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Smart and Active Packaging in the Food Industry: a Review

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Abstract

The food industry faces increasing challenges related to maintaining product quality, safety, and sustainability across complex supply chains. In this context, active and intelligent packaging systems have emerged as complementary approaches designed to both control degradation processes and monitor product conditions in real time. This paper presents a critical review of recent advances in these technologies, with particular emphasis on their mechanisms of action, materials, and application-specific performance. Key systems, including oxygen scavengers, antimicrobial packaging, time-temperature indicators, freshness indicators, and biosensors, are analyzed in relation to different categories of food products. The analysis highlights that active packaging directly modifies the internal environment of the package, whereas intelligent systems enable the assessment of product status without altering its stability. However, the effectiveness of these systems depends on the accurate correlation between detected signals and actual degradation processes, as well as on technological and economic constraints. Current trends emphasize the development of integrated packaging solutions that combine protective and monitoring functions, supporting improved quality control, reduced food waste, and more efficient supply chain management.

Keywords: *biodegradable materials; cold chain; intelligent sensors; volatile compounds.*

1. Introduction

Food packaging constitutes an essential component of the modern food system, playing a decisive role not only in protecting products against external factors, but also in maintaining their quality and safety throughout the entire distribution chain [1]. Traditionally, packaging has been designed to fulfill passive functions such as mechanical protection, preservation, and consumer information; however, the increasing complexity of contemporary food supply chains, characterized by globalization, extended transportation times, and product diversification, has necessitated a redefinition of its role. Consequently, modern packaging is increasingly integrated as an active element of quality control systems, contributing to the reduction of food losses and the optimization of logistical processes [2, 3]. The evolution of food packaging has been accelerated by advances in materials science and emerging technologies, leading to the development of systems capable of meeting the increasingly complex demands of both industry and consumers. Packaging is therefore no longer perceived solely as a physical barrier, but rather as a functional system capable of extending shelf life, reducing food waste, and

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improving product traceability [4, 5]. This transition from passive packaging to functional systems is supported by the development of polymeric materials and multilayer structures, which enable the attainment of tailored barrier properties, mechanical strength, and compatibility with specific food products [6]. In this context, packaging is no longer regarded merely as a physical barrier, but as a system designed to regulate mass and energy transfer between the product and the surrounding environment [7]. The incorporation of antimicrobial agents into these structures highlights a paradigm shift, whereby packaging becomes an active factor in controlling microbiological processes. Thus, the use of silver-based compounds or other bioactive substances contributes to inhibiting microbial growth and extending shelf life [8-11]. Moreover, this approach reflects the trend of integrating preservation functions directly into the packaging structure, reducing reliance on food additives and supporting the development of products perceived as safer and more sustainable [12]. Against this background, active and intelligent packaging systems have emerged as complementary solutions for managing food quality. Active packaging interacts with the internal environment through mechanisms of absorption or release of specific compounds, while intelligent packaging enables the monitoring and communication of product status [13-15]. The scientific literature increasingly highlights the convergence of these two directions into a unified concept of "smart packaging," which combines protection, monitoring, and communication functions within a single system capable of dynamically responding to environmental changes [16, 17]. A defining feature of this evolution is the integration of detection technologies into packaging structures. Sensors and indicators, including freshness and time–temperature indicators, enable real-time monitoring of critical parameters such as temperature, gas composition, and microbial activity [18-20]. Beyond their monitoring function, these systems facilitate predictive quality control by enabling the anticipation of product degradation and early intervention within the supply chain. The use of biosensors and advanced optical technologies illustrates the transition toward "responsive" packaging, capable of reacting to specific stimuli and providing relevant information in real time [21, 22]. In parallel, sustainability has become a central criterion in the development of food packaging, driven by the significant environmental impact of waste generated by conventional plastic materials. In this context, European regulations on packaging waste reduction and recycling promotion, together with circular economy strategies, play a crucial role in guiding the development of packaging materials. At the same time, the integration of active and intelligent packaging into sustainable systems raises additional challenges related to recyclability, material compatibility, and end-of-life management. Accordingly, the shift toward biodegradable materials and recycling within a circular economy framework represents a key direction for reducing environmental impact [23]. The incorporation of bio-based materials and natural compounds into packaging structures provides opportunities for the development of functional systems with antimicrobial and antioxidant properties [24, 25]. Nevertheless, the large-scale implementation of active and intelligent packaging is influenced by factors such as production costs, regulatory constraints, and consumer acceptance [26, 27]. At the same time, global market dynamics and the growing demand for sustainable solutions highlight the need to align technological innovation with economic and social requirements [28]. Thus, the evolution of food packaging cannot be interpreted as a linear process, but rather as the result of a complex interaction between advances in materials science, the development of monitoring technologies, and pressures arising from sustainability and food safety requirements [29]. In this context, active and intelligent packaging systems become strategic components of the modern food system, contributing to improved quality, safety, and efficiency of the supply chain. Moreover, the integration of digital technologies and traceability systems indicates a clear trajectory toward the digitalization of packaging and its transformation into an information management platform [30, 31]. Unlike previous reviews that address active and intelligent packaging separately, the present review focuses on the convergence of these technologies into integrated hybrid packaging systems combining preservation, monitoring, traceability, and sustainability functions. The paper also provides a comparative analysis of mechanisms, materials, technological limitations, and application-specific performance across different food categories, highlighting current trends toward multifunctional and sustainable packaging platforms.

