanoscale, to detect and analyze analytes. The recognition element is placed inside the nanopore, and when target analytes pass through the pore, there is a change in ionic current or electrical impedance. These changes are measured, and the concentration or type of analyte is determined based on the electrical signal. Surface-enhanced Raman scattering (SERS) biosensors use metallic nanostructures, such as silver or gold nanoparticles, to enhance the Raman scattering signal of target analytes. The identification element is attached to the nanoparticle surface at the Raman scattering signal or spectrum in which it binds to the analyte or conversion occurs. These conversions are measured using Raman spectroscopy, allowing sensitive detection and identification of the analyte [46], [47], [48].

Nanoimprint biosensors use nanoimprint lithography to create nanoscale patterns or features on a substrate. The recognition element is immobilized on a patterned surface, and binding to an analyte causes changes in optical and electromechanical properties these changes are measured, and the analyte is quantified or characterized appropriately. These types of nano biosensors provide unique benefits and are appropriate for specific analytes or sensing requirements. An appropriate type of nano biosensor is selected based on factors such as target analyte, sensitivity, selectivity, intended use in food packaging and shelf-life monitoring [49], [50], [51], [52], [53].

Nano Bio Sensors for Food Packaging

Nano biosensors are highly advanced sensing devices that use the principles of nanotechnology and biotechnology to monitor and manage food quality, safety, and shelf life. These sensors are incorporated into packaging materials or devices, continuous monitoring of important parameters such as temperature, humidity, gas concentration and microbial activity and accurate Provision of Nano biosensors enables timely intervention and manufacturing controlled to ensure the freshness and safety of packaged food products. Sensors use a variety of sensing techniques based on optical, electrochemical, or nanomechanical principles to detect and analyze specific materials of interest. Furthermore, nano biosensors contribute to intelligent packaging design by integrating sensors into packaging or devices to ensure food integrity and quality. This allows for improved monitoring and control of material conditions, including detecting increased temperatures, decreased ventilation, or bacterial growth and taking appropriate action to maintain optimal conditions [1], [12], [54], [55], [56], [57].

One of the most important advantages of nano biosensors is their ability to improve quality and safety assurance in food packaging. They enable early detection of potential sources of contamination, microbial growth, and conditions that could compromise food safety and freshness. This enables prompt action, preventing the distribution of unsafe or substandard products that have been eaten. Moreover, nano-bio sensors play an important role in the remaining shelf life of food products. This sensor provides accurate and dynamic information about material conditions by continuously monitoring parameters such as temperature, humidity and air content. This accurate determination of shelf life decreases unnecessary waste and enables better inventory management. Nano biosensors also contribute to traceability and transparency in food packaging by incorporating technologies such as RFID or QR codes. These sensors provide consumers with information on product history, shelf life, and expiration dates, enabling them to make informed purchasing decisions and increase confidence in the food supply chain. Additionally, nano biosensors contribute to sustainability efforts by reducing food waste. By precise control of production conditions, unnecessary disposal of still-safe consumables is prevented by accurately determining the remaining shelf life. This waste reduction not only reduces consumption but also meets sustainability goals [3], [4], [58], [59].

Current State of Food Packaging

The current state of the food packaging industry is characterized by continuous developments and innovations driven by consumer needs, regulatory requirements, and technological advancements. Safety and security are top priorities, with continuous enhancements in food packaging materials and technologies to safeguard foods from contamination, moisture, oxygen, light, and physical damage. Convenience drives adopting eco-friendly solutions that reduce waste, enable recycling and promote recycling. Proactive intelligent packaging technology is gaining popularity due to the ability to interact with products, monitor conditions, improve quality, and prolong shelf-life. Packaging is a crucial marketing tool, offering branding opportunities and effective communication with consumers through attractive design, labelling, and storytelling elements on the packaging [53], [60], [61], [62], [63], [64], [65].

Convenience drives the adoption of eco-friendly solutions, including standards and regulations for materials, additives, labelling claims, and recycling practices to guarantee food safety, labelling precision, and environmental compliance. E-commerce has also led to specific packaging material requirements for shipping, protecting products during transportation, and promoting efficient resource management. The current state of food packaging reflects a dynamic state driven by safety, sustainability, convenience, branding, and regulatory compliance. Technological advances and evolving consumer preferences continue to shape the industry, while future growth may focus on additional environmental sustainability, the incorporation of intelligent packaging technologies, and addressing emerging challenges related to food waste and traceability [66], [67], [68], [69].

Role of Nano Biosensors in Food Packaging

Nano biosensors play an important role in enhancing the efficiency and effectiveness of food packaging by integrating the principles of nanotechnology and biotechnology. The main application is continuous real-time monitoring by nano biosensors to monitor the temperature, humidity, and gas concentration and microbial activity in the packaging. This allows for immediate detection of deviations and timely corrective action to ensure quality and safety. Nano biosensors also contribute to quality assurance by detecting degradation indicators such as volatile organic compounds (VOCs) or microbial activity. This early detection enables immediate decision-making and mitigates the risk of substandard or unsafe products. For shelf-life extension, nano biosensors offer precise and real-time information about packaging conditions. This helps to identify and address spoilage factors more quickly, facilitating interventions to enhance product freshness and prolong shelf life. Nano biosensors contribute to food safety by detecting harmful contaminants, pathogens, and allergens. They can be designed to specifically target and detect these objects, enhancing security assurance. Furthermore, nano biosensors can be integrated into actual packaging materials for quality and authenticity control. For example, sensors embedded in packaging films can detect breakage or leaks, preventing physical damage, contamination, or exposure to adverse conditions. Nano biosensors also help enable examine and honest in packaging. Including unique indicators enables the tracking of product origin, manufacturing and storage of products, enhances visibility and prevents counterfeiting and tampering. In terms of waste reduction, nano biosensors contribute to reducing food waste by providing accurate information on freshness and shelf life. This allows for better inventory management and prevents the premature disposal of safe and edible products [33], [70], [71], [72], [73].

Enhanced Integrity and Barrier Properties

Nano biosensors are important in enhancing food packaging integrity and barrier properties. Several strategies for incorporating nano biosensors can be used to enhance the safety potential of food packaging using nanotechnology-based materials. On the one hand, nano biosensors enhance integrity by providing mechanical strength to the packaging. They can be incorporated into packaging films or coatings to provide durability and resistance to tears and physical damage during controlled storage. Nano biosensors also contribute to the gas barrier properties of materials, a packaging is excellent. Nanocomposite films can be produced by incorporating nanoparticles or nano clays into the packaging material, significantly reducing oxygen and water permeability. This provides the desired environmental properties of the packaging material to remain intact, preventing food contamination, oxidation or water-related non-degradation [33], [70], [71], [72], [73].

Another advantage is the ability to deliver antibiotics. Nano biosensors can incorporate antimicrobial compounds or nanomaterials with inherent antibacterial properties into the packaging. This actively inhibits the growth of bacteria, fungi, and other microorganisms, extends the shelf life of foods, and ensures safety. Nano biosensors can also serve as an anti-pollution barrier. The application of nanocoatings or nanoporous membranes on packaging materials prevents unwanted ingredients such as chemicals or fragrances in the food, thereby enhancing product safety, quality, and consumer acceptability. Nano biosensors can also contribute to UV protection. Packaging containing UV-repellent nanoparticles or coatings effectively protects photosensitive foods

from harmful UV rays, while retaining their sensory properties and nutritional value. Nano biosensors can also provide waterproofing solutions. Nanomaterials with absorbent or water-repellent properties can be incorporated into films or packaging bags to maintain optimal moisture content for moist products. This helps prevent texture changes, microorganisms growth and migration edges. In addition, nano biosensors help protect the taste and aroma of foods. Packaging films can be incorporated with nanomaterials containing barrier anti-taste or odour molecules to prevent loss or contamination and preserve the sensory properties of the product [72], [74], [75].

Active Packaging Systems

Dynamic packaging design involves packaging technology that interacts actively with packaged food to extend shelf life, enhance safety, and improve overall effectiveness. Nano biosensors consume plays an essential role in designing and implementing dynamic packaging systems. This framework employs various techniques and applications to create a dynamic environment that adapts to packaging material or product changes. Nano biosensors and gas laws enable a key feature of dynamic packaging. Nano biosensors enable systems to monitor and control the gas content of packaging materials. It includes the detection of oxygen, carbon dioxide, or ethylene levels, which are important factors affecting food quality and shelf life. Based on sensor readings, the packaging system can release or absorb specific gases to maintain optimal airspace for the product, thus reducing waste and preventing widespread product contamination. Hydration is another crucial aspect of dynamic packaging. Nano biosensors embedded in these systems can monitor the moisture content of the packages. Excess moisture or changes in humidity can be detected and trigger mechanisms to release or absorb moisture in the packaging. This helps prevent moisture-related issues such as microbial growth and alteration that results in moulding or spoilage, thereby improving the quality and safety of packaged foods. They observe [71], [76], [77], [78], [79].

