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Review

Revolutionizing Smart Food Packaging: The Promise and Challenges of Biosensors and Biopolymer-Based Nanocomposites

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ABSTRACT - The integration of biosensors and biopolymer-based nanocomposites in food packaging is progressively being recognized by industry professionals, fueled by growing concerns over food quality and safety. Embedded biosensors in food packaging offer the potential to revolutionize the industry by providing real-time monitoring of microbial spoilage in packaged products, a critical aspect of ensuring food safety. Simultaneously, the exploration and application of biopolymer-based nanocomposites or bionanocomposites have expanded substantially, owing to their exceptional mechanical, thermal, optical, and antimicrobial properties. These attributes facilitate the suitability of these materials for innovative packaging applications. However, exploring the potential hurdles and prospects of employing biosensors and bionanocomposites in designing intelligent food packaging systems has not yet been exhaustive. Proposing the amalgamation of bionanocomposites with biosensors represents a groundbreaking step toward redefining smart packaging industries, emphasizing the necessity for a deeper understanding of these technologies to foster the development of sustainable and economically viable smart packaging options. This review examines existing research and developmental strides in biosensors and bionanocomposites, aiming to highlight the anticipated challenges and opportunities that could spearhead progress in the smart food packaging industry in the foreseeable future.

Key words: Biosensors, Biopolymer, Nanocomposites, Bionanocomposites, Smart packaging, Food packaging

In recent years, food safety had emerged as a critical issue, driven by increasing consumer awareness and numerous high-profile incidents of contamination affecting packaged foods. These incidents, often involving dangerous pathogens such as *Escherichia coli* O157 and *Salmonella typhimurium*, were reported in various types of packaged foods, including seafood, dairy, and meat products. The outbreaks documented between 2012 and 2018 across the United States served as a stark reminder of the risks posed by inadequate food packaging and monitoring systems[1]. Similar issues were recorded globally, highlighting the universal challenge of ensuring food safety post-packaging, despite initial quality assessments based on color, odor, and texture[2,3].

Traditional food packaging had successfully extended the shelf life of products through active packaging techniques that focused predominantly on preservation and protection. However, these methods did not provide insights into the ongoing quality or safety of the food content after packaging[4,5]. This gap spurred innovations in smart packaging, integrating advancements in nanotechnology to develop packaging that not only preserved food but also actively monitored its condition and communicated this information to consumers[6]. This approach used real-time data transmission to inform consumers of the food status, leveraging both online and offline communication channels to enhance consumer trust and safety[7].

The rise of environmental concerns associated with traditional plastic packaging also prompted the development of more sustainable alternatives. Biopolymers and bio-

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nanocomposites, which combined biodegradable organic polymers with nanoparticles like nanocellulose or metal nanoparticles, offered a promising solution[8]. These materials were not only environmentally friendly but also possessed enhanced mechanical, thermal, and barrier properties, making them superior to conventional packaging materials. The global push towards reducing plastic waste, projected to reach a staggering 330 million tons by 2020, underscored the urgency for adopting these innovative materials in mainstream packaging applications[8,9].

Despite the technological advancements and the introduction of biosensor-integrated bio-nanocomposite films, the full potential of smart food packaging remained largely untapped[10]. Current research and development were still in the early stages, with a need for a comprehensive evaluation of the entire lifecycle of packaging materials from raw material extraction through to end-of-life disposal. This evaluation needed to consider not only the functional and environmental benefits but also the economic aspects, to ensure these solutions were both viable and sustainable. This review mainly focused on providing a thorough overview of the advancements in smart food packaging, particularly focusing on the role of biosensors and bio-nanocomposites. It explored the challenges and opportunities within this emerging field, aiming to identify the gaps in current research and propose directions for future development that could revolutionize the food packaging industry, making it safer, more efficient, and environmentally responsible.

Smart food packaging

Prevalent components of smart food packaging

Smart food packaging significantly extended beyond the basic functions of containing and protecting food items. It introduced a range of value-added features designed to enhance food safety, management, and consumer satisfaction. Among these features were advanced capabilities such as extending the shelf life of perishable goods and integrating sensors for continuous monitoring of critical conditions such as pH, temperature, moisture levels, and overall freshness of the food[11]. This modern packaging approach not only provided vital real-time data about food conditions directly to consumers but also integrated sophisticated tracking systems that significantly impacted the management of food safety. One of the innovative features of smart packaging was the use of blockchain technology, which allowed for secure and transparent tracking of food products throughout the supply chain. By storing data in a decentralized manner, blockchain ensured that the information about the product's journey from farm to fork was immutable and accessible, which proved particularly beneficial for precise and efficient recall processes in case of contamination. Despite its potential, the implementation of blockchain in food packaging remained at a developmental stage, facing challenges in terms of adoption and practical application[12].

Smart food packaging was equipped with various sensors and indicators, such as time-temperature indicators, freshness sensors, and moisture detectors. These technologies were critical as they monitored environmental conditions affecting the food both inside and outside the packaging, providing alerts when the food's quality was compromised. The presence of these sensors helped in maintaining the safety and integrity of food products, ultimately preventing waste and health hazards due to spoilage[11-14]. At the time, the market offered a diverse range of smart packaging options, including several under research and development. These products were detailed in resources like Table 1, which included their trade names, applications, benefits, and drawbacks, offering a detailed snapshot of the latest innovations and trends in smart food packaging technology. In the landscape of smart packaging technologies, several critical components stood out, including time-temperature indicators (TTIs), Repeat Index, freshness indicators, coloring indicators, barcodes, and radio frequency identification (RFID) systems. TTIs and RFID were especially prominent, each serving unique and vital functions. TTIs were specifically engineered to monitor the changes in the physical properties of food that occurred in response to varying temperatures and time, providing essential data that could be used to gauge food quality and safety[13]. However, their application was mostly confined to frozen food products, which significantly limited their versatility across other food sectors[15].

RFID technology represented a significant advancement in smart packaging, enabling wireless communication between packaged products and tracking systems. This system consisted of tags, which contained a transponder and an antenna with a unique identifier, readers that picked up signals from these tags, and computers that processed the collected data. The major advantage of RFID over traditional barcodes was its ability to track multiple items simultaneously without needing direct visual contact, which streamlined inventory and supply chain processes[16]. In practice, an RFID reader emitted radio waves that interacted with the tag. The tag responded with its data, which the reader then transmitted to a host computer. This computer, often connected to wider networks or the internet, was tasked with analyzing the data and integrating it into decision-making processes, often visualized in real-time system diagrams. Despite their functionality, RFIDs had not yet seen widespread adoption in the food packaging industry due to significant limitations. The primary challenges were

Table 1. Various smart devices for smart food packaging, including their principles, applications, and drawbacks

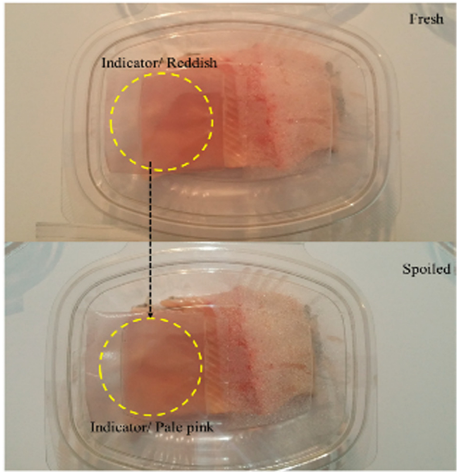
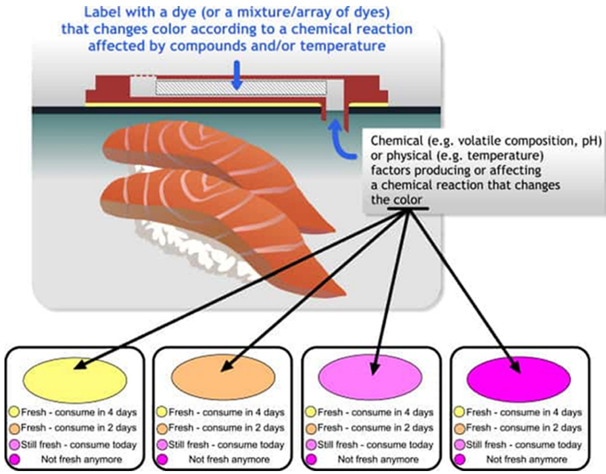
Principle/reagents	Information given	Smart devices	Advantage	Disadvantage	Application	Visual representation of smart packaging
pH dyes; Dyes that react with volatile and non-volatile metabolites	Identifying microbial degradation products	Freshness indicators	Highly sensitive, visible to the naked eye, and quantifiable using electronic devices	Potential for false negative results, and attachment inside the package may interfere with food quality	Perishable foods including meat, fish, and poultry	
Chemically sensitive dyes that react to gase	Volatile gas detection	Gas indicators	Can be embedded in the packaging, visible to the naked eye, and resistant to heat, electromagnetic interference, and agitation	Does not indicate gas concentration within the package, and its chemical dye could compromise food quality	Perishable items, particularly fish and meat	