2. Materials and Methods

The present study was conducted as a comprehensive narrative review concerning active and intelligent packaging used in the food industry. Scientific literature was identified, selected, and analyzed through a structured literature search approach aimed

at ensuring thematic relevance and adequate coverage of recent technological developments in the field. Bibliographic sources were identified through consultation of major international databases, including ScienceDirect, PubMed, Web of Science, and Scopus, as well as journals indexed on the MDPI platform. The temporal scope primarily covered the period 2000-2025, with particular emphasis on recent studies reflecting current technological developments. The search strategy employed combinations of domain-specific keywords, such as "active packaging," "intelligent packaging," "food packaging," "oxygen scavengers," "antimicrobial packaging," "time-temperature indicators," "freshness indicators," "biosensors," and "food quality monitoring." The article selection process involved an initial screening based on title and abstract, followed by full-text evaluation of studies deemed eligible. Selection criteria included thematic relevance, scientific quality, recency of publication, and applicability to food packaging systems. Included studies comprised publications in indexed journals, written in English, addressing mechanisms of action, materials used, and applications of active and intelligent packaging, as well as aspects related to performance, technological limitations, and safety. Studies were excluded if incomplete, lacking full-text access, or presenting limited relevance to the food industry. Following the selection process, a total of 48 scientific papers relevant to the study topic were analyzed. The extracted information was organized into functional categories corresponding to packaging types and mechanisms of action, thereby enabling a coherent comparative analysis. In addition, correlations between food product characteristics, usage conditions, and packaging system efficiency were examined. Data integration was performed using a comparative and interpretative approach, aimed at identifying trends, limitations, and future development directions in the field.

3. Results and Discussion

3.1. Active Packaging Systems

Active packaging systems are defined as packaging solutions designed to directly control the internal conditions of the package through components capable of interacting with the surrounding environment or the food product itself [32]. Unlike conventional packaging, whose function is predominantly passive, these systems actively influence critical parameters of product stability, such as gas composition and moisture levels [30, 33]. Through this capacity for intervention, active packaging contributes to maintaining optimal conditions throughout storage and distribution, being particularly relevant for perishable products. Their functionality is not determined solely by the intrinsic properties of the material, but rather by the overall interactions among the packaging, the product, and the storage environment [34]. In this regard, the design of such systems requires an integrated approach, in which the efficiency of action mechanisms must be aligned with safety and compatibility requirements relative to the food product [1, 35].

3.1.1. Mechanisms of Action of Active Packaging

The operation of active packaging systems is based on processes involving the absorption or controlled release of specific compounds, enabling the regulation of the internal package environment and the limitation of factors associated with food degradation, such as oxidative reactions, moisture fluctuations, and microbial growth [22]. The performance of these mechanisms depends on their adaptation to the specific characteristics of the product and the storage conditions. For instance, the effectiveness of oxygen scavenging systems or moisture control solutions is influenced by food composition and environmental parameters, necessitating a rigorous correlation between material properties and application requirements [7]. Although numerous studies highlight the high efficiency of oxygen scavengers in products of animal origin, other research points to their limitations under non-hermetic packaging conditions or in the presence of temperature fluctuations. In systems based on bioactive compounds, functionality is achieved through the gradual release of antimicrobial or antioxidant substances that directly interfere with microbiological and oxidative processes. Natural compounds, such as polyphenols or pigments, are frequently employed due to their compatibility with food products; however, their effectiveness is influenced by chemical stability and diffusion kinetics within the material matrix [36, 37]. Functional polymeric materials, including biopolymers such as pectin, play a crucial role in the incorporation and stabilization of these active compounds, contributing to the control of degradation processes [38]. Furthermore, the combination of multiple mechanisms within a single system may generate synergistic effects by simultaneously addressing different spoilage factors, although this approach entails increased design complexity [13, 39]. The efficiency of active packaging systems must be evaluated in relation to the specific application, being determined by the interaction between the

material, functional compounds, and conditions of use [32, 35]. In practice, the performance of these mechanisms is not uniform and is significantly influenced by product type and storage conditions. Consequently, the selection of an optimal mechanism involves balancing technological effectiveness with system complexity.