Nano biosensors can also be active packaging materials with antimicrobial agents or nanomaterials with innate antimicrobial properties. These biosensors detect the presence of harmful microorganisms or signs of spoilage and trigger the release of antimicrobial agents to prevent microbial growth. This tight control of microbial activity helps to prolong the shelf life of the product and enhances security. Temperature monitoring and control is another function nano biosensors enable in dynamic packaging materials. These sensors can monitor temperature changes in the packaging and detect deviations from the desired temperature. If necessary, the packaging system can trigger storage cooling and heating mechanisms to maintain optimal storage conditions. Thermal insulation helps preserve the quality and freshness of the product, especially for hot items. Nano biosensors facilitate the integration of time-temperature records into dynamic packaging materials. These signals provide visual or electronic information about the aggregation behaviour of the product under adverse temperature conditions. By looking at the temperature history, customers and stakeholders can assess the time remaining in a product and make informed decisions about its suitability [76], [77], [78], [79], [80].

Nano biosensors continually monitor various parameters in dynamic packaging systems, such as pH, colour change, or volatile emissions. Nano biosensors detect indicators of quality degradation and distribute real-time information to stakeholders. This information enables prioritization of actions, such as rearrangement, debris removal, or quality assessment. Moreover, dynamic packaging can offer an intelligent feedback mechanism that employs nano biosensors to provide stakeholders in the supply chain. Such feedback may comprise information on heat transfer, changes in air composition, or product quality conditions. These feedback systems expedite decision-making and improve supply chain management [76], [78], [79], [80].

Nano Bio Sensors for Shelf-Life Monitoring

Determining shelf life is crucial in food production and quality control. It evaluates when a food can maintain its desired quality, safety and performance under specific storage conditions. Nano biosensors are valuable in determining shelf life by offering real-time and accurate data on parameters that affect product stability. To determine shelf life, it is essential to consider a broad range of factors that may change over time. These parameters include sensory attributes such as taste, texture, colour, and nutrient content, microbial load, chemical composition, and processing characteristics. Periodic analysis of these parameters during storage can assess variability and aid in identifying when the product no longer meets acceptable quality standards. Accelerated Lifecycle Testing (ASLT) is a common method for estimating product durations. ASLT simulates the effects of rapidly changing environmental conditions, such as high temperature, humidity, or light exposure, on a shorter time scale to predict long-term storage effects. Nano biosensors assist in ASLT by continuously monitoring changes in and recording relevant parameters. Nano biosensors offer real-time feedback and valuable insights into product stability and degradation processes, aiding in determining overall shelf life. In summary, nano biosensors enhance shelf-life accuracy and efficiency by providing real-time analysis of critical parameters that enable them to determine shelf life [71], [77], [78], [79].

Traditional Methods vs Nano Biosensors for Shelf-Life Monitoring

Food product shelf-life monitoring traditionally involved manual analysis, laboratory testing, and sensory evaluation. Nano biosensors have revolutionized monitoring by offering significant advantages over conventional methods. Sensory evaluation is a traditional method where trained assessors rate attributes such as taste, smell, appearance, and texture. However, sensory evaluation can be subjective, biased, and limited in information. In contrast, nano biosensors offer real-time and objective information about traits such as volatiles, pH levels, or enzymatic activities. They offer quantitative measurements, reducing subjectivity and providing accurate and consistent information, regardless of changes in innovation and quality [81].

Cytology is another traditional method involving laboratory testing to detect the presence and growth of microorganisms or pathogens. This process can be time-consuming and may not yield immediate results. In contrast, nano biosensors allow real-time monitoring of microbial activity, enabling quick microbial detection and quantification. They offer rapid results and direct detection of signs of damage or pathogens, enabling timely intervention and ensuring microbial safety. This method can be time-consuming and requires sample preparation and complex equipment. In contrast, nano biosensors offer continuous real-time monitoring of chemical parameters such as pH, oxidation markers, or gas content. They offer sensitive and selective detection, enabling immediate detection of chemical changes that affect product properties [81].

Physical testing, including texture, colour and physical properties, is usually performed by visual inspection or instrumental measurement in traditional methods. However, these tests can be subjective, requiring human interpretation, and may not account for subtle changes in material properties. In contrast, nano biosensors can offer accurate and quantitative measurements of physical properties, such as texture, using special nanomaterials or modifiers. They enable objective and sensitive detection, enabling the identification of transcriptional changes that can affect production efficiency. Nano biosensors provide more accurate and consistent results compared to optical or manual inspection. Time-temperature indicators (TTIs) offer an alternative to traditional methods, such as using labels or devices that change colours or provide visual cues based on cumulative temperature changes. However, TTIs provide limited information about changes in the material and require visual inspection. Nano biosensors can include time-temperature monitoring features, offering precise and detailed information on temperature changes. They offer real-time monitoring of temperature history, enhancing our understanding of temperature's impact on product quality and facilitating shelf-life determination [81].

Real-Time Monitoring Techniques

Real-time monitoring techniques are vital to ensuring the quality and safety of food products throughout their shelf life. A common approach involves using nano biosensors, where nanotechnology is utilized to detect and analyze specific compounds in real-time. These sensors can be integrated into food packaging or food processing to offer rapid and precise measurements of temperature, pH, humidity, and microbial activity. Nano biosensors offer accessibility oversight, enabling timely intervention and quality and safety assurance. Another crucial area for real-time monitoring is Internet of Things (IoT) devices. These sensors and connected devices gather and transmit data wirelessly. The food industry employs IoT devices to monitor temperature, humidity, and storage conditions. Stakeholders can monitor product quality in real-time by continuously collecting and sharing information in a centralized system. IoT devices allow for remote monitoring, data analysis, and automated alerts, aiding swift decision-making. Wireless sensor networks (WSNs) are interconnected sensors that wirelessly communicate to monitor and collect data from various points in the system. In food management, WSNs can monitor temperature, humidity, and gas content in storage areas or pipelines. The sensors communicate with a central control system, providing real-time environmental data. WSNs provide scalability, flexibility, and the ability to monitor large areas or multiple locations simultaneously. Imaging and vision systems use cameras, scanners, or spectrometers to capture images or analyze visual information about the food prod [81], [82], [83], [84].

E-nose systems use gas sensor systems to detect and analyze volatile compounds generated by food processing, while e-tongue systems use sensor systems to assess taste profiles. This system provides fast and real-time food taste and aroma analysis, facilitating quality control and sensory monitoring. Data analytics and machine learning algorithms are often combined with real-time analytics techniques to derive meaningful insights from the collected data. These techniques analyze patterns, look for anomalies, and predict future events based on real-time data. Using historical data and real-time measurements, combined with data analytics and machine learning for predictive modeling and optimizing decision support systems, enables food manufacturers to monitor priorities continuously, identify deviations from desired situations, and optimize decision-making. By implementing these real-time analytics techniques, technology acts as an active enabler, facilitating real-time decision-making, increasing productivity, reducing inventory spending, and ensuring customer satisfaction [85].

Detection of Spoilage Markers

The detection of spoilage indicators plays an important role in assessing the freshness and durability of food products. Spoilage markers are specific products or symbols produced by spoiled food, indicating the presence of spoilage. Several methods are available for determining these markers, including gas chromatography (GC) for identifying markers of thermal degradation and high-performance liquid chromatography (HPLC) for identifying nonvolatile compounds associated with degradation, such as organic acids or biogenic amines. GC works well for identifying markers of thermal degradation. At the same time, HPLC is suitable for identifying nonvolatile compounds associated with degradation, such as organic acids or biogenic amines. Enzyme-based assays are often used to identify markers of damage associated with enzymatic degradation. These assays use specific enzymes or cofactors that react with the target compound, producing a measurable signal. Biosensors, including nano biosensors, are increasingly used for rapid and real-time detection of damage markers. Nano biosensors incorporate nanomaterials or nanoscale structures to enhance sensitivity, selectivity, and real-time diagnostic capabilities. Markers of degradation such as volatile compounds, specific enzymes and microbial metabolites can be detected with high specificity and sensitivity [86], [87], [88], [89].

The Electronic Nose (E-Nose) system uses an array of gas sensors to detect volatile organic compounds (VOCs) associated with food spoilage, providing a unique pattern or "scent print" for identification purposes. Mass spectrometry (MS) is a powerful identification and annotation recognition alternative. MS provides detailed information on the sample's chemical composition, facilitating the identification of specific markers of degradation. The discovery method depends on the drugs of interest, the required sensitivity and selectivity, and the need for real-time monitoring. Nano biosensors offer advantages such as early detection, high sensitivity and can be incorporated into food packaging or manufacturing processes, enabling and contributing to real-time monitoring of spoilage signals so they are assured of food quality and safety [90].

