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Smart and sustainable food packaging: recent advances in active/intelligent technologies and future directions

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ABSTRACT
This narrative review synthesizes current knowledge and technological advances in smart and sustainable food packaging and focuses on active, intelligent, and bio-based systems. No experimental units, treatments, or controlled interventions were applied because this study is based solely on structural assessments of published scientific literature, regulatory documents, and technical reports. The goal is to clarify how new packaging technologies contribute to food quality, food safety assurance, and environmental performance. Active packaging technology incorporating antimicrobial agents, antioxidant emitters, gas removers, and natural bioactive compounds has demonstrated strong potential to extend shelf life and reduce microbial and oxidative degradation across various food categories. Intelligent packaging systems, including time-temperature indicators, freshness sensors, and biosensing materials, monitor product status in real time, improving transparency across the supply chain. At the same time, bio-based and biodegradable materials such as plant-derived polymers, starch composites, and cellulose films provide environmentally responsible alternatives to existing plastics and support circular economic strategies. Sustainability assessments, environmental burdens, and regulatory reviews indicate ongoing challenges related to safety assessments, movement controls, and global harmonization. Consumer Acceptance Studies further emphasize that perceived safety, environmental benefits, and usability strongly influence the willingness to adopt new packaging systems. This comment suggests that integrating active, intelligent, and bio-based components is essential to developing safe and sustainable next-generation packaging solutions. To accelerate the commercial adoption of innovative and sustainable packaging technologies in the future, the focus should be on regulatory alignment, scalable industrial manufacturing, and digital integration.

Keywords: smart food packaging, active packaging, intelligent packaging, sustainable materials, food safety, waste reduction

INTRODUCTION

The food industry is facing increasing pressure to ensure safety, maintain quality, and minimize waste while meeting sustainability targets **[1]**. Global food loss and waste are estimated to reach nearly one-third of total production, contributing not only to economic inefficiency but also to significant greenhouse gas emissions and resource depletion **[2]**. Traditional packaging systems, primarily based on petroleum-derived plastics, have long provided protection and convenience but now pose serious environmental challenges due to their persistence, limited recyclability, and microplastic pollution **[3]**. Consequently, the development of innovative, sustainable, and intelligent packaging systems has become a central focus in modern food science and technology **[4]**. Smart packaging represents an emerging paradigm that extends beyond containment, offering active, intelligent features that interact with food and its environment **[5]**. Active packaging technologies employ components such as antimicrobial, antioxidant, and gas-scavenging systems to extend shelf life and preserve nutritional quality **[6]**.

Intelligent packaging, on the other hand, employs indicators and sensors, such as time-temperature indicators (TTIs), freshness sensors, and colorimetric labels, to monitor and communicate food quality in real time **[7]**. When combined with sustainable materials, such as bio-based polymers or biodegradable films, these technologies offer a viable pathway toward circular, resource-efficient food systems. Recent advances in materials science, nanotechnology, and digital innovation have accelerated the development of smart packaging solutions **[8]**. However, despite numerous experimental and commercial applications, several challenges remain unresolved. These include technical barriers in integrating active components without compromising food safety, limited large-scale biodegradability, regulatory uncertainty, and variable consumer acceptance across markets. Moreover, while extensive studies exist on isolated aspects of active or intelligent packaging, there remains a lack of comprehensive synthesis that connects technological innovation with environmental sustainability, regulatory frameworks, and digital transformation **[9]**. This review systematically examines recent advances in smart and sustainable food packaging, with a focus on the functional mechanisms and performance of active and intelligent packaging technologies **[10]**. Specific attention is given to the transition toward bio-based **[11]** and eco-friendly materials **[12]**, as well as to the implications of these innovations for food safety regulation **[13]**, life-cycle assessment (LCA) **[14]**, and consumer acceptance **[15]**. In addition, the review discusses emerging technological integrations, including Internet of Things (IoT)-based monitoring **[16]**, blockchain-enabled traceability **[17]**, and circular-economy frameworks **[18]**, which are increasingly shaping next-generation packaging systems **[19]**. By critically linking experimental evidence with industrial implementation, this review clarifies the opportunities and limitations of smart and sustainable packaging in improving shelf-life management **[20]**, safety assurance **[21]**, and resource efficiency within global food systems **[22]**.

Objectives

The primary objective of this narrative review is to synthesize current advances in active, intelligent, and bio-based food packaging technologies and to evaluate their collective contribution to food safety, quality preservation, and environmental sustainability.