Table 1. (Continued) Various smart devices for smart food packaging, including their principles, applications, and drawbacks

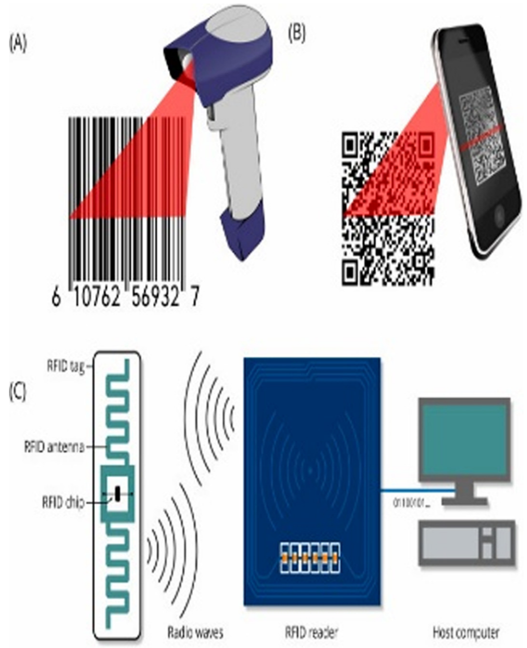
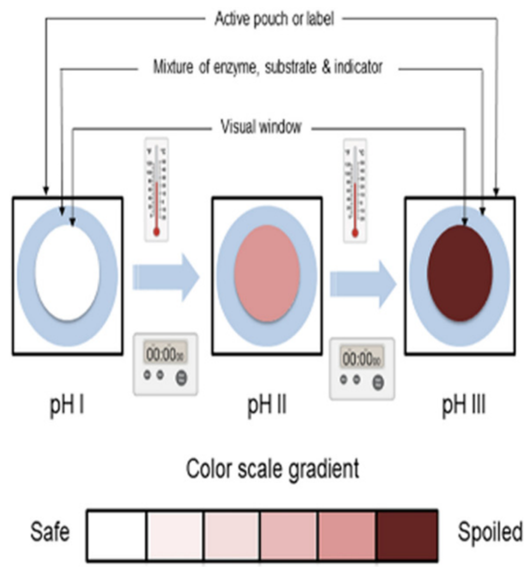
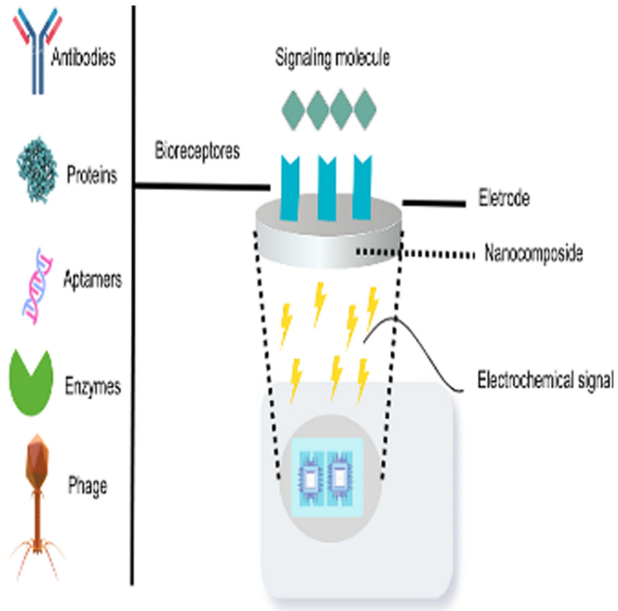
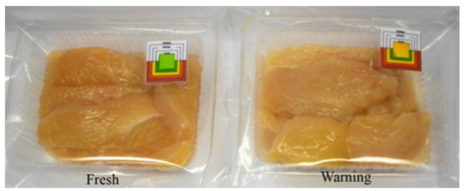
Principle/reagents	Information given	Smart devices	Advantage	Disadvantage	Application	Visual representation of smart packaging
Radio waves	Information about the product and its manufacturer	Radio frequency identification tags	Can be incorporated into barcodes using wireless technology, enabling the simultaneous and rapid, accurate reading of multiple products	The signal may be lost and commercialization can be costly	Tracking products, identifying items, managing supply chains, and controlling security	
Mechanical, chemical, enzymatic, microbiological	Storage conditions	Time temperature indicators (TTI)	Can be incorporated into packaging, detectable by electronic devices, and observable with the naked eye	Requires conditioning before use, should not contact food, and does not offer information about food quality	Meat preserved in chilled and frozen states	

Table 1. (Continued) Various smart devices for smart food packaging, including their principles, applications, and drawbacks

Principle/reagents	Information given	Smart devices	Advantage	Disadvantage	Application	Visual representation of smart packaging
Symbology	Determining product price, manufacturer information	Barcodes	Determine the origin of food products and enable tracking and tracing of individual food items	The signal may drop, and commercializing the technology can be expensive.	Product identification, inventory restocking, and checkout processes	
Electrochemical signal	Attaches targeted pathogens and toxins to the biosensor	Biosensors	Visible to the naked eye and measurable with electronic devices	Unable to detect low levels of contamination and may chemically affect the foods.	Tracking food quality	
Diverse chemical and immunochemical techniques that react with toxins	Identifying pathogenic bacteria like *E. coli* O157	Pathogen indicators	Sensitive and visible to the naked eye, measurable by electronic devices	Intend to produce false positive results, chemicals may intract with foods	Perishable foods such as fish, meat and dairy foods	