Emerging Trends in Nano Biosensors for Food Packaging and Shelf-Life Monitoring

The field of nano biosensors for food packaging and shelf-life monitoring is developing rapidly, with many emerging products shaping their future applications. One trend is to miniaturize and embed nano biosensors as much as possible for incorporation into packaging materials or directly on food surfaces. These small sensors are cost-effective, disposable, and highly sensitive, allowing real-time temperature, humidity, pH, and microbial activity monitoring. Another trend is wireless communication technology connectivity, enabling remote monitoring of foods. This wireless and remote monitoring capability provides immediate access to critical information, enhances analysis, and facilitates quick decision-making. The development of multi-parameter sensing is also an important factor, enabling nano biosensors to detect multiple quality indicators simultaneously. By combining multiple sensors or using multiple sensing channels, these sensors can monitor various components in a single pipeline, providing a comprehensive view of nutritional quality and enhancing quality control. These systems offer dynamic functions such as real-time analysis, freshness indicators, and intelligent release of additives or pesticides. Nano biosensors detect signs of degradation, triggering alerts or interventions to extend shelf life and enhance product safety. Advances in nanomaterials are leading to the developing of highly sensitive and selective nano biosensors. Nanostructured materials can be adapted to interact with specific analytes, improve sensor performance, and enable accurate detection of dissolution markers. Integrating nano biosensors into food packaging and shelf-life monitoring systems is an emerging trend [91], [92].

Integration of Wireless and IoT Technologies

The integration of wireless communications and Internet of Things (IoT) technologies is transforming the use of nano biosensors for food packaging and shelf-life analysis. This integration allows for real-time data collection, transmission, and analysis, providing valuable insights into product quality and safety. One key aspect of this integration is wireless sensor networks (WSNs), where nano biosensors communicate wirelessly to monitor various parameters such as temperature, humidity, vibration, and more at different points in the packaging or warehouse. The data collected by these sensors are transmitted wirelessly to a central control system for remote monitoring and management of food products. IoT systems provide a centralized data storage and analysis system, facilitating seamless integration and communication between nano biosensors, data storage systems, and analytical tools. This connectivity enables stakeholders to access real-time information, receive alerts, and make informed decisions based on collected data. IoT technologies, combined with nano biosensors, can revolutionize the food industry by improving product quality and safety, reducing waste, and increasing efficiency in the supply chain.

Cloud computing is key in integrating nano biosensors, enabling flexible and efficient data processing and analysis. Sensor data collected from multiple sources can be stored and processed in the cloud efficiently, eliminating the need for local storage and audit resources. Cloud-based data analytics provide real-time insights,

trend analysis, and predictive models for shelf-life estimation and quality management. The combination of wireless and IoT technologies enables sensor data visualisation through a user-friendly interface. Stakeholders can access aggregated data through web-based dashboards or mobile applications, facilitating real-time analysis and enabling informed decision-making. Active alerts and reports can be generated when nano biosensors detect parameter deviations, enabling timely intervention and prompt product development to ensure product quality and safety. Data analysis and machine learning algorithms can be applied to collect sensor data, using historical data to identify patterns and assess product quality and shelf life and potential risks. Predictive models can be used to optimize storage conditions, predict the end of shelf life, and implement targeted quality control strategies for stakeholders [93], [94], [95], [96], [97].

Smart Packaging Solutions

Smart packaging solutions in the food industry use nano biosensors to provide proactive functionality and real-time monitoring capabilities. These solutions include advanced technologies to improve the quality of food packaging. Real-time monitoring is a key enabler of nano biosensors integrated into smart packaging, allowing continuous data collection on parameters such as temperature, humidity, gas content, microbial activity etc. The immediate delivery of this information allows for timely interventions and changes to help ensure product quality and safety. Quality indicators are often combined in smart packaging to inform consumers and stakeholders about the freshness and quality of food. Specific changes detected by nano biosensors and triggered by these signals can be colour change labels or visual signs of deterioration, alerting consumers to potential hazards. Smart packaging solutions can also be active release systems with additives to extend the shelf life of food products. They can provide antibiotics or preservatives. Nano biosensors monitor environmental conditions, detect signs of pollution, and trigger reactions that occur as needed. This proactive approach protects food quality and safety in the long term [98].

Authentication and traceability are important components of a smart packaging solution. An RFID tag or QR code can be inserted to verify the authenticity and origin of the food. Nano biosensors monitor and record environmental conditions during storage and transport, ensuring that the product remains within specified parameters. Storing and accessing this information through a trust system provides traceability and transparency throughout the supply chain. Smart packaging solutions also improve customer engagement through interactive features and information. QR codes on packaging provide consumers with product descriptions, nutrition information, or cooking instructions. Nano biosensors can track consumer usage patterns, providing insights into product development and marketing strategies. Nano biosensors enable the prediction of shelf life by continuous monitoring of the composition of the packaging. This information helps in inventory management, waste reduction, and supply chain efficiency. Smart packaging solutions with shelf-life prediction can improve planning and decision-making and ensure efficient use of resources. Promoting sustainability and reducing waste is another goal of smart packaging solutions. Nano biosensors prevent premature removal of safe-to-consume products by monitoring them in real-time. Smart packaging provides information about optimal storage conditions, helping consumers reduce food waste at home. Combining biodegradable materials and environmentally friendly designs contributes to environmental sustainability [99].

Advanced Sensing Approaches

In nano biosensors for food packaging and life cycle monitoring, significant progress is being made in advanced detection techniques to improve the efficiency and effectiveness of these biosensors. Notable advanced sensing techniques include surface-enhanced Raman spectroscopy (SERS), which combines nanomaterials with Raman spectroscopy to amplify signals and provide accurate detection without labelling. Plasmonic sensing uses metallic nanostructures to interact with target molecules, resulting in higher sensitivity and faster response times. Electrochemical sensing measures electrical signals generated during analyte-electrode contact, enabling sensitive and selective detection. Microfluidics-based sensing combines nano biosensors into a microfluidic system for efficient sample handling and analysis. Nanobar codes use encoded nanostructures with recognition elements for multiple signal recognition. Bio-inspired sensing draws inspiration from biological systems to develop highly sensitive and selective biosensors. Smartphone-based sensing uses smartphone capabilities for spatial analysis and data processing. These advanced detection techniques push the limits of nano biosensor technology, enabling improved accuracy, efficiency and real-time analysis to ensure food quality, safety and shelf life expansion [71], [100], [101].

Nanomaterials and Surface Modifications

Nanomaterials and surface modification are essential in improving the performance and efficiency of nano biosensors used for food packaging and shelf-life monitoring. These advances improve sensitivity, selectivity,

and stability, and they contribute to improved sensing with different analytes. Nanomaterials, such as nanoparticles, nanowires, and nanofilms, offer unique properties that can be tailored for specific sensing applications. By mechanical means, these materials can selectively interact with target analytes, leading to increased sensitivity and selectivity of nano biosensors. In addition, the nanomaterial offers a high area-to-volume ratio, amplifying the sensing signal and overall biosensor performance. Surface modification is important for immobilization of biomolecules such as antibodies or enzymes on the sensing surfaces of nano biosensors. These modifications facilitate the specific identification and binding of targets, allowing them to be identified. Techniques such as self-assembly of monolayers, chemical reactions, and layer-by-layer deposition are being used to achieve stable and continuous biomolecules, thereby increasing the sensitivity and specificity of biosensors [102], [103], [104], [105], [106].

Bioconjugation techniques are used to covalently attach biomolecules to nanomaterials or surface coatings, creating a working interface for sensing. This adds specific receptors or recognition elements to the biosensor surface, enabling detection and monitoring of target analytes. Scripting and other bioconjugation techniques, as well as nano functionality and nanocoatings, are applied to the surface of biosensors to improve their stability, selectivity, and overall performance [107], [108], [109], [110], [111].

Quantum dots (QDs) and fluorescent probes are used as labels or tags in nano biosensors to enable sensitivity and multiplex detection. These semiconductor nanocrystals and fluorescence probes offer unique optical properties, high signal-to-noise ratio, long-lived fluorescence, and compatibility with detection methods. When conjugated with biomolecules, QDs and fluorescence probes provide unique recognition and fluorescence-based readout. Incremental, nanostructured surfaces, obtained by patterning, nanoprinting, or nanotexturing, improve the sensing performance of biosensors. This surface modification increases the effective site sensing, increases analyte capture efficiency, and enhances binding specificity. In addition, nanostructured surfaces facilitate complex biomolecules, enhance their stability and contribute to the overall sensitivity, reproducibility and performance of nano biosensors [109].