Overview of Technological Development

The development of smart food packaging technologies has evolved from passive containment systems to multifunctional platforms capable of preserving, monitoring, and even communicating food quality **[23]**. Early packaging systems were primarily designed to provide physical protection and to act as barriers to moisture, oxygen, and light. However, growing consumer demand for fresher, safer, and more sustainable food has driven a technological transition toward packaging that actively interacts with food and its surrounding environment **[24]**. This transformation is largely categorized into two domains active packaging, which modifies the internal atmosphere or prevents deterioration, and intelligent packaging, which monitors and transmits information about the food's condition in real time (Figure 1) **[25]**. Recent years have witnessed rapid innovation in both categories. Active packaging has expanded from traditional absorbers and emitters to include materials that incorporate natural antimicrobials, antioxidants, and enzymatic systems **[26]**. For example, films containing chitosan, nisin, or essential oils such as thyme and oregano have demonstrated extended shelf life in meat and dairy applications, with measurable reductions in microbial load and lipid oxidation **[27]**. The growing preference for natural active agents reflects both consumer expectations for "clean-label" ingredients and regulatory pressures to minimize synthetic additives **[28]**. In parallel, advancements in polymer science have allowed more uniform dispersion of active compounds within film matrices, improving release control and minimizing unwanted sensory effects **[29]**. Despite these achievements, active systems still face challenges related to compound stability, migration behavior, and compatibility with diverse food types, as shown in Table 1 which limit their large-scale commercialization **[30]**. In contrast, intelligent packaging technologies have shifted the role of packaging from a passive barrier to an information interface between the product, the supply chain, and the consumer **[31]**. Modern intelligent systems employ TTIs, gas sensors, and colorimetric freshness indicators that respond to physicochemical changes such as pH, CO_2 concentration, or microbial metabolites **[32]**. These indicators provide real-time visual feedback, helping consumers and distributors distinguish between genuinely spoiled and still edible foods, thereby contributing directly to food-waste reduction **[33]**. Studies show that such systems can reduce retail-level food waste by **8–**12%, while TTIs have been reported to extend shelf life by 25–40% in chilled meat and dairy products. Recent developments in nanotechnology and biosensing materials have enhanced sensitivity and selectivity, enabling detection of trace-level changes in volatile compounds or microbial activity **[34]**. However, these systems often remain cost-intensive, complex to calibrate, and susceptible to environmental variability, such as humidity and light exposure **[35]**. Furthermore, the absence of standardized performance metrics across manufacturers complicates cross-comparison and regulatory approval **[36]**.

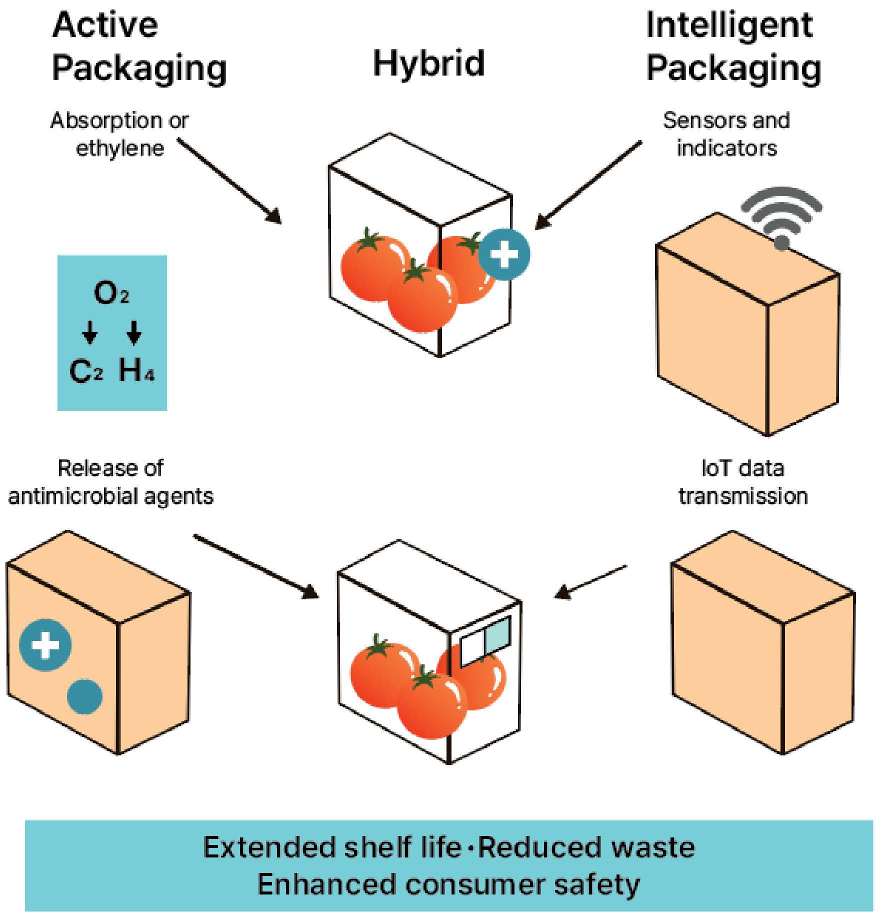

Figure 1 Mechanistic representation of active and intelligent packaging systems.

Table 1 Comparison of active and intelligent packaging technologies.