3.1.2. Materials and Functional Compounds Used in Active Packaging

The materials employed in active packaging constitute a central element in the design of these systems, being selected according to their structural properties, processability, and compatibility with food products. In this context, the development of modern packaging involves the use of materials capable of ensuring structural integrity while meeting technological and food safety requirements [40]. Natural biopolymers have gained considerable attention in recent years due to their renewable origin and biodegradability. They are widely used for the production of films and edible coatings, being characterized by their ability to form stable structures and to be tailored for diverse applications in the food industry. Moreover, their utilization is closely aligned with current trends aimed at reducing environmental impact and promoting sustainable packaging solutions [23, 24].

Conventional polymeric materials, particularly multilayer structures, remain essential in the packaging industry due to their superior barrier properties and mechanical strength. Multilayer films enable the combination of different types of polymers, resulting in materials with performance characteristics adapted to various technological requirements and storage conditions [6, 8]. Bioactive compounds represent a distinct category of functional components, incorporated into packaging materials to broaden their range of applications. These include primarily substances of natural origin, such as polyphenols, pigments, and essential oils, which are characterized by chemical diversity and the ability to be integrated into various polymer matrices [41]. Nanotechnology has opened new perspectives in the development of packaging materials by enabling the creation of structures with improved barrier properties, enhanced mechanical resistance, increased thermal stability, and antimicrobial activity. The incorporation of nanomaterials into polymer matrices contributes to reduced gas and moisture permeability, improved structural strength, and enhanced preservation performance, thereby supporting the extension of food shelf life; however, their use entails stringent requirements regarding safety assessment and compliance with food-related regulations [42, 43]. Emerging bio-based materials, such as lignin, are being investigated as sustainable alternatives to conventional materials due to their availability and structural properties. These can be combined with other biopolymers to develop innovative materials, contributing to reduced reliance on fossil resources and supporting the transition toward a circular economy [28, 44]. Therefore, the selection of materials and functional compounds in active packaging is governed by the need to balance technological performance with safety and sustainability requirements, highlighting the essential role of materials in the advancement of modern packaging systems.

3.1.3. Types of Active Packaging and Their Applications in the Food Industry

Active packaging systems can be classified according to their mechanism of action into absorption systems, release systems, and systems based on functional compounds integrated into the material matrix. This classification reflects the way in which packaging interacts with the internal environment and highlights its adaptation to the requirements of different food products [34, 35]. In practice, the selection of a specific type of active packaging is determined by the dominant degradation mechanisms, such as oxidation, microbial activity, or moisture fluctuations.

Oxygen Scavenging Systems

These systems are employed to reduce residual oxygen within the package. By limiting oxygen availability, oxidative processes and the growth of aerobic microorganisms are slowed [12; 43]. They are particularly important in the packaging of meat and fish products. Oxygen promotes lipid oxidation and color changes, which negatively affect product acceptability. The use of oxygen scavengers contributes to maintaining the red color of meat and delaying rancidity [2, 13]. In ready-to-eat products, such systems reduce the risk of aerobic microbial growth. In bakery products, oxygen absorption systems are used to prevent mold development, especially under extended storage conditions [40]. Consequently, these systems are primarily associated with products sensitive to oxidation and aerobic contamination. From a technological perspective, oxygen scavenging systems are mainly based on compounds such as iron powders, ascorbic acid, enzymes (e.g., glucose oxidase), or reactive polymer systems, incorporated in the form of sachets, labels, or directly into the packaging material structure. These components react with the oxygen present within the package, reducing its concentration to very low levels and ensuring a stable environment for the

product [34, 35].

Moisture Control Systems

Moisture control is achieved through the use of absorbent or regulating materials that maintain an optimal level of water activity within the package [22]. In the case of fresh meat, the use of absorbent pads enables the retention of exudate, thereby reducing contamination risk and improving product appearance [2, 45]. At the same time, moisture control limits microbial growth. For fruits and vegetables, maintaining moisture balance is essential for preserving firmness and preventing deterioration. To this end, moisture control systems based on hygroscopic materials, such as silica gel, inorganic salts, or superabsorbent polymers, are employed to retain excess water within the package [22, 35]. In addition, polymeric films with controlled water vapor permeability allow the regulation of moisture transfer and the maintenance of a stable microclimate within the package [24, 43]. In bakery products, moisture control is achieved through the use of absorbent materials or packaging with tailored barrier properties that limit water migration between product components. This aspect is particularly important in complex products, where moisture redistribution may affect texture and stability. In this way, both drying and softening are prevented, preserving sensory characteristics throughout storage [40, 45].