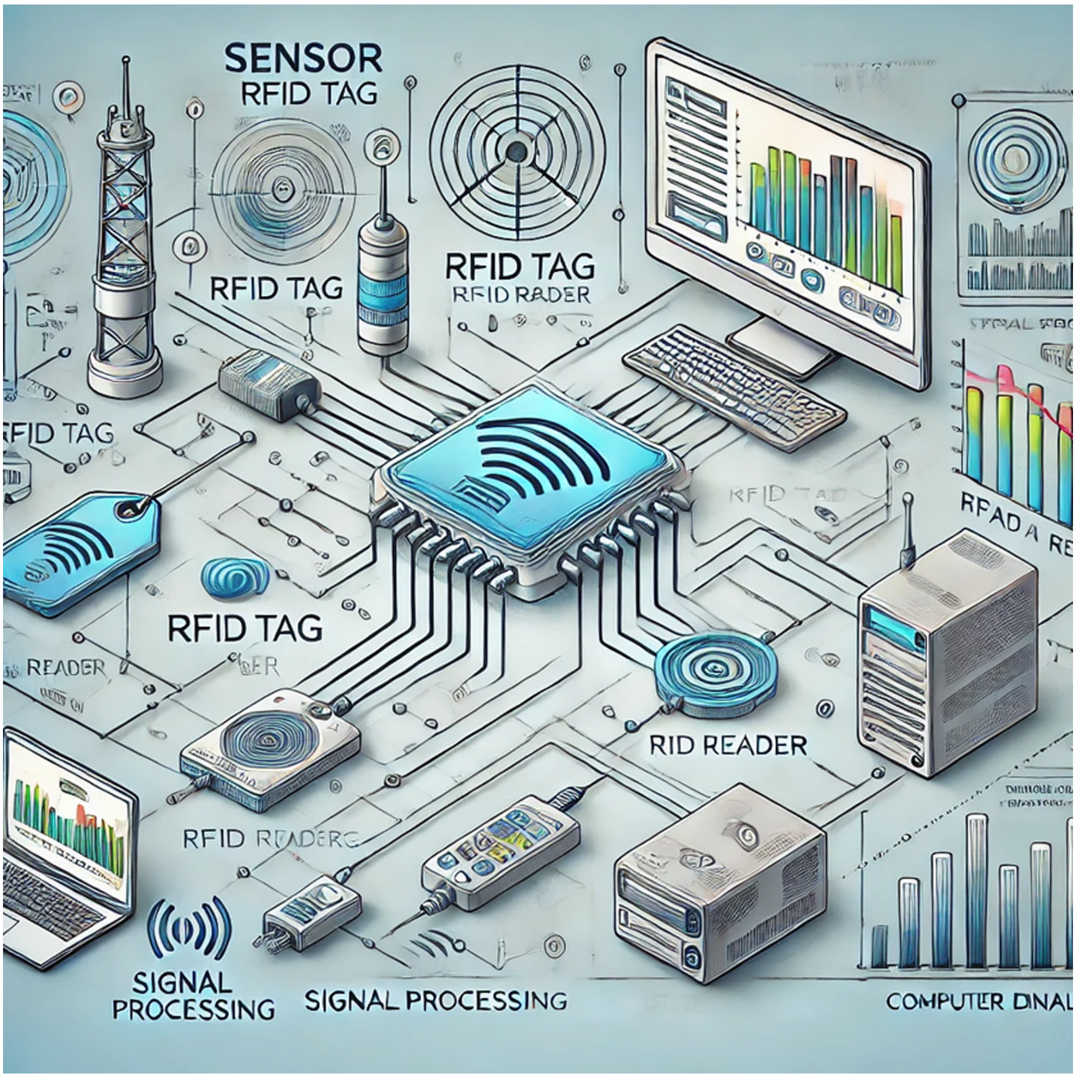


Fig. 1. A basic RFID system for meat packaging likely depicts how a Radio Frequency Identification (RFID) system operates within the meat packaging industry. This system comprises RFID tags attached to meat packages that store vital data such as origin, slaughter, and expiry dates. RFID readers and antennas are strategically placed throughout production and shipping areas to scan these tags, transmitting data to a centralized database integrated with inventory and supply chain management systems for enhanced traceability and real-time updates. Network integration allows stakeholders like suppliers and retailers remote access to this data, facilitating immediate responses to inventory or quality issues. Overall, the use of RFID in meat packaging significantly enhances efficiency, reduces errors, improves regulatory compliance, and boosts consumer trust through greater transparency.

the high costs associated with RFID technology (Fig. 1) and the inability to reuse the tags, which undermined their economic viability for frequent and widespread use in the food industry[14,16]. These factors necessitated further research and development efforts focused on creating cost-effective, reusable RFID solutions. Advancements in this area could have substantially increased the adoption of smart packaging technologies, enhancing supply chain efficiency and sustainability in the food sector.

Market for smart packaging

Recent data from the U.S. Department of Agriculture (USDA) highlighted a notable increase in the consumption of packaged foods among adults in the United States, with the average monthly intake climbing from 1.9 to 2.4 times between the years 2007-08 and 2015-16. This 26% surge in consumption demonstrated a growing reliance on packaged goods, correlating with an increased demand for smarter packaging solutions. By 2019, the market value for intelligent food packaging in the U.S. reached approximately $1.5 billion, reflecting burgeoning interest in this technology-driven sector[17,18].

Globally, the smart packaging sector has showed robust growth, with its valuation rising from around $35.33 billion in 2018 to about $36 billion in 2019. Future forecasts were even more optimistic, predicting the market to expand to approximately $44.39 billion by 2024. The food industry, which made up over half of the advanced packaging market, was a significant contributor to this growth, driven by the increasing consumer demand for packaging that ensures food safety and enhances shelf life[17]. It was estimated that by 2024, the segment of smart food packaging a market value nearing $22.19 billion.

The rising popularity of smart packaging is become a global phenomenon, especially favored by younger consumers who valued immediate access to product information. North America currently led this market, holding more than 35% of the global share as of 2019. Future projections place the U.S. market value at close to $3.6 billion in the upcoming decades. Japan and Australia were also major players, with market values expected to reach $2.36 billion and $1.69 billion, respectively. The UK and Germany were not far behind, with predicted market values of $1.27 million and $1.4 million, respectively[17,19].

Biosensors for smart food packaging

A biosensor was a sophisticated analytical device designed to convert varied types of input signals into a continuous, measurable output, essential for real-time analytics. At its core, a biosensor consisted of two primary components: the receptor and the transducer. The receptor's role was to detect and capture either physical or chemical stimuli, transforming these inputs into a form of energy. This energy was then relayed to the transducer, which converted it into an easily measurable analytical output, typically in the form of an electrical signal. This innovative technology originated in the 1960s, developed by pioneers Clark and Lyons, and has since evolved significantly across various fields[20].

Despite their success in sectors such as environmental monitoring and biomedical diagnostics, the integration of biosensors into food packaging faced certain challenges. These challenges included the biosensors' microstructural requirements, their sensitivity and specificity, their stability under different conditions, and the costs associated with their development and deployment. Nevertheless, research continued, and several types of biosensors have were specifically engineered and tested for use in food-related applications. Notable examples included fluorescent biosensors, which could detect biomolecular interactions; microfluidics sensors, which analyzed small volumes of liquids; gas detection sensors, which identified changes in gas composition; electrochemical/imprinted biosensors, which detected chemical changes; immunosensors, which used antibody-antigen interactions; and thermal biosensors, which responded to temperature changes. These biosensors (Table 2) have showed potential in improving food safety by providing timely information about food quality and safety[21,22].

In the context of smart food packaging, biosensors was increasingly regarded as essential components due to their ability to provide real-time, actionable data about the food's condition. They offered potential benefits such as extending the shelf life of perishable goods and ensuring the safety of packaged food by monitoring for spoilage or contamination indicators. This capability not only enhanced consumer confidence in packaged food products but also supported the industry's need for innovative, efficient, and consumer-friendly packaging solutions. As technology progressed, the development of more sophisticated, cost-effective, and adaptable biosensors continued to be a crucial area of focus, promising to revolutionize the standards and practices of food packaging[21-23].

Fluorescent and microfluidics biosensors

The fluorescent-based biosensor employed a sophisticated mechanism involving a fluorescent or phosphorescent dye, which was securely immobilized within a solid polymer matrix. This dye-polymer composite was then integrated into thin film coatings that formed the core construct of the biosensor[24]. The key operational principle of this biosensor lay in its ability to detect and measure molecular oxygen present in the packaging's headspace. The sensitive fluorescent coatings absorbed oxygen through diffusion, which in turn affected the luminescence emitted by the dye. This alteration in luminescence characterized by changes in intensity and wavelength was quantitatively analyzed using a pre-established calibration curve, providing a direct measurement of the oxygen concentration[25].

This type of biosensor was notable not only for its functionality but also for its reversible operation, meaning it did not consume the dye or oxygen during the detection process, nor did it produce any harmful byproducts. Moreover, the sensor's ability to exhibit different colors upon encountering various food pathogens made it an invaluable tool in the rapid detection of contaminants, functioning similarly to an electronic tongue or nose. This capability significantly expedited the pathogen detection process, reducing it from days to mere hours. Another innovative approach within biosensor technology was the application of microfluidic devices, known for their efficacy in pathogen detection with real-time results and high sensitivity. These devices, often described as 'laboratory-on-a-chip,' utilized small, silicon-based systems capable of handling minuscule amounts of samples efficiently[24].