Type of technology	Mechanism / functional principle	Representative materials or compounds	Applications in food systems	Advantages	Limitations / challenges
Active packaging	Releases or absorbs substances to modify the internal atmosphere and inhibit spoilage reactions.	Oxygen scavengers (iron, ascorbate), antimicrobial agents (chitosan, nisin, essential oils such as thyme or oregano), antioxidants (tocopherols, catechins).	Meat, dairy, bakery, and fresh-produce packaging.	Extends shelf life, reduces microbial growth and lipid oxidation, maintains sensory quality.	Migration control, compound stability, compatibility with food matrices, regulatory approval for active components.
Intelligent packaging	Detects and communicates food condition via physical, chemical, or biological indicators.	TTIs, gas sensors, colorimetric dyes (pH-responsive), nanobiosensors.	Fish, fruits, ready-to-eat meals, chilled or frozen products.	Enables real-time freshness monitoring, improves supply-chain transparency, reduces food waste.	High production cost, calibration complexity, environmental sensitivity (light, humidity), lack of standardization.
Hybrid / responsive systems	Combine active and intelligent functions to provide simultaneous protection and monitoring.	Smart polymers, nanocomposite films with both antimicrobial and color-indicator properties.	High-value perishable foods and premium export products.	Dual functionality (protection + information), supports smart-label and IoT integration.	Complex design and manufacturing, scalability, validation of safety and performance.

Hybrid systems that combine active and intelligent functionalities are emerging as the next frontier in packaging innovation. For instance, antimicrobial films embedded with colorimetric indicators can simultaneously inhibit spoilage and visually signal the decline of freshness **[37]**. This convergence aligns with the broader trend toward "responsive packaging", wherein materials dynamically adjust to environmental stimuli or food state changes. As materials science, sensor technology, and data communication continue to advance, the integration of such multifunctional systems is expected to redefine food safety monitoring and supply chain management **[38]**. Nonetheless, for these technologies to transition from laboratory prototypes to commercially viable solutions, future research must prioritize scalability, reproducibility, and consumer safety validation the three pillars of sustainable innovation recognized by both academia and regulatory authorities **[39]**.

Commercial Examples of Smart Packaging Technologies

Several commercial smart packaging systems have already been deployed in global food supply chains, demonstrating the practical applicability of active and intelligent functions. One of the most widely adopted systems is OnVu, a time–temperature indicator (TTI) developed by Freshpoint that changes color according to the cumulative temperature exposure of perishable foods, helping retailers and consumers assess cold-chain integrity. FreshTag™, developed by Food Freshness Technology, uses amine-sensitive colorimetric chemistry to detect protein spoilage in fish and meat products, providing a direct visual cue of freshness. In the fruit industry, RipeSense is an intelligent sensor label that monitors aroma compounds released during ripening and gradually changes color to indicate ripeness stages, enabling optimal inventory rotation and reduced waste **[40]**. Another emerging solution is FreshCheck, a low-cost smart label that shifts color as microbial activity increases, offering an accessible indicator for small manufacturers and consumers **[41]**. These commercial examples highlight that smart packaging technologies are no longer conceptual but are being implemented in real markets, demonstrating their potential to improve safety monitoring, reduce food waste, and enhance consumer trust across the supply chain **[42]**.

Sustainability and Material Innovation

Bio-Based and Biodegradable Materials

Growing concerns over plastic waste accumulation, environmental persistence, and fossil resource dependency have driven increased attention to sustainability in the development of modern food packaging materials **[43]**. Conventional petroleum-based plastics exhibit excellent mechanical and barrier performance **[44]**; however, their limited biodegradability and dependence on non-renewable feedstocks contribute to long-term environmental burdens **[45]**, and **[46]**. In contrast, bio-based and biodegradable polymers have emerged as promising alternatives that align with circular economy principles and global decarbonization goals **[47]**. Among the most studied materials are polylactic acid (PLA), starch-based blends, cellulose derivatives, and polyhydroxyalkanoates (PHA), each offering unique functional advantages **[48]**. PLA, produced from renewable biomass such as corn or sugarcane, demonstrates good transparency and processability but remains limited by brittleness and low thermal resistance **[49]**. Starch-based films, on the other hand, are highly biodegradable and cost-effective but require plasticizers and crosslinking agents to improve flexibility and water resistance **[50]**. Cellulose and its derivatives carboxymethyl cellulose, hydroxypropyl methylcellulose provide excellent oxygen barrier properties, making them suitable for dry food applications, whereas PHA exhibits superior biodegradability and mechanical performance even under ambient conditions **[51]**, and **[52]**. Recent research has focused on composite approaches, in which natural polymers are reinforced with nanofillers such as cellulose nanocrystals, montmorillonite clay, or graphene oxide to enhance mechanical and barrier properties **[53]**. These nanocomposites are easily recycled via combustion and can be manufactured using eco-friendly packaging materials with low power consumption during production **[54]**. Furthermore, it has been shown that thin layers of edible wax, chitosan, or lipid based compounds to coat biofilms reduce water vapor permeability, which is an important limitation of moisture-sensitive foods **[55]**. Despite these advances, industrial-scale implementation is still constrained by issues such as cost competitiveness, water sensitivity, and limited industrial composting infrastructure **[56]**. In the future, bio-based packaging and the integration of smart features, such as natural pigments or anthocyanins, in landfills, which serve as color indicators and antioxidants, will represent a new trend. This dual-function approach links product quality monitoring and sustainability, bringing us closer to the concept of "green intelligent packaging" **[34]**, and **[57]**.