Antimicrobial Packaging

Antimicrobial packaging systems are designed to inhibit the growth of microorganisms either through the controlled release of active compounds or through their direct interaction with the surface of the food product [37, 41]. These compounds commonly include silver ions, organic acids, bacteriocins (antimicrobial peptides produced by certain bacteria that inhibit the growth of spoilage and pathogenic microorganisms), or natural extracts with antimicrobial activity [46]. Such systems are primarily applied to perishable products. In the case of meat and ready-to-eat products, they reduce microbial load and enhance food safety, being incorporated into polymeric films or multilayer packaging structures [9, 10]. For fruits and vegetables, biopolymer-based edible coatings play a significant role. These form a protective barrier and may incorporate antimicrobial compounds, thereby contributing to the extension of shelf life [38]. In practice, these systems are applied as films or coatings directly onto the product surface, reducing post-harvest losses. In recent years, the use of natural compounds such as polyphenols or essential oils has increased significantly, driven by the demand for safer and more natural products [36, 39]. These substances are incorporated into the material matrix, enabling controlled release and prolonged antimicrobial activity.

Antioxidant Packaging

Antioxidant packaging systems are employed to limit oxidation reactions, which predominantly affect lipid-rich products. Oxidation leads to undesirable changes in taste, odor, and nutritional value [1, 43]. These systems are widely used for meat, fish, and processed products, where lipid oxidation represents the primary degradation pathway. In practice, antioxidants such as phenolic compounds, tocopherols, or plant extracts are incorporated into polymer films or multilayer structures, allowing controlled release and continuous product protection [36]. This approach enables the control of oxidative processes without the direct addition of additives to the food product. In bakery products and snacks, antioxidant packaging contributes to lipid stability and prevents rancidity. These systems are particularly used in flexible packaging, where barrier properties combined with active compound integration help maintain product quality during storage [40].

Gas-Releasing Systems

Gas-releasing systems are used to modify the internal atmosphere of the package, with the most common being those based on CO_2 and ethanol [34]. CO_2-emitting systems are applied in the packaging of meat and fish, where the gas inhibits microbial growth and contributes to shelf-life extension [13]. These systems are often used in combination with modified atmosphere packaging. Ethanol-emitting systems are primarily used in bakery products. Ethanol inhibits mold growth and helps preserve product freshness [11]. These systems are particularly effective for products with extended shelf life.

Systems Based on Biopolymers and Bioactive Compounds

An important direction in the development of active packaging involves the use of biopolymers and bioactive compounds. These systems may simultaneously exhibit antimicrobial and antioxidant effects [24, 36]. Materials such as pectin are used to produce edible coatings and functional films, contributing to product stabilization and the preservation of sensory characteristics [38]. At the same time, the use of lignin and other biopolymers enables the development of sustainable materials with functional properties [44]. These systems are particularly suitable for fresh and minimally processed products, where maintaining freshness without the use of synthetic additives is essential. Furthermore, they align with current requirements related to sustainability and the circular economy [4].

Correlation between Packaging Type and Food Product

The selection of active packaging is dependent on the characteristics of the food product. Meat and fish products require complex systems that combine oxygen scavenging, antimicrobial activity, and antioxidant protection [13, 43]. Fruits and vegetables primarily require moisture control and the use of bioactive compounds to maintain freshness and visual quality. Bakery products are associated with moisture control systems and ethanol emitters, while dairy products frequently utilize antimicrobial packaging and atmosphere control systems [31, 35]. This correlation highlights that no universally optimal system exists, as each packaging type is tailored to specific degradation mechanisms. Consequently, current industry trends are oriented toward the development of multifunctional systems capable of integrating multiple protective mechanisms simultaneously.

This relationship is illustrated in Figure 1, which synthesizes the main types and functions of active packaging systems.