Despite their widespread use in fields such as medical diagnostics, biological, and chemical research, their

Table 2. Various smart devices for smart food packaging: principles, applications, and drawbacks

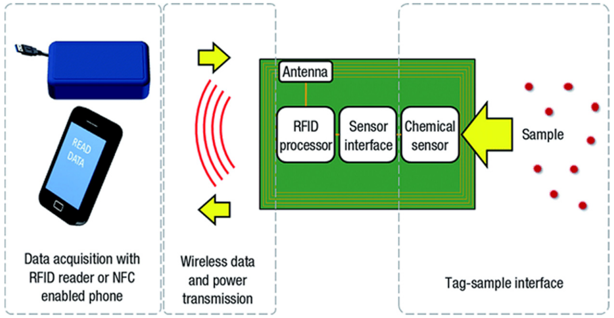
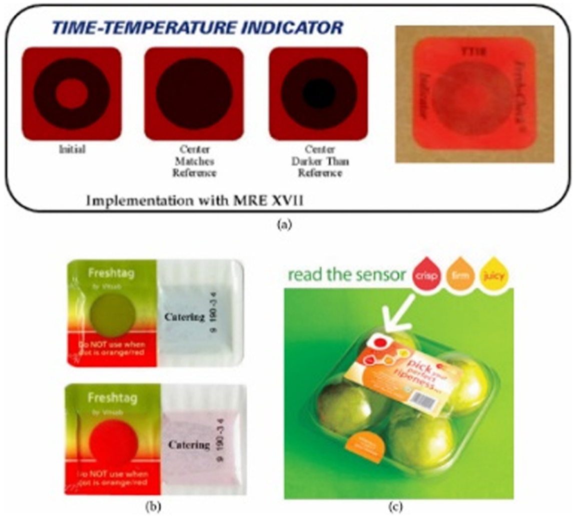
Device	Principle	Application	Drawbacks	Visual representation of smart packaging
RFID (Radio Frequency Identification)	Wireless data transmission via electromagnetic fields	Product tracking, inventory management	Signal loss, high cost of commercialization	
pH Sensors	Detects changes in pH levels	Monitoring freshness of meat and fish	Limited lifespan, may interfere with food	
Time-Temperature Indicators (TTI)	Tracks cumulative temperature exposure over time	Monitoring temperature-sensitive products	Limited accuracy, affected by storage conditions	

Table 2. (Continued) Various smart devices for smart food packaging: principles, applications, and drawbacks

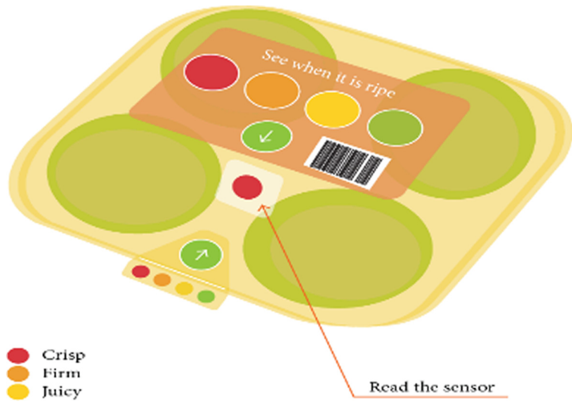
Device	Principle	Application	Drawbacks	Visual representation of smart packaging
Oxygen Sensors	Measures oxygen levels within packaging	Ensures proper sealing and freshness	Cannot indicate exact gas concentration	
Smart Labels	Visual indicators for ripeness or spoilage	Fruits and vegetables, meat packaging	Short lifespan, requires consumer education	
Nanosensors	Detects pathogens, toxins, or gases	Pathogen detection, real-time monitoring	Expensive, requires advanced technology	

Table 2. (Continued) Various smart devices for smart food packaging: principles, applications, and drawbacks

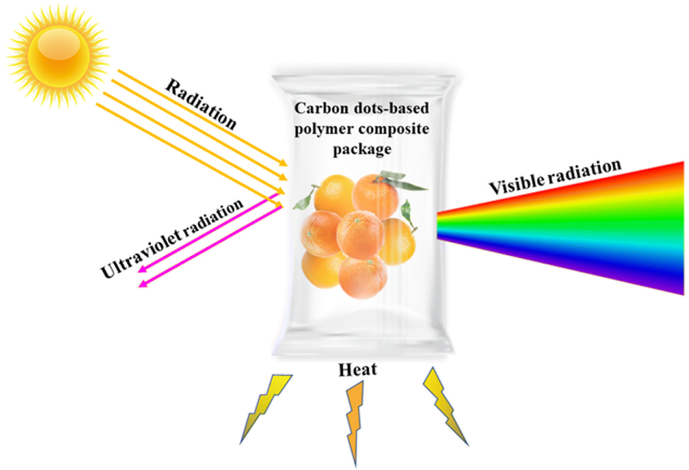
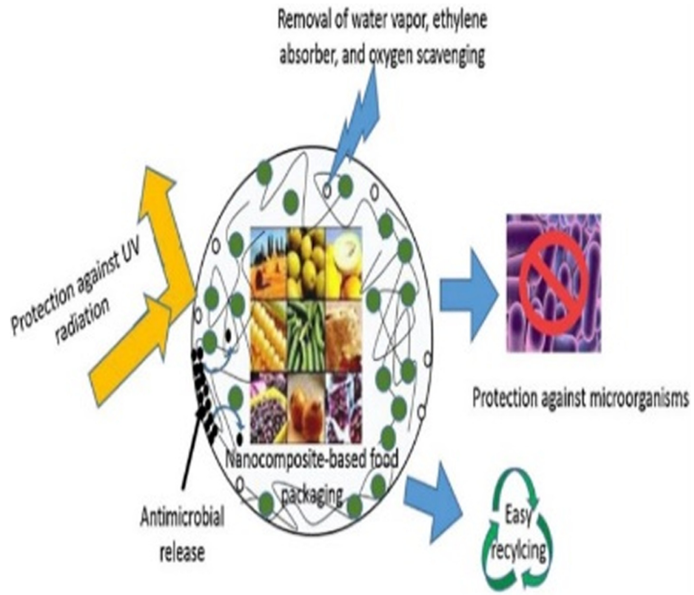
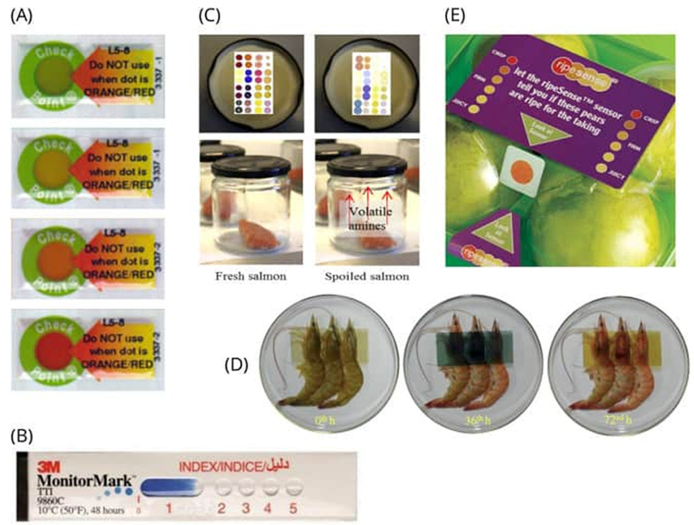
Device	Principle	Application	Drawbacks	Visual representation of smart packaging
Gas Sensors	Responds to gases like CO_2 or oxygen	Detecting food spoilage in sealed packages	Limited sensitivity, may affect food quality	
Fluorescence-Based Sensors	Emits light in response to specific compounds	Detecting food spoilage in sealed packages	Limited sensitivity, may affect food quality	

Table 2. (Continued) Various smart devices for smart food packaging: principles, applications, and drawbacks

Device	Principle	Application	Drawbacks	Visual representation of smart packaging
Biosensors	Detects biological interactions (e.g., pathogens)	Monitoring microbial contamination	Can be sensitive to interference, costly	
Conducting Polymer Sensors	Responds to gas release through electrical changes	Detecting food spoilage gases	Sensitive to environmental conditions	

potential in food packaging had not yet been explored. This presented a significant opportunity for pioneering work in the development of smart food packaging, where microfluidic biosensors could provide groundbreaking advancements in monitoring food safety and quality on a microscale. This underexplored avenue held promise for enhancing the capabilities of food packaging, merging cutting-edge technology with everyday consumer products to ensure safety and extend shelf life[26].