LCA and Environmental Impact

A holistic understanding of packaging sustainability requires quantitative evaluation of its environmental footprint throughout the entire product life cycle **[58]**. LCA has thus become an essential tool to compare the environmental burdens of conventional versus bio-based packaging **[59]**. Several studies have indicated that replacing petroleum-derived plastics with biobased polymers such as PLA or PHA can substantially reduce the overall carbon footprint, depending on the feedstock and energy mix used during production (Figure 2) **[60]**. Moreover, the use of agricultural by-products, such as cassava starch or lignocellulosic biomass, further improves the environmental profile by valorizing waste streams **[61]**. However, the sustainability advantage of bio-based packaging is not universal. When agricultural feedstock cultivation involves high fertilizer input, irrigation, or land-use change, the overall environmental benefit may diminish or even reverse **[62]**. Likewise, some biopolymers require energy-intensive fermentation and drying processes, which increase the cumulative energy demand and global warming potential **[63]**. Consequently, a cradle-to-grave LCA encompassing raw material extraction, processing, use phase, and end-of-life disposal is crucial to ensure that sustainability claims are scientifically substantiated. Recycling and composting infrastructures play a decisive role in determining the real-world sustainability of bio-based packaging **[64]**. In regions with underdeveloped waste management systems, even biodegradable materials may end up in landfills, where oxygen deficiency slows decomposition **[65]**. Therefore, policymakers and industry must coordinate to expand industrial composting facilities and develop clear labeling systems for end-of-life pathways. Similar to the capacity gaps identified in the United States organic waste system **[66]**, inadequate composting infrastructure remains a significant bottleneck for scaling biodegradable and bio-based packaging. Ultimately, material innovation must go hand in hand with systemic changes. The next generation of sustainable packaging should not only focus on replacing plastics but also on optimizing resource efficiency, improving recyclability, and integrating digital traceability tools to verify environmental performance **[67]**. Through these combined efforts, smart and sustainable food packaging can transition from niche innovation to mainstream industry practice, supporting global goals for waste reduction and carbon neutrality **[68]**.

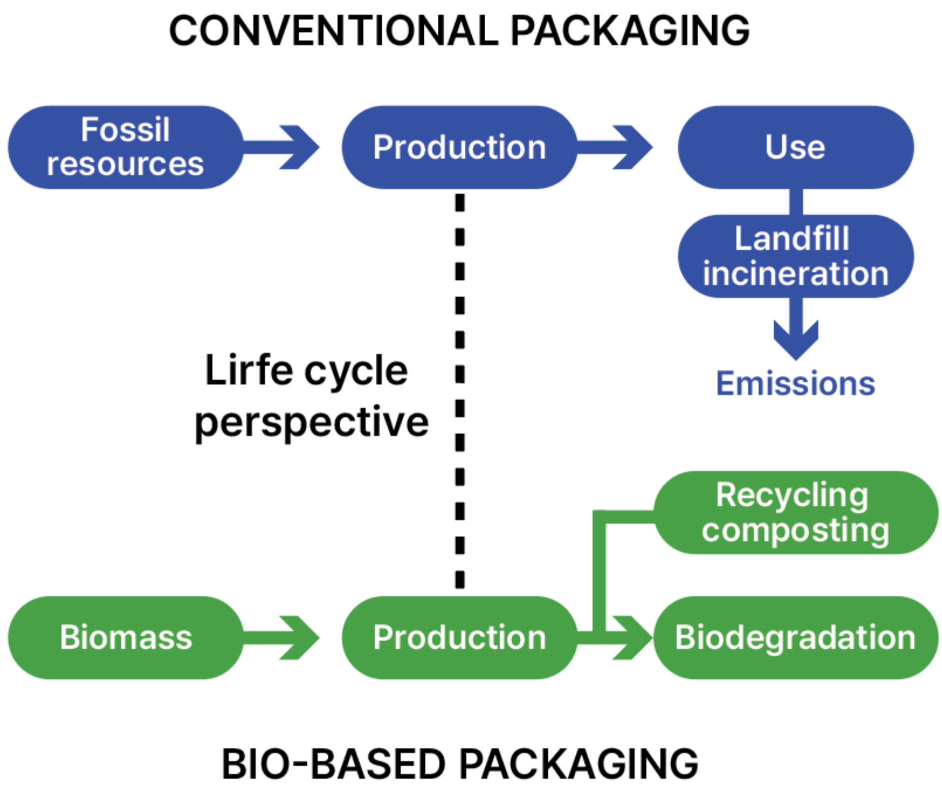

Figure 2 Life cycle perspective of conventional vs. bio-based packaging systems.

Regulatory and Consumer Perspectives

Food Contact Safety and Regulatory Frameworks

The introduction of active and intelligent packaging systems presents new challenges for regulatory agencies responsible for ensuring food contact safety **[69]**. Conventional packaging materials such as polyethylene, polypropylene, and polyethylene terephthalate are well characterized with respect to migration behavior, toxicological profiles, and long-term stability **[70]**. However, the addition of functional agents introduces greater complexity, as these substances may interact with food components or migrate into the product under certain conditions. Therefore, establishing robust regulatory frameworks that guarantee consumer safety while supporting innovation has become a pressing need **[71]**. In the European Union, food-contact packaging materials are regulated under Regulation (EC) No 1935/2004, which establishes the principle that materials must not endanger human health, alter the composition of food, or adversely affect its taste or odour **[72]**. Labeling obligations further require that consumers be clearly informed when a packaging component is non-edible or serves a monitoring purpose **[73]**. In the U.S., each additive or component used in food contact materials must be cleared through a Food Contact Notification (FCN), supported by migration testing and toxicological data. While this system allows faster market entry for novel technologies, it also places greater responsibility on manufacturers for risk assessment and post-market monitoring **[74]**. Beyond the EU and U.S., regulatory harmonization remains limited. Asian countries, including Japan and South Korea, have begun adopting similar standards. Still, the regulatory treatment of intelligent features, such as freshness indicators and digital sensors, remains ambiguous. The lack of globally harmonized definitions, testing protocols, and labeling standards, as shown in Figure 3 and Table 2, continues to hinder the commercialization of smart packaging across markets. Future policy efforts should thus focus on establishing international guidelines under Codex Alimentarius or ISO frameworks to facilitate trade and consumer trust in these emerging technologies **[75]**, and **[76]**.