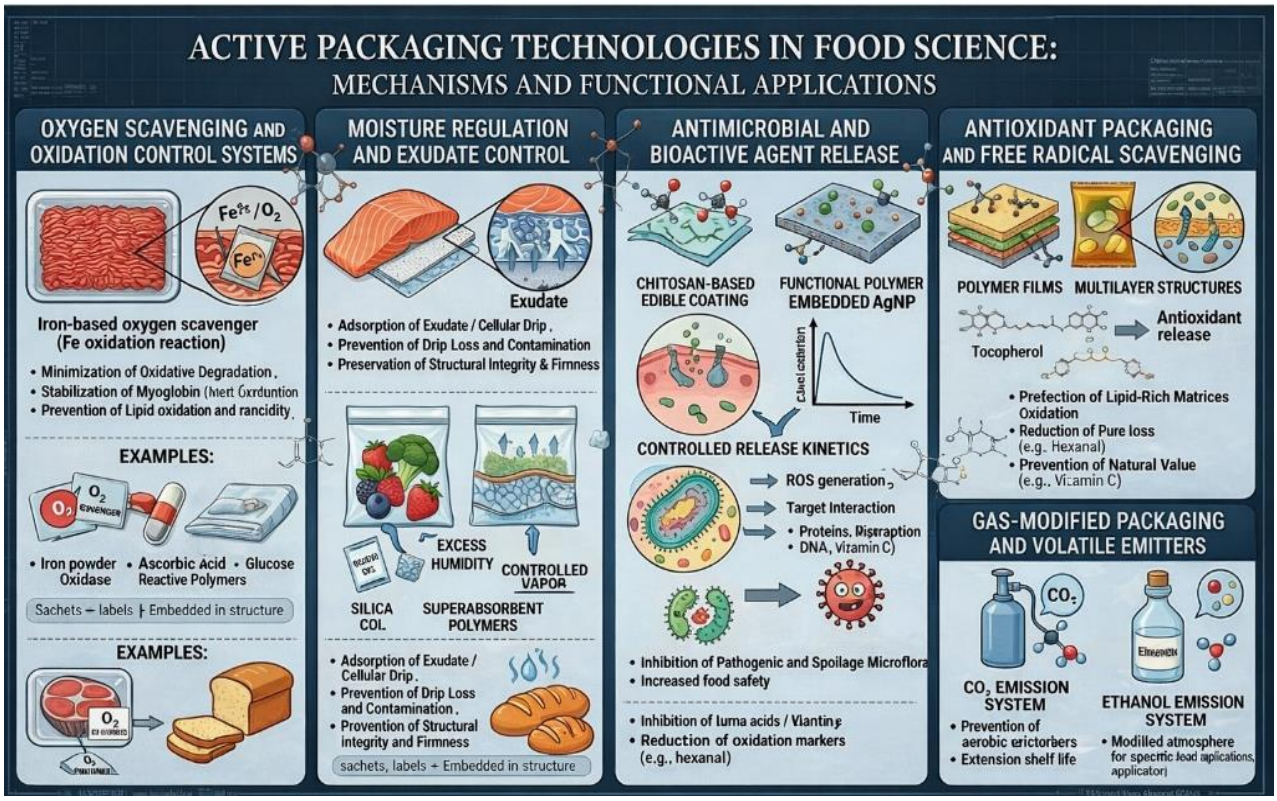

Figure 1. Advanced active packaging technologies in food science: mechanisms and functional application

Figure 1 synthesizes the main development directions of active packaging, highlighting the relationship between system type, the compounds employed, and their functional effects on food products. It can be observed that these technologies are primarily oriented toward controlling major degradation factors, such as oxygen, moisture, and microbial activity. The figure also emphasizes the trend toward integrating multiple functions within a single packaging system, indicating a transition toward multifunctional solutions adapted to the modern requirements of the food industry.

3.1.4. Advantages and Limitations of Active Packaging

Active packaging systems contribute to improving the performance of packaging solutions through their direct interaction with the internal environment of the package. However, their effectiveness depends on a range of technological factors, including the stability of active compounds, material properties, and storage conditions [35, 43]. In practice, these limitations may reduce their industrial applicability, particularly for low-value products, where the additional costs are not economically justified. A synthesis of active packaging systems and their characteristics is presented in Table 1.

Table 1 Active packaging systems

Type of Active System	Specific Advantages	Critical Limitations	Factors Influencing Efficiency	References
Oxygen Scavenging Systems	Allow reduction of modified atmosphere requirements; easy application (sachets, labels, or active elements)	Inefficient in non-hermetic packaging; risk of premature activation	Residual air volume, gas permeability of the packaging, temperature	[12, 43]
Moisture Control Systems	Improve visual stability (reduce liquid accumulation); contribute to product acceptability	Limited absorption capacity; requires proper sizing for the application	Water activity of the product, temperature, contact surface area	[22, 45]
Antimicrobial Packaging	Can reduce the use of direct preservatives; localized action at the product surface	Possible migration of compounds; limited acceptance by consumers	Type of active compound, release rate, interaction with the food matrix	[37, 41]
Antioxidant Packaging	Provides continuous protection without altering the product; applicable in multilayer structures	Degradation of active compounds over time; non-uniform distribution	Antioxidant stability, exposure to light and oxygen	[36]
Gas-Emitting Systems	Active control of the atmosphere without complex equipment; adaptable to various products	Difficult to control the release rate; risk of overconcentration	Package volume, release rate, product type	[11, 34]
Systems Based on Biopolymers and Bioactive Compounds	Integration with biodegradable materials; respond to sustainability requirements	High variability in properties; challenging industrial scalability	Polymer structure, compatibility with active compounds	[24, 44]

Table 1 summarizes the main advantages and limitations of active packaging systems, as well as the factors influencing their efficiency across different food applications. The comparative analysis of these systems highlights that, although active packaging offers significant benefits in quality control, its implementation is constrained by factors such as costs, technological complexity, and regulatory requirements. In this context, the selection of an optimal solution depends on achieving a balance between performance and feasibility at an industrial scale.