Technical Challenges

The successful implementation of nano biosensors for food packaging and shelf-life monitoring faces several technical challenges that need to be addressed. These challenges include ensuring the stability and durability of the sensors to withstand the harsh conditions encountered during food processing, transportation, and storage. Standardization and reproducibility are crucial to ensure consistent and reliable sensor performance. Establishing standardized processes, materials, and characterization methods is essential to achieve comparable and consistent sensor performance, enabling widespread adoption and consumption of this technology in the market. Furthermore, the sensitivity and selectivity of the sensors need to be improved to ensure accurate and reliable monitoring of food products, and the scalability and manufacturing cost must be optimized to make the technology economically viable. Addressing these technical challenges is critical to successfully applying nano biosensors for food packaging and shelf-life monitoring.

Achieving high sensitivity and selectivity is an ongoing challenge in biosensor development. A major research objective is to increase the sensitivity of nano biosensors to detect low concentrations of analytes while maintaining their selectivity to distinguish between specific markers and interfering substances. Limits to improve portable detection and reducing false positives or false negatives are important. Scalability and manufacturing cost are important considerations for adopting nano biosensors. Ensuring that manufacturing becomes cost-effective on a large scale requires developing processes that can be manufactured, optimizing material costs, and simplifying manufacturing. Such efforts will enable the integration of nano biosensors into food packaging and monitoring systems, making them commercially viable and accessible [38], [112], [113].

Future Prospects and Opportunities

Nano-biosensors for food packaging and shelf-life monitoring hold great promise for the future, offering many possibilities and opportunities for development. One exciting opportunity is that artificial intelligence (AI) technology and nano biosensors will be combined. Using AI algorithms, analyzing complex data generated by sensors to predict shelf life, optimize warehousing conditions, and provide real-time feedback, machine learning models can be seen modelling and correlating data to improve nutrition management and decision-making. Another promising possibility is the development of multiple sensing mechanisms. Integrating multiple sensing methods such as optical, electrical, and biological, nano biosensors provide increased performance and versatility. These sensing techniques provide information that enables accurate and comprehensive monitoring of nutrition data. It opens up new possibilities for detecting analytes and monitoring multiple parameters simultaneously. The combination of wireless communication and Internet of Things (IoT) technologies is another area of great potential. Integrating nano biosensors into wireless networks allows real-time data to be transmitted and analyzed

remotely. This connectivity allows continuous monitoring of foods throughout the supply chain, providing valuable insights into their status and enabling prompt production in case of delays. The IoT integration also facilitates seamless communication between various stakeholders in the food industry, fostering collaboration and effective decision-making.

Conclusion

Nano biosensors offer exciting properties that can revolutionize food packaging and shelf life. These advanced sensing technologies have the potential to improve food safety, quality and sustainability by providing real-time, accurate and reliable information about the state of a of packaged foods. In this paper, we investigated the aspects of nano-biosensors for food packaging and storage time monitoring. Integrating nano biosensors into food packaging enables improved integrity and barrier characterization and provides improved protection against external factors that can affect food quality and shelf life, extending the life of the food products for storage. For shelf-life monitoring, nano biosensors offer advantages over conventional methods by providing real-time non-destructive monitoring of key parameters such as temperature, humidity, air content, and signals that indicate spoilage. This enables the sensor to detect quality and deterioration quickly, enabling timely intervention and reducing food waste. However, several challenges must be addressed to apply nano biosensors in the food industry successfully. Additional research and development efforts are needed for technical challenges such as sensor stability, standardization, feed matrix absorption, and scalability. Regulatory considerations for safety assessment, labelling, and appropriate regulation are also needed to ensure the safe and responsible use of nano biosensors. The future prospects and opportunities for nano biosensors on food packaging and shelf life are promising. Artificial intelligence (AI) technology can improve data analysis and decision-making, while multi-sensing techniques provide complete and accurate information. Wireless connectivity and IoT integration enable real-time and remote monitoring food packaging systems, improving efficiency and quality control. . In conclusion, nano biosensors represent a transformative technology in food packaging and shelf-life monitoring. By addressing the technical challenges, regulatory considerations and leveraging emerging trends, nano biosensors can revolutionize the food industry, ensuring safer, longer-lasting, and higher-quality food products while reducing waste and promoting sustainability. Continued research, innovation, and collaboration among scientists, engineers, regulators, and industry stakeholders will pave the way for the successful adoption and implementation of nano biosensors in the food packaging and monitoring landscape.

REFERENCES

1. Kumar, V., Raghuvanshi, S. K., & Kumar, S. (2022). Advances in Nanocomposite Thin-Film-Based Optical Fiber Sensors for Environmental Health Monitoring—A Review. In *IEEE Sensors Journal* (Vol. 22, Issue 15, pp. 14696–14707). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/jsen.2022.3185004>
2. Taleski, V., Bosnakovski, D., Zdravkowska, M., Nasov, I., & Trajkovska-Petkoska, A. (2015). Applications of nanotechnology and nanomicrobiology in food safety and health science. In *Proceedings of the 2nd National Food Conference with International Participation, Sofia, Bulgaria*. New Bulgarian University.
3. Kumar, D., Farrukh, Md., & Faisal, N. (2021). Nanocomposites in the Food Packaging Industry. In *Research Anthology on Food Waste Reduction and Alternative Diets for Food and Nutrition Security* (pp. 122–146). IGI Global. <https://doi.org/10.4018/978-1-7998-5354-1.ch006>
4. Tekmen, D. C. (2017). Nanofibers in Food Packaging. In *WEB Journal* 107.
5. Hribar, J., Pozrl, T., & Vidrih, R. (2018). Novel technologies in fruit and vegetable processing. In *Croatian Journal of Food Science and Technology* (Vol. 10, Issue 1, pp. 112–117). Faculty of Food Technology Osijek. <https://doi.org/10.17508/cjfst.2018.10.1.14>
6. Kaur, G., Bhari, R., & Kumar, K. (2023). Nanobiosensors and their role in detection of adulterants and contaminants in food products. In *Critical Reviews in Biotechnology* (pp. 1–15). Informa UK Limited. <https://doi.org/10.1080/07388551.2023.2175196>
7. Biswas, R., Alam, M., Sarkar, A., Haque, M. I., Hasan, Md. M., & Hoque, M. (2022). Application of nanotechnology in food: processing, preservation, packaging and safety assessment. In *Heliyon* (Vol. 8, Issue 11, p. e11795). Elsevier BV. <https://doi.org/10.1016/j.heliyon.2022.e11795>
8. Alkilany, A. M., Lohse, S. E., & Murphy, C. J. (2012). The Gold Standard: Gold Nanoparticle Libraries To Understand the Nano–Bio Interface. In *Accounts of Chemical Research* (Vol. 46, Issue 3, pp. 650–661). American Chemical Society (ACS). <https://doi.org/10.1021/ar300015b>
9. Wang, J., Zhou, Y., & Jiang, L. (2021). Bio-inspired Track-Etched Polymeric Nanochannels: Steady-State Biosensors for Detection of Analytes. In *ACS Nano* (Vol. 15, Issue 12, pp. 18974–19013). American Chemical Society (ACS). <https://doi.org/10.1021/acsnano.1c08582>