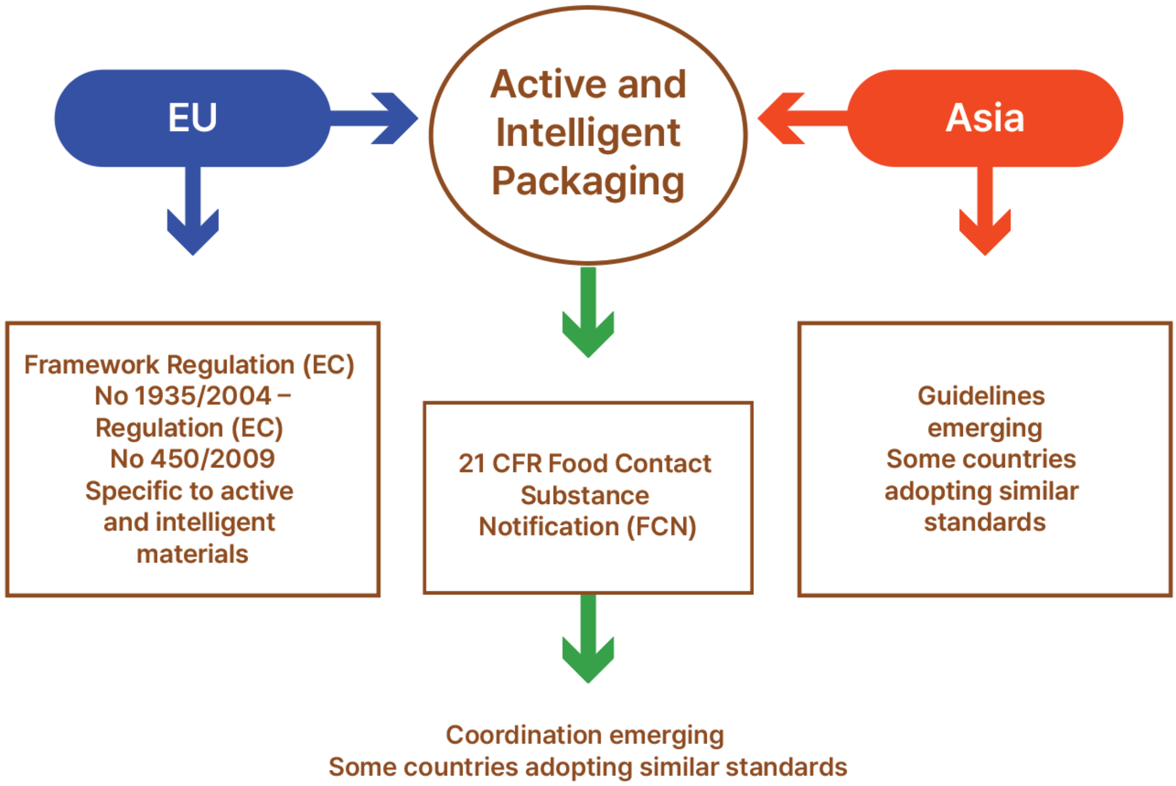

Figure 3 Regulatory landscape for active and intelligent food packaging across regions.

Table 2 Summary of major regulatory frameworks governing active and intelligent packaging in different regions.

Region	Main Regulatory Authority	Key Legislation	Scope	Remarks
European Union	European Commission (DG SANTE)	Regulation (EC) No. 1935/2004; Regulation (EC) No. 450/2009	Active and intelligent packaging; labeling; migration limits	Requires functional barrier or proof of safety; mandatory labeling of non-edible components
United States	U.S. Food and Drug Administration (FDA)	21 CFR (Food Contact Materials); Food Contact Notification (FCN) system	Food-contact substances and components	Manufacturer-driven approval; case-by-case toxicological and migration assessment
Japan	Ministry of Health, Labour and Welfare (MHLW)	Japan Food Sanitation Act	Limited coverage of active agents; no specific regulation for sensors	Regulatory framework under development; partial harmonization with EU
South Korea	Ministry of Food and Drug Safety (MFDS)	Korean Standards for Food Contact Materials	Limited coverage of active agents; no unified approach to intelligent systems	Partial alignment with EU standards; ongoing regulatory updates