Electrochemical based biosensors

Electrochemical-based biosensors played a crucial role in enhancing food quality monitoring through their refined biological recognition mechanisms. These biosensors were categorized into two primary types: 1) biocatalytic sensors, which employed redox enzymes, whole cells, or tissue slices as bio-recognition elements to detect specific biomolecules, and 2) affinity-based biosensors, where the detection was facilitated by antibodies, antibody fragments, or aptamers, providing precise molecular recognition[27]. The biocatalytic sensors were highly valued for their straightforward design, compactness, cost-efficiency, and user-friendliness. These attributes made them ideally suited for integration with food packaging materials, offering a practical approach to monitoring food safety[28]. These devices were particularly selective and specific to their targets, operating effectively without the need for any prior treatment or separation of samples[28]. Additionally, the use of whole cells or tissue slices in these biosensors minimized the need for extensive purification and preserved better enzymatic activity than isolated enzymes, enhancing their functional utility. Despite these advantages, biocatalytic sensors may faced challenges such as a reduction in selectivity and specificity due to the interference from other contaminant enzymes and a relatively slower response time, which could limit their effectiveness in rapid detection applications[29].

Electrochemical biosensors were known for their low detection thresholds, simplicity in operation, and minimal background noise, which were significant benefits in food safety applications. Examples of these biosensors in action included SWCNT-based biosensors for microbial detection, DAO-based biosensors for monitoring amines in atmospherically packaged foods, and DNA-based biosensors for identifying potential carcinogens in food samples[30,31]. Various immobilization methods were employed to enhance the biosensors' selectivity and specificity. Techniques such as covalent binding, surface adsorption, nanoparticle conjugation, encapsulation, and enzyme entrapment in polymers or gels were commonly used to stabilize these devices[30]. While these methods improved biosensor stability, extending their lifespan, the typical operational duration of biocatalytic sensors, which ranged from 2 to 8 weeks, remained a challenge. This duration was often too short for many food packaging applications, which required long-term monitoring capabilities to ensure ongoing freshness and safety. There was a clear need for continued research and development to create more durable, long-lasting biosensor systems that maintained functionality over extended periods, thereby advancing their applicability in the food industry.

Gas sensors

Gas sensors were integral to ensuring food safety by detecting leaks and measuring the concentration of gases within food packaging, which were indicators of spoilage[32]. These devices were specifically tuned to detect gases such as basic nitrogen compounds, oxygen, and carbon dioxide—all byproducts of the food decomposition process[33,34]. Additionally, their application extended to assessing meat rancidity and detecting harmful carbamate pesticides in fruits and vegetables.

The design of a gas sensor typically included three essential components: the sensing electrode (also known as the working electrode), the counter electrode, and the reference electrode. The working electrode was the primary site for gas detection, where the target gas interacted with a specialized sensing element that triggered an electrochemical reaction. The counter electrode supported this process by completing the electrical circuit, allowing current to flow, and was separated from the working electrode by a thin layer of electrode material. When gas penetrated the sensor through a hydrophobic barrier, it reached the working electrode, where it was detected and measured based on the strength of the electrochemical signal produced[35].

One prominent example is the carbon dioxide sensor, which utilized these principles to accurately determine CO2 levels in food packaging—an operation depicted. These sensors were notably superior to traditional sensing techniques due to their ability to function effectively in potentially hazardous conditions, their high specificity to targeted gas molecules, and their resistance to electromagnetic disturbances. This made them invaluable tools in the food industry, where ensuring the integrity and safety of food products was paramount[33].

Opportunities of biosensors for smart food packaging

Biosensors found widespread applications across various sectors including the food industry, medical science, environmental monitoring, engineering, and marine studies due to their enhanced stability and sensitivity compared to traditional methods. These devices were particularly celebrated for their precision and reliability in detecting and measuring biological or chemical changes. The incorporation of biosensors into these fields paved the way for innovative developments and improvements in diagnostics and monitoring processes. In the realm of food packaging, the integration of biosensors offered significant potential for advancement[36]. They played a crucial role in the development of smart food packaging solutions, which aimed to enhance food safety, extend shelf life, and improve the overall quality of packaged food products. The specific opportunities that biosensors presented for revolutionizing food packaging technologies were detailed in Fig. 4. This visual representation highlighted how biosensors could be effectively utilized within food packaging systems to ensure real-time monitoring and responsive measures against potential hazards, thereby promoting health and safety in food consumption[37].

Biosensor for food freshness

Food freshness varied across food types, encapsulating foods that remained unspoiled and preserved near their natural state. For fruits and vegetables, freshness meant recent harvest and proper post-harvest treatment; for meat and fish, it implied recent slaughter or catch, respectively, coupled with proper storage. Biosensors were instrumental in monitoring food freshness by detecting metabolites associated with spoilage. Notable examples included calorimetric-based biosensors for detecting nitrogen compounds in meat and fish, and glucose biosensors for monitoring increases in glucose levels in spoiling meat[30,31]. Despite their efficacy, the commercial integration of these biosensors into food packaging was still in nascent stages. Moreover, xanthanin, a degradation product of adenine nucleotides in animal tissues, served as a freshness indicator. Biosensors measuring xanthanin levels, such as those immobilized with xanthine, could be embedded in meat and fish packaging to ensure freshness, assessing the protein degradation in these foods[31,38]. These biosensors offered a dynamic approach to ensuring food safety, enhancing consumer confidence through real-time freshness monitoring.

Biosensor for meat and fish integrity

Food integrity is a multifaceted concept that encompassed three crucial aspects: food safety, food quality, and food authenticity. Food safety referred to managing both chronic and acute risks that could potentially harm consumers. Food quality pertained to the attributes that affected a product's appeal and market value, such as taste, texture, and appearance. Food authenticity focused on ensuring that food products were genuine and not adulterated, which was crucial for maintaining consumer trust. Particularly in controlled environments like supermarkets or storage facilities, meat and fish were vulnerable to spoilage due to microorganism activity, which rapidly altered their pH levels, a key indicator of spoilage and freshness[39]. To address this, pH indicating sensors were employed. These sensors utilized dyes that visibly changed color in response to the acidic or basic conditions triggered by spoilage, providing a straightforward and immediate means to assess food safety and quality. The integration of these sensors into food packaging for meats and fish allowed for the continuous monitoring of pH levels, enabling real-time assessments of product integrity[38].

The development of pH indicating sensors could have been expanded by incorporating mixed-dye calorimetric systems, which would have enhanced the sensor's ability to detect and indicate spoilage through more pronounced color changes. This advancement could have broadened the application scope of pH sensors to include a wider range of food products such as poultry, seafood, bakery items, and even fresh-cut fruits and vegetables, extending the benefits of smart packaging[39]. While the literature frequently discussed pH sensors, there was a significant opportunity for innovation in creating pH-based biosensors that were rapid, sensitive, specific, and reusable for smart food packaging. Moreover, biosensors modeled after biological noses and tongues, designed to detect food adulterants, demonstrated how advanced sensory technology could be adapted to ensure food authenticity[40]. Although these technologies had not yet been commercialized, they held potential for future applications in smart packaging materials. Such sensors could have revolutionized the way food authenticity was monitored, offering a new layer of security and trust by verifying the genuineness of food products, thus enhancing consumer confidence and safety.

Biosensor for assessing fruit ripeness

The sale of unripe fruits presented a significant challenge, as these fruits were highly susceptible to bruising and damage, rendering them unsuitable for consumption. On the other hand, determining the precise ripeness of fruits when were are fully ripe was often difficult, especially in market settings. This challenge becomes even more pronounced when fruits were packaged for sale in ready-to-eat formats. The packaging materials acted as barriers, making it difficult for consumers and retailers to visually or physically assess the ripeness of the fruit. Consequently, determining the optimal time for consumption or sale become problematic[41].