3.2. Smart Packaging Systems

Smart packaging systems are designed to monitor, in real time, critical parameters related to food quality and to provide relevant information throughout the supply chain. Unlike active packaging, which interacts with the internal environment, these systems transform packaging into a tool for evaluating and communicating product status [18, 29]. The integration of monitoring functions into packaging structures addresses the limitations of traditional quality control systems, which rely predominantly on indirect estimates such as expiration dates. In this context, smart packaging enables a dynamic evaluation of products, adapted to actual storage and distribution conditions, thereby reducing uncertainties associated with shelf life [32, 47]. From an application perspective, these systems contribute not only to enhanced food safety but also to the optimization of logistical processes, by providing precise information regarding transport and storage conditions. Thus, smart packaging aligns with the broader trend of digitalization in the food industry, becoming part of more complex data management and traceability systems [31, 48].

3.2.1. Mechanisms of Operation of Smart Packaging

The operating mechanisms of smart packaging systems are based on the conversion of signals generated during food degradation into measurable or visible responses. This process involves the detection of specific changes, such as temperature variations, gas composition, or the formation of compounds resulting from microbiological activity [21]. A commonly used mechanism involves monitoring volatile compounds generated during spoilage. For example, in products of animal origin, degradation leads to the formation of biogenic amines and sulfur-containing compounds, which are used as indicators of freshness [20]. In other cases, variations in CO_2 levels or pH changes reflect the progression of biochemical processes and can be correlated with

product condition [47]. From a technological standpoint, these mechanisms are implemented through the integration of detection systems based on different principles. Optical sensors provide immediate visual responses and are suitable for applications where rapid interpretation is essential [48]. Electrochemical sensors enable the quantification of detected compounds, offering a higher level of precision [19]. In the case of biosensors, detection relies on specific biological interactions, ensuring high selectivity, although involving more complex technological requirements [35]. Indicators operate through chemical reactions that produce visible changes, particularly color variations correlated with product condition. These systems are widely used and generally provide qualitative rather than quantitative information [47]. From an application perspective, the performance of these mechanisms depends on their ability to correlate detected signals with actual degradation processes. In the absence of such correlation, the information provided may be difficult to interpret or may lead to inaccurate assessments. Therefore, the development of smart packaging systems requires both the optimization of detection sensitivity and the validation of their relevance for different categories of food products [32]. In this context, the literature highlights differences among sensor types, with biosensors offering higher specificity compared to colorimetric indicators, albeit with increased technological complexity and cost.

3.2.2. Materials and Technologies Used in Smart Packaging

The development of smart packaging is closely linked to the use of functional materials capable of responding to specific stimuli and generating detectable signals. Material selection is determined not only by barrier properties but also by the ability to incorporate components sensitive to environmental changes [43]. Materials responsive to pH and gas composition play a significant role, particularly in systems based on colorimetric indicators. Natural pigments, such as anthocyanins, are frequently incorporated into packaging matrices due to their ability to change color in response to chemical variations within the package environment [36]. These materials enable the development of simple yet effective visual systems for assessing product freshness. In parallel, the use of biopolymers represents an important direction in the development of sustainable smart packaging. Materials such as pectin and other polysaccharides are used as matrices for incorporating functional compounds, contributing both to system stability and to the preservation of food product characteristics. However, the performance of these materials is influenced by their sensitivity to moisture and their limited mechanical properties, which necessitates the use of composite systems [24]. Nanotechnology plays a crucial role in the advancement of smart materials, enabling the integration of nanosensors and nanocomposites into packaging structures. Metallic or metal oxide nanoparticles can enhance detection properties and system stability, facilitating the identification of contaminants or quality changes at the molecular level [33, 42]. Nevertheless, their application raises challenges related to food safety and regulatory constraints concerning compound migration into the product. In addition to responsive materials, the development of smart packaging is supported by the integration of digital technologies. RFID systems, connected sensors, and Internet of Things-based platforms enable real-time data collection and transmission, facilitating traceability and the monitoring of storage conditions [16, 48]. These technologies extend packaging functionality beyond monitoring, transforming it into an active component of modern logistics systems.

At the same time, the development of these systems is influenced by economic and environmental constraints. The high cost of advanced materials and the complexity of integration processes limit large-scale implementation, particularly for low-value products [23, 28]. Consequently, current trends are oriented toward the development of hybrid materials that combine functionality with sustainability and economic feasibility [4].

3.2.3. Types of Smart Packaging and Their Applications in the Food Industry

Smart packaging systems can be classified according to the parameters monitored and the detection mechanisms employed, including time–temperature indicators, freshness indicators, gas indicators, biosensors, and digital systems. This classification reflects their adaptation to different degradation processes affecting food products [14, 18]. Time-temperature indicators are used to assess the cumulative exposure of products to temperature variations, providing relevant information regarding storage history. These are typically labels or integrated packaging systems containing temperature-sensitive compounds that progressively change color or signal intensity depending on storage conditions [22]. Their operation is based on chemical reactions or diffusion processes dependent on temperature, which lead to irreversible changes in the visual

properties of the system [32]. The rate of these reactions increases at elevated temperatures, thereby accelerating the visual response of the indicator and reflecting the cumulative thermal exposure of the product [47]. In this way, the indicator reflects not only instantaneous conditions but also integrates the cumulative effect of thermal exposure on the product [14, 47]. In practice, these systems are particularly applied to perishable products such as meat and fish, where temperature deviations have a direct impact on microbial growth dynamics and shelf life [13]. Examples include commercial labels based on enzymatic or polymeric reactions, such as Fresh-Check® or MonitorMark®, used for monitoring the cold chain [13, 22].