10. Adam, T., Dhahi, T. S., Gopinath, S. C. B., & Hashim, U. (2021). Novel Approaches in Fabrication and Integration of Nanowire for Micro/Nano Systems. In *Critical Reviews in Analytical Chemistry* (Vol. 52, Issue 8, pp. 1913–1929). Informa UK Limited. <https://doi.org/10.1080/10408347.2021.1925523>
11. Rai, V. R., & Bai, J. A. (2018). *Nanotechnology Applications in the Food Industry* (V. R. Rai & J. A. Bai, Eds.). CRC Press. <https://doi.org/10.1201/9780429488870>
12. Johnson, M. S., Sajeev, S., & Nair, R. S. (2021). Role of Nanosensors in agriculture. In *2021 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE)*. 2021 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE). IEEE. <https://doi.org/10.1109/iccike51210.2021.9410709>
13. Bratovic, A., Odobasic, A., Catic, S., & Sestan, I. (2015). Application of polymer nanocomposite materials in food packaging. In *Croatian Journal of Food Science and Technology* (Vol. 7, Issue 2, pp. 86–94). Faculty of Food Technology Osijek. <https://doi.org/10.17508/cjfst.2015.7.2.06>
14. Kumar, N., Kaur, P., & Bhatia, S. (2017). Advances in bio-nanocomposite materials for food packaging: a review. In *Nutrition & Food Science* (Vol. 47, Issue 4, pp. 591–606). Emerald. <https://doi.org/10.1108/nfs-11-2016-0176>
15. El-Sayed, S. M., & Youssef, A. M. (2023). Eco-friendly biodegradable nanocomposite materials and their recent use in food packaging applications: a review. In *Sustainable Food Technology* (Vol. 1, Issue 2, pp. 215–227). Royal Society of Chemistry (RSC). <https://doi.org/10.1039/d2fb00021k>
16. Thekkethil, A. J., Nair, R., & Madhavan, A. (2019). The Role Of Nanotechnology In Food Safety: A Review. In *2019 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE)*. 2019 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE). IEEE. <https://doi.org/10.1109/iccike47802.2019.9004412>
17. Stavrov, V., Stavreva, G., Tomerov, E., Villani, M., Kotsev, S., & Kostadinov, K. (2021). Piezoresistive cantilevers' platform for bio-chemical sensing. In *2021 IEEE International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO)*. 2021 IEEE International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO). IEEE. <https://doi.org/10.1109/3m-nano49087.2021.9599795>
18. Kato, L. S., & Conte-Junior, C. A. (2021). Safety of Plastic Food Packaging: The Challenges about Non-Intentionally Added Substances (NIAS) Discovery, Identification and Risk Assessment. In *Polymers* (Vol. 13, Issue 13, p. 2077). MDPI AG. <https://doi.org/10.3390/polym13132077>
19. Dr. T., K., A., V., K., M., K., & K., K. (2023). Food Quality Monitoring System Based On IoT. In *International Journal of Innovative Research in Engineering* (pp. 375–378). Fifth Dimension Research Publications. <https://doi.org/10.59256/ijire.20230403103>
20. Benefo, E. O., Karanth, S., & Pradhan, A. K. (2022). Applications of advanced data analytic techniques in food safety and risk assessment. In *Current Opinion in Food Science* (Vol. 48, p. 100937). Elsevier BV. <https://doi.org/10.1016/j.cofs.2022.100937>
21. Yousefi, H., Su, H.-M., Imani, S. M., Alkhalidi, K., M. Filipe, C. D., & Didar, T. F. (2019). Intelligent Food Packaging: A Review of Smart Sensing Technologies for Monitoring Food Quality. In *ACS Sensors* (Vol. 4, Issue 4, pp. 808–821). American Chemical Society (ACS). <https://doi.org/10.1021/acssensors.9b00440>
22. Mustafa, F., & Andreescu, S. (2018). Chemical and Biological Sensors for Food-Quality Monitoring and Smart Packaging. In *Foods* (Vol. 7, Issue 10, p. 168). MDPI AG. <https://doi.org/10.3390/foods7100168>
23. Hassan, R. Y. A. (2022). Advances in Electrochemical Nano-Biosensors for Biomedical and Environmental Applications: From Current Work to Future Perspectives. In *Sensors* (Vol. 22, Issue 19, p. 7539). MDPI AG. <https://doi.org/10.3390/s22197539>
24. Rahman, B. M. A., Viphavakit, C., Chitaree, R., Ghosh, S., Pathak, A. K., Verma, S., & Sakda, N. (2022). Optical Fiber, Nanomaterial, and THz-Metasurface-Mediated Nano-Biosensors: A Review. In *Biosensors* (Vol. 12, Issue 1, p. 42). MDPI AG. <https://doi.org/10.3390/bios12010042>
25. Aquino, A., Paschoalin, V. M. F., Tessaro, L. L. G., Raymundo-Pereira, P. A., & Conte-Junior, C. A. (2022). Updating the use of nano-biosensors as promising devices for the diagnosis of coronavirus family members: A systematic review. In *Journal of Pharmaceutical and Biomedical Analysis* (Vol. 211, p. 114608). Elsevier BV. <https://doi.org/10.1016/j.jpba.2022.114608>
26. Steffens, C., Leite, F. L., Bueno, C. C., Manzoli, A., & Herrmann, P. S. D. P. (2012). Atomic Force Microscopy as a Tool Applied to Nano/Biosensors. In *Sensors* (Vol. 12, Issue 6, pp. 8278–8300). MDPI AG. <https://doi.org/10.3390/s120608278>
27. Thanaraj, M., Rathanasamy, R., & Jaganathan, S. K. (2021). Advancements in Ultra-Sensitive Nanoelectronic Biosensors for Medical Applications. In *Current Nanoscience* (Vol. 17, Issue 5, pp. 679–693). Bentham Science Publishers Ltd. <https://doi.org/10.2174/1573413717666210121141858>

28. Chawla, P. A., Sharma, D., Teli, G., Gupta, K., Bansal, G., & Gupta, G. D. (2022). Nano-biosensors from Agriculture to Nextgen Diagnostic Tools. In *Current Nanomaterials* (Vol. 7, Issue 2, pp. 110–138). Bentham Science Publishers Ltd. <https://doi.org/10.2174/240546150766220131104843>
29. Zhang, X., Shi, Y., Chen, G., Wu, D., Wu, Y., & Li, G. (2022). CRISPR/Cas Systems-Inspired Nano/Biosensors for Detecting Infectious Viruses and Pathogenic Bacteria. In *Small Methods* (Vol. 6, Issue 10, p. 2200794). Wiley. <https://doi.org/10.1002/smtd.202200794>
30. Sharma, A., Ranjit, R., Pratibha, Kumar, N., Kumar, M., & Giri, B. S. (2023). Nanoparticles based nanosensors: Principles and their applications in active packaging for food quality and safety detection. In *Biochemical Engineering Journal* (Vol. 193, p. 108861). Elsevier BV. <https://doi.org/10.1016/j.bej.2023.108861>
31. Sobhan, A., Muthukumarappan, K., & Wei, L. (2021). Biosensors and biopolymer-based nanocomposites for smart food packaging: Challenges and opportunities. In *Food Packaging and Shelf Life* (Vol. 30, p. 100745). Elsevier BV. <https://doi.org/10.1016/j.fpsl.2021.100745>
32. Chen, S., Hwang, M. T., Wang, J., Ganguli, A., Park, I., Kim, Y., Valera, E., Nam, S., Aluru, N. R., Van Der Zande, A. M., & Bashir, R. (2022). Advances in Electronic Nano-biosensors and New Frontiers in Bioengineering. In *2022 International Electron Devices Meeting (IEDM). 2022 IEEE International Electron Devices Meeting (IEDM)*. IEEE. <https://doi.org/10.1109/iedm45625.2022.10019512>
33. Wasilewska, A., Bielicka, M., Klekotka, U., & Kalska-Szostko, B. (2023). Nanoparticle applications in food – a review. In *Food & Function* (Vol. 14, Issue 6, pp. 2544–2567). Royal Society of Chemistry (RSC). <https://doi.org/10.1039/d2fo02180c>
34. Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. In *RSC Advances* (Vol. 10, Issue 33, pp. 19309–19336). Royal Society of Chemistry (RSC). <https://doi.org/10.1039/d0ra01084g>
35. Manjunatha, R. L., Naik, D., & Usharani, K. V. (2019). Nanotechnology Application in Agriculture: A Review. In *Journal of Pharmacognosy and Phytochemistry* (Vol. 8, Issue 3, pp. 1073–1083). Society of Pharmacognosy and Phytochemistry.
36. Nguyen, J. T., & Cheng, W. (2022). A Review on Epidermal Nanogenerators: Recent Progress of the Future Self-Powered Skins. In *Small Structures* (Vol. 3, Issue 8, p. 2200034). Wiley. <https://doi.org/10.1002/ssstr.202200034>
37. Dutta, S., Corni, S., & Brancolini, G. (2022). Atomistic Simulations of Functionalized Nano-Materials for Biosensors Applications. In *International Journal of Molecular Sciences* (Vol. 23, Issue 3, p. 1484). MDPI AG. <https://doi.org/10.3390/ijms23031484>
38. Feng, L., Song, S., Li, H., He, R., Chen, S., Wang, J., Zhao, G., & Zhao, X. (2023). Nano-Biosensors Based on Noble Metal and Semiconductor Materials: Emerging Trends and Future Prospects. In *Metals* (Vol. 13, Issue 4, p. 792). MDPI AG. <https://doi.org/10.3390/met13040792>
39. Kierk, I., Bockrath, M., & Landi, M. (2007). Novel nano-biosensors for life science systems and their applications in early, accurate, and non-invasive melanoma and other types of cancer detection. In *2007 IEEE/NIH Life Science Systems and Applications Workshop. 2007 IEEE/NIH Life Science Systems and Applications Workshop*. IEEE. <https://doi.org/10.1109/lssa.2007.4400901>
40. Mohamed, A. T. (2021). Emerging Nanotechnology Applications in Electrical Engineering. In *Advances in Computer and Electrical Engineering*. IGI Global. <https://doi.org/10.4018/978-1-7998-8536-8>
41. Moulahoum, H., Ghorbanizamani, F., Guler Celik, E., & Timur, S. (2022). Nano-Scaled Materials and Polymer Integration in Biosensing Tools. In *Biosensors* (Vol. 12, Issue 5, p. 301). MDPI AG. <https://doi.org/10.3390/bios12050301>
42. Zhao, L., Zhou, Y., Niu, G., Gao, F., Sun, Z., Li, H., & Jiang, Y. (2022). Advances in Chiral Gold Nano-Assemblies and Their Bioapplication Based on Optical Properties. In *Particle & Particle Systems Characterization* (Vol. 39, Issue 4, p. 2100231). Wiley. <https://doi.org/10.1002/ppsc.202100231>
43. Malhotra, B. D., Srivastava, S., & Augustine, S. (2015). Biosensors for Food Toxin Detection: Carbon Nanotubes and Graphene. In *MRS Proceedings* (Vol. 1725). Springer Science and Business Media LLC. <https://doi.org/10.1557/opl.2015.165>
44. Domínguez-Aragón, A., Domínguez, R. B., & Zaragoza-Contreras, E. A. (2021). Simultaneous Detection of Dihydroxybenzene Isomers Using Electrochemically Reduced Graphene Oxide-Carboxylated Carbon Nanotubes/Gold Nanoparticles Nanocomposite. In *Biosensors* (Vol. 11, Issue 9, p. 321). MDPI AG. <https://doi.org/10.3390/bios11090321>
45. Burdanova, M. G., Kharlamova, M. V., Kramberger, C., & Nikitin, M. P. (2021). Applications of Pristine and Functionalized Carbon Nanotubes, Graphene, and Graphene Nanoribbons in Biomedicine. In *Nanomaterials* (Vol. 11, Issue 11, p. 3020). MDPI AG. <https://doi.org/10.3390/nano11113020>