To overcome these obstacles, a range of biosensors was developed to evaluate fruit maturity with greater precision. For example, a bioelectronic tongue was designed to detect key markers of ripeness such as sugar and phenolic compounds in grapes, providing an effective method for gauging grape maturity[42]. Similarly, an imprinted polymer biosensor was engineered to detect volatile compounds such as α-pinene, γ-terpinene, and terpinolene, which were known maturity indicators in mangoes[43]. Another important development was the amperometric biosensor that measured L-mallic acid, a naturally occurring compound in fruits that serves as a reliable indicator of ripeness[30,31]. These biosensors could have been integrated into packaging materials, creating smart packaging solutions that provided real-time data on the ripeness and maturity of fruits like apples, grapes, bananas, tomatoes, and mangoes.

One of the most promising applications of this technology was the ripeSense sensor, which utilized sensor labels that changed color in response to the aromatic compounds released by ripening fruits[31]. As fruits ripen, the sensor color shifted from red to orange and finally to yellow, indicating full ripeness. This color change provided an intuitive way for both retailers and consumers to determine the optimal time to sell or consume the fruit. By offering a visual cue for ripeness, these sensors helped reduce fruit spoilage and waste, while improving the consumer experience by ensuring that they can choose fruits at their preferred ripeness level. This integration of biosensor technology into packaging materials represented a significant step forward in the development of smart packaging, with the potential to revolutionize the management of fruit freshness and ripeness in the food industry[41].

Biosensor for food contaminations

Food contamination posed a significant global health risk, stemming from physical sources like heavy metals, chemical contaminants (Fig. 2) such as pesticides, and microbial pathogens. Traditional detection methods like mass spectrometry and chromatography were accurate but often too cumbersome and expensive for routine use. Consequently, biosensors emerged as a swift and cost-effective alternative, capable of integrating with smart food packaging to enhance safety monitoring[44]. Recent developments in biosensor technology included fluorescence-based sensors for mercury detection, colorimetric sensors for aflatoxin, and dual-

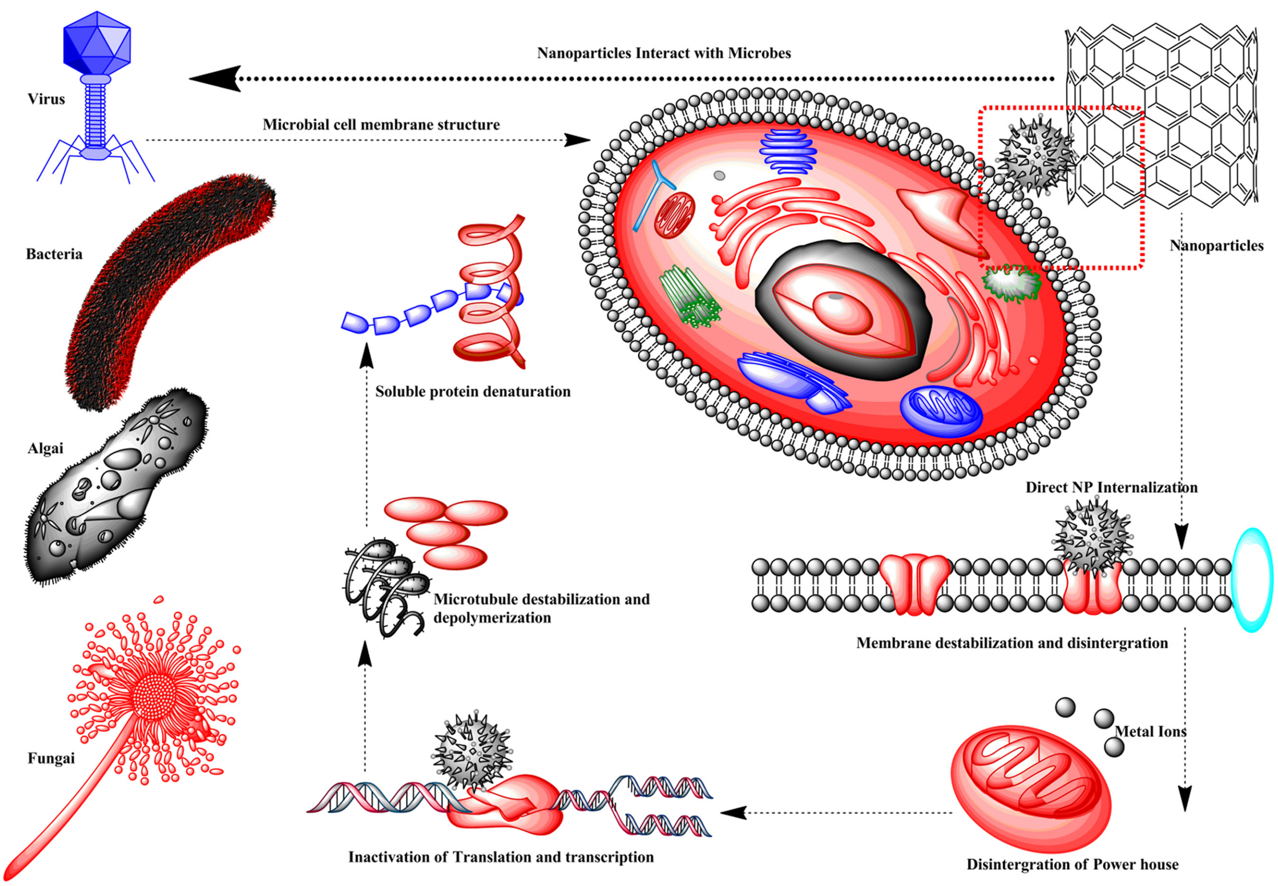


Fig. 2. The biosynthesized nanoparticles (dotted red-colored box) interact with various biological entities (virus, bacteria, algai, fungi) to exhibit antibacterial properties. It features depictions of viruses, bacteria, algae, and fungi to demonstrate the broad spectrum of nanoparticle efficacy. Central to the illustration is a complex cell structure showing potential intracellular targets and mechanisms of action, such as membrane disruption or penetration, which are relevant for applications like cancer therapy

responsive sensors for pesticides. These innovations enabled real-time contaminant monitoring during food storage and transport. Additionally, optical biosensors could detect bacterial pathogens by changing color in their presence, offering a quick visual indication of microbial contamination[45]. Conducting polymer-based biosensors detected spoilage gases, changing their electrical resistance in response to gas concentrations, indicating spoilage levels. The integration of these biosensors into food packaging could have revolutionized safety protocols by providing continuous, real-time monitoring of food freshness and contamination. This approach not only enhanced consumer safety but also reduced food waste and the economic impact of foodborne diseases, setting a new standard for food industry practices[44, 45].

Biosensor for tracking and tracing of food package

Blockchain technology, which operated as a distributed digital ledger, significantly enhanced transparency in the food industry by utilizing QR codes. These codes stored comprehensive details about the origin and cultivation locations of products, offering consumers direct access to the product's backstory and enhancing traceability. While QR code-based sensors have successfully tracked aquatic products through the cold chain, demonstrating their utility[46], their application in smart food packaging was still emerging. This new application promised to revolutionize how food traceability was monitored, though it faced challenges like high costs, increased energy consumption, and complexity.

The integration of modern technology extended beyond blockchain. Optical-based biosensors, for instance, have were employed in bioprocessing to monitor critical quality attributes and are poised to improve supply chain efficiency in the food industry[47]. Furthermore, incorporating GPS technology into food packaging offered a method for real-time tracking of products during transport, providing precise data on location and handling conditions through a network of satellites[48]. Although still in developmental stages, GPS could have significantly benefited large-scale food distribution by enhancing the security and integrity of food transportation. Together, these technologies presented powerful tools for meeting consumer demands for safety and transparency, potentially transforming food packaging into a highly interactive interface between producers and consumers.