Freshness Indicators

Freshness indicators enable the direct assessment of food product condition by detecting compounds generated during degradation processes. In protein-rich products, spoilage is associated with the accumulation of biogenic amines and sulfur-containing compounds, which serve as markers of freshness [20, 47]. Their mechanism of operation is based on the interaction between these compounds and sensitive substances incorporated into the indicator, typically natural or synthetic pigments. An increase in amine concentration leads to changes in the pH of the environment, which in turn induces structural transformations of the pigments, resulting in visible color variations [20, 36]. In practice, these systems are primarily applied to products of animal origin, where spoilage processes are rapid and highly dependent on storage conditions. In fish, for instance, monitoring volatile compounds such as trimethylamine or ammonia provides a more accurate assessment of freshness compared to conventional methods based solely on expiration dates [47]. Examples include labels based on pH-sensitive pigments such as anthocyanins or bromocresol derivatives, used to monitor chemical changes within the package [36].

Gas Indicators

Gas indicators are used to monitor the composition of the internal atmosphere of packaging, particularly in modified atmosphere systems. They enable the detection of variations in oxygen and carbon dioxide concentrations, which may be associated with both degradation processes and potential packaging leakage [18, 45]. These systems operate through interactions between the gases present and sensitive compounds incorporated into the indicator, typically dyes or chemical sensors. Oxygen can initiate oxidation reactions, while variations in CO_2 concentration influence acid–base equilibrium, leading to visually detectable color changes [20, 47]. Thus, the color variation of the indicator indirectly reflects changes in the internal atmosphere of the package. In practice, these systems are mainly used for products packaged under modified atmosphere conditions, where maintaining gas composition is essential for product stability and safety. Examples include oxygen indicators based on redox dyes and CO_2-sensitive systems used in the packaging of meat, dairy products, and ready-to-eat foods [18, 45].

Biosensors

Biosensors are analytical systems used for the selective detection of microorganisms or specific metabolites through biological recognition elements such as enzymes, antibodies, or nucleic acids. These systems are characterized by high specificity and sensitivity, enabling the detection of low concentrations of target compounds [19, 48]. Signal generation occurs as a result of the specific interaction between the biological element and the detected analyte, leading to measurable changes in electrical, optical, or electrochemical parameters. The signal intensity is directly correlated with analyte concentration, allowing for quantitative evaluation of contamination or degradation levels [19].

In practice, biosensors are employed in applications with stringent food safety requirements, particularly for ready-to-eat products, where rapid detection of contaminants is essential. Examples include electrochemical biosensors for detecting pathogenic bacteria such as *Salmonella* or *Escherichia coli*, as well as optical systems for identifying toxins or metabolites formed during food degradation [48].

Digital and RFID Systems

Digital systems, including RFID technologies, are used for monitoring and managing information associated with food products throughout the supply chain. These systems enable the recording and transmission of environmental parameters without involving direct chemical reactions [48]. Changes in recorded information are determined by variations in parameters detected by integrated sensors, which are transmitted in real time to management systems. This approach allows continuous evaluation of storage and transport conditions [16]. These systems are particularly applicable to perishable products, where cold chain control is essential for maintaining quality [31].

Correlation between Types of Smart Packaging and Food Products

The selection of smart packaging systems is determined by the nature of degradation processes

specific to each food product. Freshness indicators are suitable for protein-rich products, where microbial degradation generates specific volatile compounds. Time–temperature indicators are used for products sensitive to thermal variations, while gas indicators are integrated into modified atmosphere packaging systems. Biosensor-based and digital technologies are applied in contexts requiring advanced monitoring and high traceability. This diversity highlights the application-specific nature of these systems, with selection being conditioned by technological requirements, the level of monitoring needed, and economic constraints [15, 16].

3.2.4. Advantages and Limitations of Smart Packaging

Smart packaging systems contribute to improved monitoring of food product quality by providing real-time information regarding storage conditions and product status [32]. Their effectiveness depends on the sensitivity of detection components, the stability of the materials used, and the conditions of application, while also being influenced by economic and technological factors [48]. Additionally, the interpretation of generated signals may be affected by external conditions, which can limit the accuracy of these systems in real-world applications.A synthesis of smart packaging systems and their characteristics is presented in Table 2.