46. Ma, C., Gao, Q., Hong, W., Fan, J., & Fang, J. (2016). Real-Time Probing Nanopore-in-Nanogap Plasmonic Coupling Effect on Silver Supercrystals with Surface-Enhanced Raman Spectroscopy. In *Advanced Functional Materials* (Vol. 27, Issue 2, p. 1603233). Wiley. <https://doi.org/10.1002/adfm.201603233>
47. Chen, S., Li, M., Weng, T., Wang, D., & Geng, J. (2023). Recent progress of biosensors for the detection of lung cancer markers. In *Journal of Materials Chemistry B* (Vol. 11, Issue 25, pp. 5715–5747). Royal Society of Chemistry (RSC). <https://doi.org/10.1039/d2tb02277j>
48. Koh, E. H., Lee, W.-C., Choi, Y.-J., Moon, J.-I., Jang, J., Park, S.-G., Choo, J., Kim, D.-H., & Jung, H. S. (2021). A Wearable Surface-Enhanced Raman Scattering Sensor for Label-Free Molecular Detection. In *ACS Applied Materials & Interfaces* (Vol. 13, Issue 2, pp. 3024–3032). American Chemical Society (ACS). <https://doi.org/10.1021/acscami.0c18892>
49. Lee, S.-K., Jung, J.-M., Lee, J.-S., & Jung, H.-T. (2010). Fabrication of Complex Patterns with a Wide Range of Feature Sizes from a Single Line Prepattern by Successive Application of Capillary Force Lithography. In *Langmuir* (Vol. 26, Issue 17, pp. 14359–14363). American Chemical Society (ACS). <https://doi.org/10.1021/la100414c>
50. Acevedo, D. A., Lasagni, A. F., Barbero, C. A., & Mücklich, F. (2007). Simple Fabrication Method of Conductive Polymeric Arrays by Using Direct Laser Interference Micro-/Nanopatterning. In *Advanced Materials* (Vol. 19, Issue 9, pp. 1272–1275). Wiley. <https://doi.org/10.1002/adma.200601693>
51. Barbillon, G. (2013). Sub-30 nm Plasmonic Nanostructures by Soft UV Nanoimprint Lithography. In *Updates in Advanced Lithography*. InTech. <https://doi.org/10.5772/56119>
52. Lee, K.-L., Wu, T.-Y., Hsu, H.-Y., Yang, S.-Y., & Wei, P.-K. (2017). Low-Cost and Rapid Fabrication of Metallic Nanostructures for Sensitive Biosensors Using Hot-Embossing and Dielectric-Heating Nanoimprint Methods. In *Sensors* (Vol. 17, Issue 7, p. 1548). MDPI AG. <https://doi.org/10.3390/s17071548>
53. Chen, Y., Li, Z., Zhang, Z., & Scherer, A. (2011). Fabrication of Circular Grating Distributed Feedback Dye Laser by Nanoimprint Lithography. In *Recent Advances in Nanofabrication Techniques and Applications*. InTech. <https://doi.org/10.5772/20577>
54. Biosensor for detection of bacteria with probiotic potential and food pathogens. (2020). In *Letters in Applied NanoBioScience* (Vol. 9, Issue 1, pp. 800–807). AMG Transcend Association. <https://doi.org/10.33263/lianbs91.800807>
55. S, B., & S, B. (2016). Plasmonic Sensors for Disease Detection - A Review. In *Journal of Nanomedicine & Nanotechnology* (Vol. 7, Issue 3). OMICS Publishing Group. <https://doi.org/10.4172/2157-7439.1000373>
56. Lymberis, A. (2008). Converging micro-nano-bio technologies towards integrated biomedical systems: State of the art and future perspectives under the EU-information & communication technologies program. In *2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE. <https://doi.org/10.1109/iembs.2008.4649076>
57. Su, J., Liu, W., Chen, S., Deng, W., Dou, Y., Zhao, Z., Li, J., Li, Z., Yin, H., Ding, X., & Song, S. (2020). A Carbon-Based DNA Framework Nano–Bio Interface for Biosensing with High Sensitivity and a High Signal-to-Noise Ratio. In *ACS Sensors* (Vol. 5, Issue 12, pp. 3979–3987). American Chemical Society (ACS). <https://doi.org/10.1021/acssensors.0c01745>
58. Halonen, N., Pálvölgyi, P. S., Bassani, A., Fiorentini, C., Nair, R., Spigno, G., & Kordas, K. (2020). Bio-Based Smart Materials for Food Packaging and Sensors – A Review. In *Frontiers in Materials* (Vol. 7). Frontiers Media SA. <https://doi.org/10.3389/fmats.2020.00082>
59. Mylvaganam, H. (2020). Application of Nanotechnology in Food Packaging: A Review. In *Journal of Food Technology and Preservation* (Vol. 4, Issue 4, pp. 1–4). Pubtexto Publishers.
60. Hefft, D. I. (2017). Developments and Properties of Plastic Mimicking Biopolymers for Food Packaging Application. In *Journal of Applied Packaging Research* (Vol. 9, Issue 2, pp. 47–60). The Rochester Institute of Technology.
61. Cheng, C., Chen, S., Su, J., Zhu, M., Zhou, M., Chen, T., & Han, Y. (2022). Recent advances in carrageenan-based films for food packaging applications. In *Frontiers in Nutrition* (Vol. 9). Frontiers Media SA. <https://doi.org/10.3389/fnut.2022.1004588>
62. Avila, L. B., Schnorr, C., Silva, L. F. O., Morais, M. M., Moraes, C. C., da Rosa, G. S., Dotto, G. L., Lima, É. C., & Naushad, Mu. (2023). Trends in Bioactive Multilayer Films: Perspectives in the Use of Polysaccharides, Proteins, and Carbohydrates with Natural Additives for Application in Food Packaging. In *Foods* (Vol. 12, Issue 8, p. 1692). MDPI AG. <https://doi.org/10.3390/foods12081692>
63. Doderò, A., Escher, A., Bertucci, S., Castellano, M., & Lova, P. (2021). Intelligent Packaging for Real-Time Monitoring of Food-Quality: Current and Future Developments. In *Applied Sciences* (Vol. 11, Issue 8, p. 3532). MDPI AG. <https://doi.org/10.3390/app11083532>