Opportunities of bionanocomposites for smart food packaging

Nanocomposites and bionanocomposites both involve the incorporation of nanoscale materials into a matrix to enhance properties, but they differ in composition and focus. Nanocomposites typically consist of synthetic matrices, such as polymers, metals, or ceramics, combined with nanostructures like carbon nanotubes, nanoclays, or metal oxides, to improve mechanical strength, thermal stability, or electrical conductivity. They are widely used in industries like aerospace, automotive, and electronics. In contrast, bionanocomposites involve at least one biologically derived component, often using biodegradable or biocompatible polymers (e.g., polylactic acid, chitosan) and natural nanomaterials (e.g., nanocellulose, chitin), designed for applications where sustainability, biodegradability, and biocompatibility are critical. These materials are particularly relevant in medical devices, drug delivery systems, eco-friendly packaging, and the food industry. While nanocomposites prioritize performance enhancements, bionanocomposites focus on combining enhanced material properties with environmental sustainability and biological safety.

Bionanocomposites were increasingly recognized for their potential to revolutionize smart food packaging, thanks to their exceptional properties including enhanced physical strength, superior barrier functions, effective antimicrobial activity, and environmental sustainability. Specific materials such as alkyd/epoxy/graphene oxide and polyester/clay composites were highlighted for their robust mechanical and thermal properties, making them highly effective in improving the structural integrity and temperature resilience of food[49]. Beyond traditional applications, bionanocomposites like agar-based ones infused with copper nanoparticles and reducing agents such as sodium hydroxide and ascorbic acid, excelled in biodegradability and UV light absorption. These qualities made them environmentally beneficial alternatives to conventional non-degradable composites that could have lead to pollution and reduce soil fertility by impeding oxygen flow[50]. The transition to bionanocomposites aligned with global sustainability goals, offering a solution that did not compromise the health of the ecosystem or human populations.

Moreover, bionanocomposites brought additional functional benefits to food packaging. Their transparency and lightweight nature were advantageous for enhancing consumer convenience and reducing transportation costs[51]. The moisture resistance of these materials also protected food products from humidity and water damage, further preserving food quality and extending shelf life. Antimicrobial properties were another critical aspect of bionanocomposites. By incorporating inorganic antimicrobial agents such as metal nanoparticles (silver, copper) and metal oxides (TiO_2, ZnO), these materials provided durable, high-temperature resistant protection against microbial growth, which was particularly valuable for food safety[52]. Unlike organic antimicrobial agents, these inorganic compounds maintained their stability under extreme conditions, making them more suitable for dynamic food packaging environments. They ensured that antimicrobial agents did not leach into the food, thereby preventing adverse reactions with food components and ensuring sustained microbial inhibition.

Incorporating these bionanocomposites into packaging films enabled a controlled migration of antimicrobial agents, effectively managing microbial contamination risks during transportation, processing, and storage of food products. This controlled release mechanism not only enhanced food security but also reduced the potential for toxic effects commonly associated with direct food contact with antimicrobial substances[53)]. As the application of bionanocomposites in smart food packaging continues to evolve, it promised to play a pivotal role in enhancing food quality, safety, and consumer satisfaction while adhering to environmental stewardship.

Challenge for biosensor for smart food packaging

Developing smart food packaging with integrated biosensors presented several challenges needed must be addressed to fully leverage their potential in enhancing food safety and quality. Key obstacles include ensuring the compatibility of biosensors with packaging materials without compromising food integrity, maintaining cost-effectiveness for widespread adoption, and achieving high durability and stability under varying environmental conditions. Additionally, biosensors needed to be highly sensitive and specific to avoid inaccurate readings, comply with stringent food safety regulations, and gain consumer trust. Effective data management, ensuring privacy and security, and scalability for mass production were also critical. Overcoming these challenges was essential for the successful commercialization of biosensor-equipped smart packaging, which aimed to revolutionize food safety, extend product shelf life, and build consumer confidence[30,31,54)].

Size and integration challenge for biosensor

The structure and size of biosensors varied depending on the type of detection required, and in food packaging, small-sized biosensors were ideal. However, integrating tiny biosensors into packaging presented challenges due to the need for high sensitivity and specificity. Nanosensors, such as invisible chips embedded in packaging, allowed for real-time monitoring of food quality. However, they faced limitations like restricted energy capacity, requiring the development of wireless nanosensor networks (WNSNs), which were still in early research stages[30,31,55)].

Several nanobiosensors, such as fluorescence-based, microfluidic-based, and SPR nanobiosensors, were effective for detecting pathogens, pollutants, and toxins[56,57)]. Despite their potential, these sensors faced challenges in smart food packaging due to size constraints, the need for high sensitivity, and cost concerns. Imprinted polymeric sensors, while effective in detecting food pathogens through color changes, were expensive and had not yet integrated into packaging materials due to high production costs and technical difficulties[58)]. Additionally, these biosensors often required complex instrumentation and skilled evaluation, making their commercialization for smart packaging a challenging task.

Properties' improvement challenge for biosensor

Biosensors played a pivotal role in the medical and agricultural fields, detecting harmful chemicals, toxins, and food pathogens with precision. However, adapting these technologies for use in food packaging introduced several significant challenges, including setting optimal detection limits, reducing detection times, ensuring high specificity, and achieving sufficient stability. Ideally, biosensors in food packaging should have had detection limits lower than the threshold that poses health risks, typically between 10^1–10^2 CFU/mL for infectious pathogens. Current biosensors, however, often detected pathogens at levels between 10^2–10^6 CFU/mL[59)], which exceeded the safe threshold and underscored the need for more sensitive technologies. Additionally, the detection time on how quickly a biosensor could identify contaminants, which was crucial for timely interventions to prevent foodborne illnesses, necessitating faster-than-current capabilities.

Specificity and stability were also critical for biosensors in food packaging applications. High specificity was essential to distinguish harmful pathogens or chemicals from similar non-target substances within complex food samples, which if not correctly identified, could have lead to false positives. This precision was particularly challenging when non-harmful elements like benign bacterial cells, fibers, or proteins might have confounded the biosensor's readings[60)]. Stability was another major concern; biosensors needed to maintain their functionality under variable environmental conditions over time. For instance, while certain gas sensors showed good stability for up to 50 days at 20ºC, their effectiveness diminished significantly within a week at room temperature due to reduced sensitivity to CO_2. Enhancing the stability of biosensors in food packaging was crucial for their practical application in monitoring food safety, particularly in products like meat, where prolonged and consistent sensor performance was needed[61)]. Addressing these challenges was essential for leveraging biosensor technology in smart food packaging, which promised to transform food safety practices by enabling real-time monitoring and extending the shelf life of perishable goods (Fig. 3).