Table 2. Smart packaging systems

Type of Smart System	Specific Advantages	Critical Limitations	Factors Influencing Efficiency	References
Time–Temperature Indicators	Allow cumulative evaluation of product exposure to temperature	Do not directly reflect the actual level of microbiological or chemical degradation	Storage temperature, duration of exposure, type of reaction used	[32, 47]
Freshness Indicators	Detect compounds formed during product degradation	Response may be influenced by packaging conditions (e.g., humidity, gas composition)	Product type, nature of volatile compounds, pigment stability	[20, 36]
Gas Indicators	Monitor changes in the internal atmosphere composition of the package	Do not provide specific information about the type or level of product degradation	Gas composition, packaging permeability, package volume	[18, 45]
Biosensors	Enable selective detection of microorganisms or contaminants	Stability of biological components is limited under real use conditions	Storage conditions, duration of use, type of biological element	[19, 48]
Digital and RFID Systems	Ensure continuous monitoring and product traceability	Do not provide direct information on the microbiological or chemical status of the product	Communication systems, transport conditions, available infrastructure	[16, 31]

Table 2 summarizes the main advantages and limitations of smart packaging systems, as well as the factors influencing their efficiency across different food applications. The comparative analysis highlights that, although smart packaging provides an advanced level of monitoring and control of storage conditions, it does not always ensure a direct assessment of product quality. In this context, the application of these systems depends on the correlation between the information provided, the specific characteristics of the food product, and the requirements of the distribution chain.

Although active and smart packaging are often addressed separately, the fundamental difference between them lies in their mode of interaction with the food product. Active packaging directly influences degradation processes, whereas smart packaging provides information without intervening in them. This distinction limits the independent use of each system in complex applications, which explains the current trend toward the development of integrated systems that combine protection and monitoring functions, as illustrated in Figure 2.

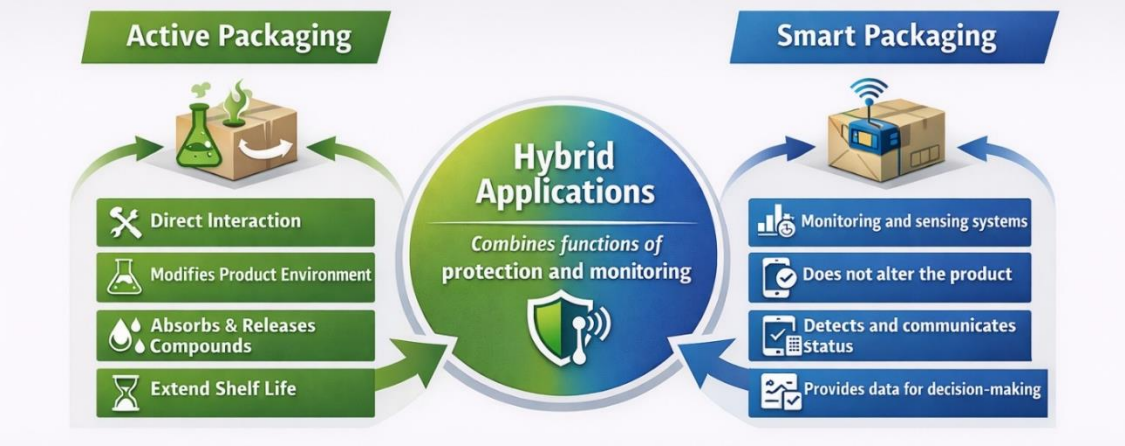

Figure 2. Integration of active and intelligent systems into hybrid packaging platforms.

4. Conclusion

The analysis of modern packaging systems highlights the complexity of interactions among materials, products, and the usage environment, moving beyond the traditional paradigm of packaging as a simple barrier. Packaging performance is determined by its ability to respond dynamically to degradation processes and to variations in storage and distribution conditions. The findings indicate that the effectiveness of these solutions depends on the functional integration of protective and monitoring mechanisms and on their adaptation to the specific characteristics of food products. Unlike conventional reviews that discuss active and intelligent packaging separately, the present study emphasizes the convergence of these technologies into integrated hybrid packaging systems combining preservation, monitoring, traceability, and sustainability functions. This integrated perspective highlights the transition from passive packaging toward multifunctional platforms capable of simultaneously improving food quality, safety, and supply chain management.

The identified limitations are associated with technological constraints, economic feasibility, regulatory requirements, and the difficulty of accurately interpreting the information generated under real usage conditions. In addition, large-scale industrial implementation remains challenging due to material compatibility, recycling limitations, and the stability of active and sensing components during storage and distribution. Current development directions focus on the design of integrated systems capable of combining protective and monitoring functions, particularly for perishable products where real-time quality assessment can contribute to reducing food losses and improving shelf-life management. Future research should prioritize the development of sustainable hybrid packaging platforms based on biodegradable materials, nanotechnology, biosensors, and digital traceability systems integrated with IoT and smart supply-chain technologies. Despite the significant technological progress achieved in recent years, further studies are still required to improve system reliability, reduce production costs, and ensure regulatory compliance for effective industrial-scale implementation.

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