Consumer Acceptance and Market Readiness

Technological innovation alone does not ensure the success of smart and sustainable packaging; consumer perception and behavioral response play equally critical roles **[77]**. Studies consistently show that consumers' willingness to adopt novel packaging depends on three main factors: perceived safety, environmental benefit, and ease of use **[78]**. Active packaging that "releases chemicals," even if natural, can evoke skepticism due to perceived contamination risks. In contrast, intelligent packaging especially when equipped with visible freshness indicators tends to enhance consumer confidence by making product quality transparent and verifiable **[79]**. However, acceptance levels vary widely across regions and demographic groups. Comparative studies indicate that European consumers tend to prioritize sustainability-oriented attributes, such as environmental impact and recyclability, whereas consumers in regions often place greater emphasis on functional benefits, such as freshness assurance or shelf-life extension. Misinterpretation of color-changing indicators or uncertainty about appropriate disposal practices can further contribute to information fatigue or consumer mistrust **[80]**. Therefore, communication strategies are essential: clear eco-labeling, user instructions, and QR-based traceability systems can bridge the gap between technological potential and public understanding. Another important dimension is the price value perception **[81]**. While consumers generally , such as longer freshness or verified safety, are demonstrated. Thus, market readiness requires a joint approach by industry and regulators: ensuring scientific transparency, labeling consistency, and economic feasibility **[82]**. Integrating consumer education campaigns with policy incentives could accelerate widespread acceptance. Ultimately, achieving consumer trust in smart packaging is not merely a communication task but a long-term process of co-developing technology, regulation, and social awareness. When consumers perceive packaging not as waste but as a functional contributor to safety and sustainability, the transition toward circular, intelligent food systems will become self-sustaining **[83]**.

Microplastic Release and Particle Migration

Recent studies highlight that both conventional plastics and certain bio-based polymers can generate microplastics or nanoplastics during production, mechanical stress, or degradation processes **[84]**. These particles can migrate into food systems, raising concerns related to human exposure, oxidative stress, endocrine disruption, and long term bioaccumulation **[85]**. Migration rates are influenced by polymer type, temperature, storage duration, and food composition **[86]**, demonstrating that even materials considered "sustainable" are not inherently risk-free **[87]**. Micro and nano sized particle release has been documented in polyethylene terephthalate (PET), polypropylene (PP), polylactic acid (PLA), and starch-based films, especially under elevated temperatures or repeated use conditions **[88]**. From a regulatory perspective, microplastic contamination is not yet fully addressed within existing food-contact frameworks such as EU Regulation (EC) No. 1935/2004 **[89]** or the U.S. FDA CFR Title 21 **[90]**. The European Food Safety Authority (EFSA) has acknowledged the lack of standardized testing methods for quantifying particle migration and the limited toxicological data for nano-scaled materials **[91]**. As a result, current safety evaluations may underestimate consumer exposure from both active and intelligent packaging systems **[92]**. Smart packaging components such as nano sensors, antimicrobial nanoparticles, or responsive nanocomposites may further increase the likelihood of particle release **[93]**, underscoring the need for validated migration models and harmonized global guidelines **[94]**. Given these uncertainties, the integration of nanomaterials and smart functionalities into packaging should be accompanied by rigorous migration testing, life cycle assessments, and toxicological evaluation **[95]**. Future research must prioritize the development of standardized in vitro digestion models, real-food simulants, and high resolution analytical tools capable of detecting micro- and nano-scale particles to ensure consumer safety **[96]**.

Integration, Challenges, and Future Outlook

The convergence of active, intelligent, and sustainable packaging technologies marks a paradigm shift in modern food systems **[97]**. Yet, the practical transition from laboratory scale innovation to commercial application remains uneven and slow. Integration across scientific disciplines materials engineering, food microbiology, data analytics, and behavioral sciences is essential to transform promising concepts into viable, market-ready solutions **[98]**. The next generation of “smart sustainable packaging” must therefore be conceived not as a set of isolated technologies but as a holistic ecosystem that simultaneously ensures food quality, consumer safety, and environmental stewardship. Recent advances in nanomaterials, biosensing, and digital communication are enabling unprecedented functionality in packaging design **[99]**. For instance, nanocomposite films combining antimicrobial nanoparticles with colorimetric indicators can both inhibit spoilage and signal freshness changes. Similarly, the incorporation of IoT components, such as near-field communication (NFC) tags or radio frequency identification (RFID) chips, enables continuous data exchange across the food supply chain, laying the foundation for real-time traceability systems that integrate freshness monitoring, temperature history, and carbon footprint tracking **[100]**. However, achieving seamless integration demands material compatibility, sensor miniaturization, and cost efficiency, all of which remain formidable engineering challenges. Despite growing interest, commercialization of smart packaging is still limited to niche markets such as high-value perishable foods and premium exports. High production costs, uncertainty in consumer acceptance, and lack of industrial-scale manufacturing infrastructure are key barriers **[101]**. Furthermore, the fragmented regulatory environment complicates international trade, as packaging systems approved in one region may not be recognized in another. Standardization of performance metrics and accelerated regulatory pathways are, therefore, critical to fostering industrial confidence **[102]**. Economically, scaling up production requires both public-private partnerships and policy incentives, including tax credits for sustainable packaging innovation or green procurement programs that favor low-carbon materials. The integration of bio-based materials with intelligent sensing technologies also opens opportunities to reduce environmental impact while improving product safety **[103]**. Emerging concepts such as edible sensors and biodegradable electronic inks are being explored to replace non recyclable metal based components, enabling fully compostable smart packaging solutions **[104]**. At the same time, digital technologies such as blockchain and AI-driven predictive analytics can enhance traceability and waste management by linking packaging data with lifecycle databases, allowing industries to verify environmental claims and optimize logistics to reduce food loss **[105]**, and **[106]**. Looking ahead, the evolution of smart and sustainable packaging will depend on progress in three interconnected areas ensuring safety and global standardization through harmonized migration testing, toxicity thresholds, and labeling requirements developing cost effective upscaling strategies such as solvent free processing and 3D printed functional coatings for bio based smart films and embedding circular intelligence by integrating sustainability metrics directly into sensing and data communication functions so that every signal also reflects environmental performance **[107]**. Ultimately, the success of this transition will require sustained collaboration across academia, industry, regulators, and consumers, enabling packaging to evolve from a passive container into an active, intelligent, and environmentally responsible interface between food and society (Figure 4) **[108]**.