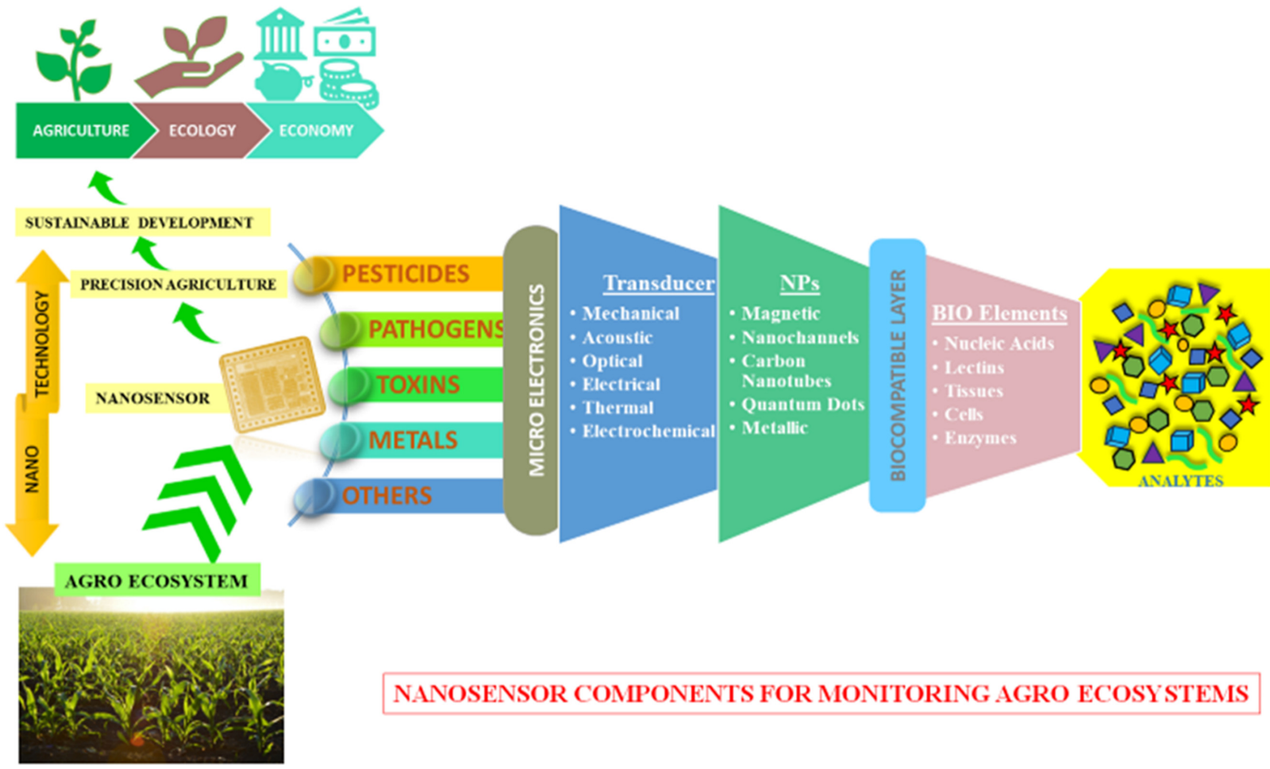


Fig. 3. The integration of nanotechnology in agricultural monitoring, highlighting its role in sustainable development. The nanosensors are applied to detect various environmental analytics like pesticides, pathogens, toxins, and metals within the agro ecosystem, contributing to precision agriculture. These sensors are broken down into three key components: Transducers that convert responses into measurable signals using various mechanisms; Nanoparticles including materials like magnetic nanoparticles and carbon nanotubes that enhance sensor functionality; and a Bio-Compatible Layer composed of biological elements such as nucleic acids and enzymes that interact with target analyses.

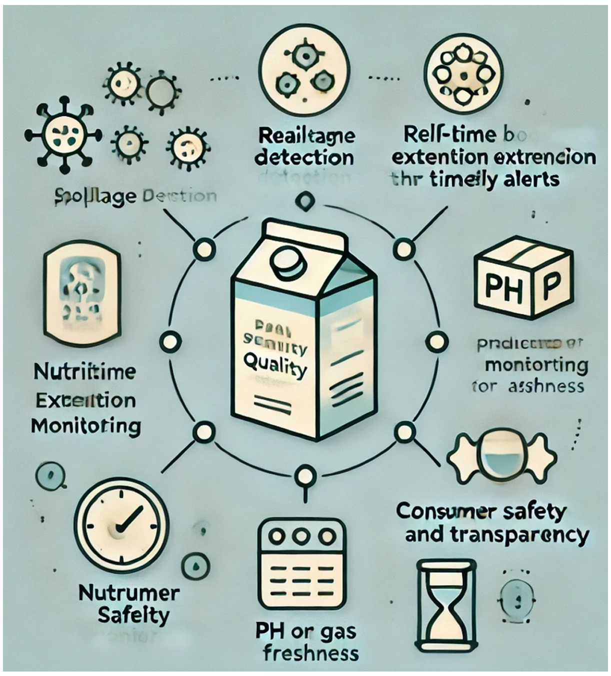


Fig. 4. Biosensors enhance food packaging by providing real-time data on spoilage detection, quality monitoring, and safety assurance—ensuring freshness, extending shelf life, and protecting consumers.

Challenge for screen printed sensor

Thin-film electronics and printed sensor systems were essential for developing screen-printed biosensors that monitored key parameters such as temperature and gas levels in smart food packaging, crucial for maintaining the freshness of perishable goods[62]. However, their application in food packaging was challenged by issues such as poor gas diffusion barriers and inconsistent sensor responses to changes in oxygen levels, could have compromised the sensors' reliability[63]. Moreover, the industry still lacked reusable thin-film technologies, which limited cost efficiencies crucial for scaling[64].

While smart packaging technologies like innovative labels and stickers—such as the Food Sentinel System barcode and Ageless-eye^{TM} oxygen indicators, offered modern solutions to food safety, they faced problems with limited sensitivity and stability, often degrading within days. Addressing these issues involves refining the properties of the materials used, optimizing production processes, and managing costs effectively. Additionally, there was a significant educational challenge, as companies had to ensure consumers understand how to correctly interpret and responsibly dispose of smart packaging. This necessitated clear communication and support from food packaging companies, underlining the need for comprehensive solutions that tackled both the technological and consumer education aspects of smart food packaging[65].

Challenge of bionanocomposite for food packaging

Bionanocomposites, which blended nanomaterials with polymer matrices, held promise for enhancing food packaging by improving durability and barrier properties. Despite their potential, significant challenges existed regarding their safe use[66]. These composites often involved nanoparticles that might have migrated into foods, potentially crossing cellular barriers and causing oxidative damage[67]. Although migration levels were generally low and often below detectable thresholds, the long-term health effects of ingesting these nanoparticles, especially their impact on vital organs and fetal development, remained largely unknown and require further investigation.

Furthermore, the environmental impact of nanoparticle release from food packaging into ecosystems posed additional risks. These particles could have interacted with and exacerbate the presence of heavy metals in soil and water, threatening plant and animal life and potentially reducing soil fertility[68]. Although naturally derived nanomaterials offered a lower perceived risk by minimizing food spoilage, their extraction was challenging and costly, particularly in the face of limited natural resources. Thus, while bionanocomposites offered innovative solutions for food packaging, their health, environmental, and economic impacts required careful evaluation and management to fully realize their benefits.

Conclusion

The field of smart food packaging, enriched by bionanocomposites and biosensors, held promising prospects for enhancing food safety and quality. Bionanocomposites contributed superior mechanical, thermal, and antimicrobial properties to packaging, albeit with considerations for health safety and material migration into food. Biosensors offered rapid and reliable monitoring for food integrity, facing challenges in commercialization, including integration with packaging materials and cost-effectiveness. Future development had to address these technological and health-related challenges to realize the potential of smart packaging. This entailed refining biosensor size and stability, ensuring the safety of bionanocomposites, and maintaining affordability. Successfully navigating these considerations would have been crucial for advancing smart packaging technologies, ultimately benefiting the food industry and consumers alike.

국문요약

식품 포장 분야에서 바이오센서와 바이오폴리머 기반 나노복합체, 즉 바이오나노복합체의 통합이 점차 산업 전문가들에 의해 인식되고 있으며, 이는 식품의 품질과 안전에 대한 우려가 증가함에 따라 주도되고 있습니다. 식품 포장에 내장된 바이오센서는 포장된 상품의 미생물에 의한 변질을 지속적으로 모니터링함으로써 식품의 완전성을 유지하는 핵심 요소로 업계를 변화시킬 준비가 되어 있다. 동시에, 탁월한 기계적, 열적, 광학적, 항균적 특성으로 인해 바이오폴리머 기반 나노복합체의 연구와 적용이 크게 확대되었다. 이러한 특성은 이들을 혁신적인 포장 솔루션에 적합한 주요 재료로 만든다. 그러나 지능형 식품 포장 시스템 발전에 바이오센서와 바이오나노복합체를 사용하는 잠재적인 장애물과 전망을 탐구하는 것은 아직 충분하지 않다. 바이오나노복합체와 바이오센서의 융합을 제안하는 것은 스마트 포장 산업을 재정의하는 획기적인 단계로, 이 기술들을 더 깊이 이해하여 지속 가능하고 경제적으로 실행 가능한 스마트 포장 옵션의 개발을 촉진할 필요성을 강조한다. 이 리뷰는 바이오센서와 바이오나노복합체에 대한 기존 연구와 개발 동향을 철저히 검토하고, 가까운 미래에 스마트 식품 포장 산업에서 진전을 이끌어낼 앞으로의 도전과 기회를 강조하는 데 전념하고 있다.

Conflict of interests

The authors declare no potential conflict of interest.

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