64. Tan, C., Han, F., Zhang, S., Li, P., & Shang, N. (2021). Novel Bio-Based Materials and Applications in Antimicrobial Food Packaging: Recent Advances and Future Trends. In *International Journal of Molecular Sciences* (Vol. 22, Issue 18, p. 9663). MDPI AG. <https://doi.org/10.3390/ijms22189663>
65. Salgado, P. R., Di Giorgio, L., Musso, Y. S., & Mauri, A. N. (2021). Recent Developments in Smart Food Packaging Focused on Biobased and Biodegradable Polymers. In *Frontiers in Sustainable Food Systems* (Vol. 5). Frontiers Media SA. <https://doi.org/10.3389/fsufs.2021.630393>
66. Jian, W. (2014). Analysis on Food Packaging Materials Laws and Regulations and Standards Between China and Some Developed Countries. *Journal of Food Safety and Quality*.
67. Amirullah, N. A., Samsudin, M. H., Norrahim, M. N. F., Ilyas, R. A., Nurazzi, N. M., Jenol, M. A., Hawanis, H. S. N., & Gunny, A. A. N. (2023). Regulations for food packaging materials. In *Physical Sciences Reviews* (Vol. 0, Issue 0). Walter de Gruyter GmbH. <https://doi.org/10.1515/psr-2022-0033>
68. Tarina, D.D.Y., Hutabarat, S.M.D., & Sakti, M. (2019). Implementation of Labeling Standards for Food Packaging Products in Indonesia. *International Journal of Multicultural and Multireligious Understanding (IJMMU)*, 6(Special Issue 1), 1-20.
69. B T, C., A, K., & K Sanikop, N. (2021). Food Packaging in India: An Overview. In *International Research Journal on Advanced Science Hub* (Vol. 3, Issue Special Issue 7S, pp. 103–110). RSP Science Hub. <https://doi.org/10.47392/irjash.2021.218>
70. Prakash, A., Sen, S., & Dixit, R. (2013). The Emerging Usage and Applications of Nanotechnology in Food Processing Industries: The New Age of Nanofood. In *International Journal of Pharmaceutical Sciences Review and Research* (Vol. 22, Issue 21, pp. 107–111). Global Research Online.
71. Wegari Dera, M., & Bogale Teseme, W. (2020). Review on the Application of Food Nanotechnology in Food Processing. In *American Journal of Engineering and Technology Management* (Vol. 5, Issue 2, p. 41). Science Publishing Group. <https://doi.org/10.11648/j.ajetm.20200502.12>
72. Berekaa, M. M. (2015). Nanotechnology in Food Industry: Advances in Food Processing, Packaging, and Food Safety. In *International Journal of Current Microbiology and Applied Sciences* (Vol. 4, Issue 5, pp. 345–357). Self publishing.
73. H. G. Prakash, S. D., & Seema Sonkar, P. M. (2021). Potential Application of Nanotechnology in Food Processing and Packaging: A Review. In *International Journal of Current Microbiology and Applied Sciences* (Vol. 10, Issue 10, pp. 601–613). Excellent Publishers. <https://doi.org/10.20546/ijcmas.2021.1010.070>
74. Frewer, L. J., Norde, W., Fischer, A., & Kampers, F. (Eds.). (2011). *Nanotechnology in the Agri-Food Sector*. Wiley. <https://doi.org/10.1002/9783527634798>
75. EA, H. (2016). Nano-biotechnology breakthrough and food-packing industry- A Review. In *Microbial Biosystems* (Vol. 1, Issue 1, pp. 50–69). Egypt's Presidential Specialized Council for Education and Scientific Research. <https://doi.org/10.21608/mb.2016.5257>
76. John, A., Črešnar, K. P., Bikiaris, D. N., & Zemljčič, L. F. (2023). Colloidal Solutions as Advanced Coatings for Active Packaging Development: Focus on PLA Systems. In *Polymers* (Vol. 15, Issue 2, p. 273). MDPI AG. <https://doi.org/10.3390/polym15020273>
77. Baghi, F., Gharsallaoui, A., Dumas, E., & Ghnimi, S. (2022). Advancements in Biodegradable Active Films for Food Packaging: Effects of Nano/Microcapsule Incorporation. In *Foods* (Vol. 11, Issue 5, p. 760). MDPI AG. <https://doi.org/10.3390/foods11050760>
78. Soria-Lopez, A., Carpena, M., Nuñez-Estevez, B., Garcia-Oliveira, P., Collazo, N., Otero, P., Garcia-Perez, P., Cao, H., Xiao, J., Carocho, M., Barros, L., Simal-Gandara, J., & Prieto, M. A. (2021). Essential Oils as Possible Candidates to Be Included in Active Packaging Systems and the Use of Biosensors to Monitor the Quality of Foodstuff. In *The 1st International Electronic Conference on Chemical Sensors and Analytical Chemistry*. CSAC2021. MDPI. <https://doi.org/10.3390/csac2021-10485>
79. E Trujillo, L., & Avalos, R. (2016). Nanotechnology Applications for Food and Bioprocessing Industries. In *Biology and Medicine* (Vol. 08, Issue 03). OMICS Publishing Group. <https://doi.org/10.4172/0974-8369.1000289>
80. Gao, F., Feng, S., Chen, Z., Li-Chan, E. C. Y., Grant, E., & Lu, X. (2014). Detection and Quantification of Chloramphenicol in Milk and Honey Using Molecularly Imprinted Polymers: Canadian Penny-Based SERS Nano-Biosensor. In *Journal of Food Science* (Vol. 79, Issue 12, pp. N2542–N2549). Wiley. <https://doi.org/10.1111/1750-3841.12705>
81. Dautta, M., Dia, K. K. H., Hajiaghajani, A., Escobar, A. R., Alshetaiwi, M., & Tseng, P. (2021). Multiscale, Nano- to Mesostructural Engineering of Silk Biopolymer-Interlayer Biosensors for Continuous Comonitoring of Nutrients in Food. In *Advanced Materials Technologies* (Vol. 7, Issue 2, p. 2100666). Wiley. <https://doi.org/10.1002/admt.202100666>

82. Naresh, Varnakavi., & Lee, N. (2021). A Review on Biosensors and Recent Development of Nanostructured Materials-Enabled Biosensors. In *Sensors* (Vol. 21, Issue 4, p. 1109). MDPI AG. <https://doi.org/10.3390/s21041109>
83. Guo, Z. (2014). Development of Electrochemical Biosensors for Environmental Pollutant and Food Safety Monitoring. [Doctoral dissertation, Université Claude Bernard - Lyon]. Retrieved from <https://theses.hal.science/tel-01128300/document>.
84. Kadam, A. A., Saratale, G. D., Ghodake, G. S., Saratale, R. G., Shahzad, A., Magotra, V. K., Kumar, M., Palem, R. R., & Sung, J.-S. (2022). Recent Advances in the Development of Laccase-Based Biosensors via Nano-Immobilization Techniques. In *Chemosensors* (Vol. 10, Issue 2, p. 58). MDPI AG. <https://doi.org/10.3390/chemosensors10020058>
85. Santos, A. S. (2017). Meat and Meat Chain - Development of a New Molecular Diagnostic Test. [Doctoral dissertation, Universidade do Porto]. Retrieved from <https://repositorio-aberto.up.pt/bitstream/10216/104296/2/193401.pdf>.
86. Asano, S., Shimokawa, M., & Suzuki, K. (2018). PCR Analysis Methods for Detection and Identification of Beer-Spoilage Lactic Acid Bacteria. In *Lactic Acid Bacteria* (pp. 95–107). Springer New York. https://doi.org/10.1007/978-1-4939-8907-2_9
87. Longin, C., Laforgue, R., Badet-Murat, M.-L., & Alexandre, H. (2022). Flow cytometry, a sustainable method for the identification and quantification of microorganisms in enology - Part 1/2 Review of the usual methods applied in wine microbiology and the principle of flow cytometry. In *IVES Technical Reviews, vine and wine*. Université de Bordeaux. <https://doi.org/10.20870/ives-tr.2022.7303>
88. Carraturo, F. (2017). Metabolomic profiling and molecular characterization of food matrices: identification of potential markers of microbial contamination. UNINA/FEDOA. <https://doi.org/10.6093/UNINA/FEDOA/11474>
89. Chen, H., Wortmann, A., & Zenobi, R. (2007). Neutral desorption sampling coupled to extractive electrospray ionization mass spectrometry for rapid differentiation of biosamples by metabolomic fingerprinting. In *Journal of Mass Spectrometry* (Vol. 42, Issue 9, pp. 1123–1135). Wiley. <https://doi.org/10.1002/jms.1282>
90. MD, O., PA, B., AG, P., & AM, P. (2009). Protein analysis: progress of analytical techniques. In *International Journal of Chemical Research* (Vol. 1, Issue 2, pp. 8–17). Bioinfo Publications. <https://doi.org/10.9735/0975-3699.1.2.8-17>
91. Ghosh, T., Raj, G. V. S. B., & Dash, K. K. (2022). A comprehensive review on nanotechnology based sensors for monitoring quality and shelf life of food products. In *Measurement: Food* (Vol. 7, p. 100049). Elsevier BV. <https://doi.org/10.1016/j.meafoo.2022.100049>
92. Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. In *RSC Advances* (Vol. 10, Issue 33, pp. 19309–19336). Royal Society of Chemistry (RSC). <https://doi.org/10.1039/d0ra01084g>
93. Sharma, S. K., & Wang, X. (2017). Live Data Analytics With Collaborative Edge and Cloud Processing in Wireless IoT Networks. In *IEEE Access* (Vol. 5, pp. 4621–4635). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/access.2017.2682640>
94. Mirza Baig, M., & Sonekar, Dr. S. (2022). Improving Health WSN with Distinguished Cloud Computing for Multi-Sensor Analytics. In *International Journal of Next-Generation Computing*. Perpetual Innovation Media Pvt. Ltd. <https://doi.org/10.47164/ijngc.v13i5.972>
95. Raghavendra, P. & Naika, S. C. L. (2018). Mobile Edge Cloud Computing with Big Data Analytics in IoT Networks. In *International Journal of Creative Research Thoughts* (Vol. 6, Issue 2, pp. 166–170). IJPUBLICATION.
96. Krishna, P. V., Yenduri, S., & Ariwa, E. (Eds.). (2020). In *International Journal of Communication Systems* (Vol. 33, Issue 13). Wiley. <https://doi.org/10.1002/dac.v33i13>
97. Ndunagu, J. N., Ukhurebor, K. E., Akaaza, M., & Onyancha, R. B. (2022). Development of a Wireless Sensor Network and IoT-based Smart Irrigation System. In M. Turjaman (Ed.), *Applied and Environmental Soil Science* (Vol. 2022, pp. 1–13). Hindawi Limited. <https://doi.org/10.1155/2022/7678570>
98. Shamrao, B.P. & Sadashivrao, P.V. (2022). Antioxidant Properties of Silver Nanoparticles and Methanol Extract of Cinnamomum verum Bark. In *International Journal of Creative Research Thoughts* (Vol. 10, Issue 2, pp. 526–534). IJPUBLICATION.
99. Fernandez, C. M., Alves, J., Gaspar, P. D., Lima, T. M., & Silva, P. D. (2022). Innovative processes in smart packaging. A systematic review. In *Journal of the Science of Food and Agriculture* (Vol. 103, Issue 3, pp. 986–1003). Wiley. <https://doi.org/10.1002/jsfa.11863>