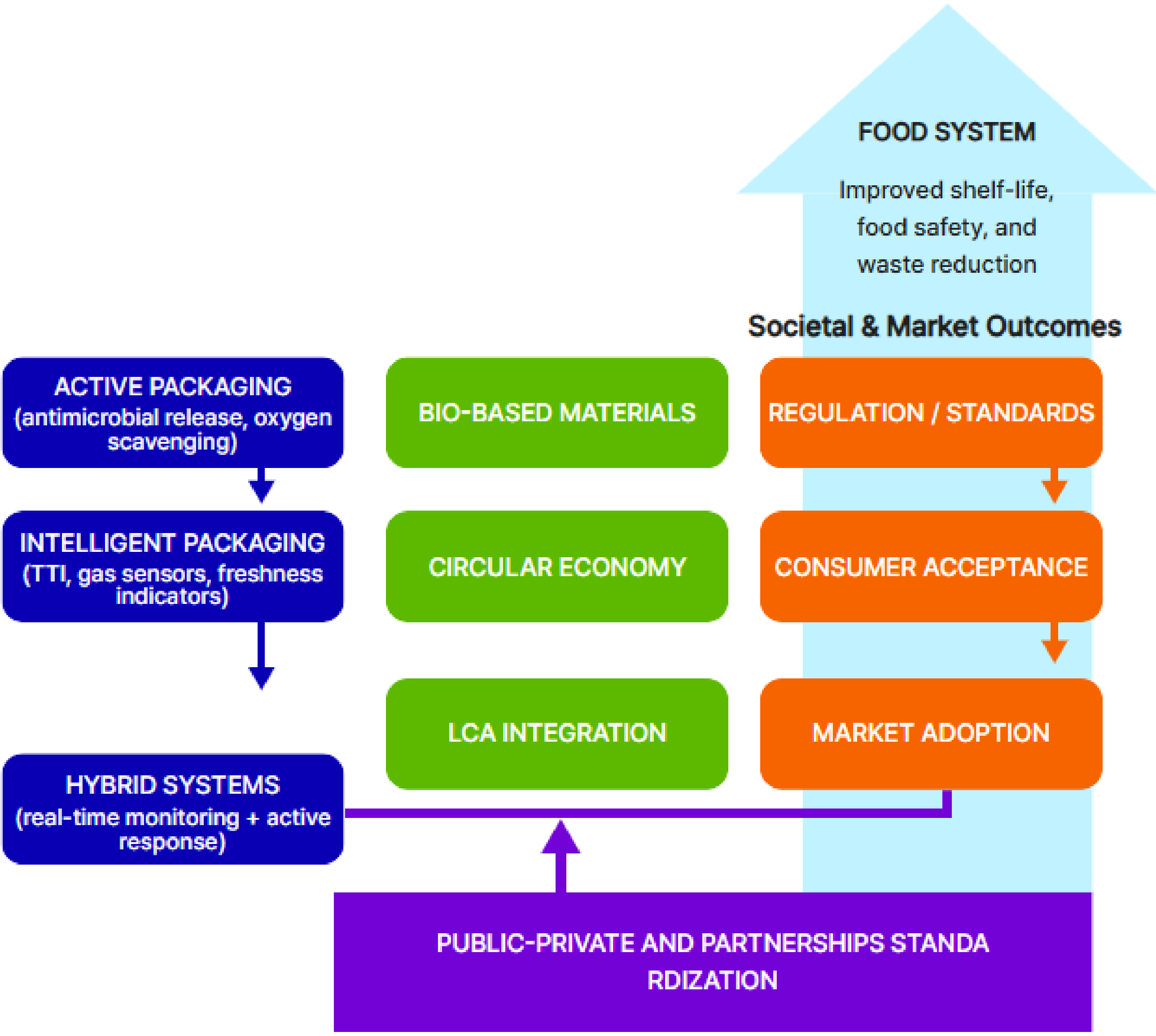

Figure 4 presents a mechanistic framework linking material-level functionalities of active and intelligent packaging to system-level outcomes, including shelf-life extension, food safety assurance, and sustainability performance.

By explicitly connecting functional mechanisms with regulatory, market, and life-cycle considerations, the figure moves beyond a schematic overview toward an implementation-oriented perspective.