100. Yousefi, H., Su, H.-M., Imani, S. M., Alkhalidi, K., M. Filipe, C. D., & Didar, T. F. (2019). Intelligent Food Packaging: A Review of Smart Sensing Technologies for Monitoring Food Quality. In ACS Sensors (Vol. 4, Issue 4, pp. 808–821). American Chemical Society (ACS). <https://doi.org/10.1021/acssensors.9b00440>
101. Kumar, V., Raghuvanshi, S. K., & Kumar, S. (2022). Recent Advances in Carbon Nanomaterials Based SPR Sensor for Biomolecules and Gas Detection—A Review. In IEEE Sensors Journal (Vol. 22, Issue 16, pp. 15661–15672). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/jсен.2022.3191042>
102. Aggudey, D.D. (2020). Graphene-like 2-D Nanomaterials and Their Properties. [Doctoral dissertation, Montclair State University]. Retrieved from <https://digitalcommons.montclair.edu/etd/342/>.
103. Narayanan, K. B., & Han, S. S. (2017). Helical plant viral nanoparticles—bioinspired synthesis of nanomaterials and nanostructures. In Bioinspiration & Biomimetics (Vol. 12, Issue 3, p. 031001). IOP Publishing. <https://doi.org/10.1088/1748-3190/aa6bfd>
104. Ratre, P., Nazeer, N., Kumari, R., Thareja, S., Jain, B., Tiwari, R., Kamthan, A., Srivastava, R. K., & Mishra, P. K. (2023). Carbon-Based Fluorescent Nano-Biosensors for the Detection of Cell-Free Circulating MicroRNAs. In Biosensors (Vol. 13, Issue 2, p. 226). MDPI AG. <https://doi.org/10.3390/bios13020226>
105. Gupta, P., Mittal, A. K., Mishra, K., Handa, N., & Paul, M. K. (2023). Current Expansion of Silver and Gold Nanomaterials towards Cancer Theranostics: Development of Therapeutics. In Current Nanoscience (Vol. 19). Bentham Science Publishers Ltd. <https://doi.org/10.2174/1573413719666230503144904>
106. Singhal, J., Verma, S., Kumar, S., & Mehrotra, D. (2021). Recent Advances in Nano-Bio-Sensing Fabrication Technology for the Detection of Oral Cancer. In Molecular Biotechnology (Vol. 63, Issue 5, pp. 339–362). Springer Science and Business Media LLC. <https://doi.org/10.1007/s12033-021-00306-x>
107. Wang, H., Xue, Z., Dardir, K., & Fabris, L. (2021). Bioconjugation strategies toward efficient intracellular nanoparticle probes. In M. Osiński & A. G. Kanaras (Eds.), Colloidal Nanoparticles for Biomedical Applications XVI. SPIE. <https://doi.org/10.1117/12.2583250>
108. Mohd Asri, M. A., Nordin, A. N., & Ramli, N. (2021). Low-cost and cleanroom-free prototyping of microfluidic and electrochemical biosensors: Techniques in fabrication and bioconjugation. In Biomicrofluidics (Vol. 15, Issue 6). AIP Publishing. <https://doi.org/10.1063/5.0071176>
109. Hunt, H. K., & Armani, A. M. (2014). Bioconjugation Strategies for Label-Free Optical Microcavity Sensors. In IEEE Journal of Selected Topics in Quantum Electronics (Vol. 20, Issue 2, pp. 121–133). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/jstqe.2013.2272916>
110. Liébana, S., & Drago, G. A. (2016). Bioconjugation and stabilisation of biomolecules in biosensors. In P. Estrela (Ed.), Essays in Biochemistry (Vol. 60, Issue 1, pp. 59–68). Portland Press Ltd. <https://doi.org/10.1042/ebc20150007>
111. Hunt, H. K., Soteropoulos, C., & Armani, A. M. (2010). Bioconjugation Strategies for Microtoroidal Optical Resonators. In Sensors (Vol. 10, Issue 10, pp. 9317–9336). MDPI AG. <https://doi.org/10.3390/s101009317>
112. Manam, Dr. V. K. (2021). Nano Biosensors Containing Non-Carbon-Based Nanomaterials to Access Environmental Pollution Level. In SSRN Electronic Journal. Elsevier BV. <https://doi.org/10.2139/ssrn.3869459>
113. Kang, M.-J., Cho, Y.-W., & Kim, T.-H. (2023). Progress in Nano-Biosensors for Non-Invasive Monitoring of Stem Cell Differentiation. In Biosensors (Vol. 13, Issue 5, p. 501). MDPI AG. <https://doi.org/10.3390/bios13050501>

Funds:

This research was funded by Ministry of Science and Higher Education of Republic of Kazakhstan, grant number IRN AP09260805.

Conflict of Interest:

No potential conflict of interest was reported by the author(s).

Ethical Statement:


This article does not contain any studies that would require an ethical statement.


Contact Address:


Zhainagul Kakimova, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: +7 747 408 4943


E-mail: zhaynagul.kakimova@mail.ru


 ORCID: <https://orcid.org/0000-0002-3501-3042>


Duman Orynbekov, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: +7 722 231 6029
E-mail: duman_r@mail.ru
 ORCID: <https://orcid.org/0000-0001-9647-7046>


Klara Zharykbasova, Alikhan Bokeikhan University, Department of applied biology, 11 Mangilik El Street, Semey city, 071400, Kazakhstan,
Tel.: +7 722 236 0323
E-mail: klara_zharykbasova@mail.ru
 ORCID: <https://orcid.org/0000-0002-2027-3183>


Aitbek Kakimov, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: + 7 7222 314 602
E-mail: bibi.53@mail.ru
 ORCID: <https://orcid.org/0000-0002-9607-1684>

***Yerlan Zharykbasov**, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: + 7 7222 314 602
E-mail: erlan-0975@mail.ru
 ORCID: <https://orcid.org/0000-0001-9707-0539>

Gulmira Mirasheva, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: + 7 7222 314 602
E-mail: gulmira_mir@mail.ru
 ORCID: <https://orcid.org/0000-0003-4286-4563>

Sandugash Toleubekova, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: + 7 7222 314 602
E-mail: saltosha-sandu@mail.ru
 ORCID: <https://orcid.org/0000-0003-2658-9514>

Alibek Muratbayev, Shakarim University, Department of Food technology and biotechnology, 20A Glinki Street, 071412, Semey, Kazakhstan,
Tel.: + 7 7222 314 602
E-mail: great_mister@mail.ru
 ORCID: <https://orcid.org/0000-0002-0830-5007>

***Godswill Ntsomboh Ntsefong**, Department of Plant Biology, Faculty of Science, University of Yaounde I, P. O. Box 812, Yaounde, Cameroon,
Tel.: (237) 679 941 910
E-mail: ntsomboh@yahoo.fr
 ORCID: <https://orcid.org/0000-0002-6876-8847>

Corresponding author: *

© 2023 Authors. Published by HACCP Consulting in www.potravinarstvo.com the official website of the *Potravinarstvo Slovak Journal of Food Sciences*, owned and operated by the HACCP Consulting s.r.o., Slovakia, European Union www.haccp.sk. The publisher cooperate with the SLP London, UK, www.slplondon.org the scientific literature publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License CC BY-NC-ND 4.0 <https://creativecommons.org/licenses/by-nc-nd/4.0/>, which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.