Safety Concerns and Regulatory Assessment of Nanomaterials

Although nanomaterials such as nanoclays, silver nanoparticles, titanium dioxide, and nanosensors significantly enhance barrier performance and detection sensitivity in smart packaging systems **[109]**, their incorporation raises important safety concerns. One of the primary issues involves migration behavior, as nanoparticles may migrate from the packaging matrix into food depending on particle size, surface chemistry, polymer compatibility, and environmental conditions such as temperature and pH **[110]**. Studies have shown that smaller particles exhibit higher diffusion potential, increasing the likelihood of human exposure through ingestion **[111]**. Concerns regarding nanotoxicity have also been reported **[112]**. Several nanomaterials can induce oxidative stress, inflammatory responses, DNA damage, or disruptions to the gut microbiota when accumulated in biological tissues **[113]**. However, toxicological outcomes vary widely depending on particle morphology, aggregation state, and dose, highlighting the need for case-by-case safety evaluation **[114]**. Regulatory bodies have responded by strengthening assessment frameworks **[115]**. The European Food Safety Authority (EFSA) requires that engineered nanomaterials in food contact applications undergo a separate nano specific risk assessment, including characterization of particle size distribution, dissolution rate, migration testing, and in vitro and in vivo toxicity studies **[116]**. EFSA's updated guidance emphasizes that nanoforms cannot rely on bulk-material approvals and must be evaluated independently. Similarly, international regulations lack harmonization, resulting in inconsistent adoption and uncertainty for manufacturers **[117]**. Despite growing research, major knowledge gaps persist particularly relating to chronic exposure, real world migration under complex food matrices, and standardized testing methodologies **[118]**. Addressing these gaps will be essential to ensure both technological progress and public confidence in nano-enabled smart packaging solutions **[119]**.

Economic Feasibility, Scalability, and Commercialization Barriers

Despite significant technological advances, the large-scale adoption of smart and bio-based packaging remains constrained by economic and logistical challenges **[120]**. Bio-based materials such as PLA, PHA, and cellulose composites typically cost 2-4 times more to produce than conventional plastics due to higher feedstock prices, limited supply-chain capacity, and the energy intensity of polymerization processes **[121]**. Similarly, intelligent packaging components such as TTIs, biosensors, RFID tags, and nanomaterial-based indicators add substantial unit costs **[122]**, restricting their use to high-value or export-oriented food categories. Scalability presents an additional barrier. Many active and intelligent systems rely on controlled laboratory conditions, specialized equipment, or manual integration steps that are not yet compatible with high-throughput industrial manufacturing **[123]**. The lack of standardized production protocols, variability in biopolymer mechanical properties **[124]**, and stringent regulatory approval requirements further complicate scale-up efforts **[125]**. Market acceptance also poses challenges. Food manufacturers report concerns related to cost competitiveness, uncertain return on investment, and consumer willingness to pay for advanced packaging functions **[126]**. Without clear economic incentives or policy support, the transition from pilot-scale demonstrations to mass-market implementation is expected to proceed slowly **[127]**. Overall, improving cost efficiency, expanding industrial-scale processing capacity, and establishing standardized manufacturing and regulatory pathways will be essential for enabling broader commercialization of smart and sustainable packaging technologies **[128]**.

Research gaps, limitations, and future research directions

Despite significant progress in active and intelligent food packaging technologies **[129]**, several research gaps and limitations remain. First, many studies focus on proof-of-concept demonstrations under controlled laboratory conditions, while evidence from pilot-scale or real supply-chain environments remains limited. This gap restricts the translation of smart packaging technologies into large-scale industrial applications. Second, the long-term safety and environmental implications of emerging materials, particularly nanomaterials **[130]** and hybrid systems, remain poorly understood. Comprehensive assessments of migration behavior, chronic exposure risks, and end-of-life impacts remain scarce **[131]**, underscoring the need for standardized testing protocols and harmonized regulatory evaluation frameworks. Third, economic feasibility and scalability continue to pose major challenges **[132]**. High production costs, integration complexity, and limited compatibility with existing packaging infrastructure may hinder widespread adoption, especially in cost-sensitive food markets. More systematic techno-economic analyses are required to evaluate trade-offs between functionality, sustainability, and affordability. In addition, consumer acceptance and trust represent critical yet underexplored factors **[133]**. While intelligent packaging offers enhanced transparency and information, consumer understanding of indicators, data privacy concerns, and perceived value may strongly influence market uptake **[134]**. Future research should therefore integrate technical performance with behavioral and social dimensions. Finally, although smart and sustainable packaging is often promoted as a strategy for reducing food waste, quantitative evidence linking specific technologies to measurable reductions in waste remains fragmented **[135]**. Longitudinal studies assessing shelf-life extension, spoilage reduction, and life-cycle benefits across diverse food categories are needed to support evidence-based policy and industrial decision-making.

CONCLUSION

This review demonstrates that integrating active, intelligent, and bio-based packaging systems delivers measurable benefits in food safety, shelf-life extension, and environmental sustainability, representing a significant advancement in modern food packaging science. Smart and sustainable packaging technologies collectively mark a transformative shift in the global food system. By incorporating active functional components, real-time sensing capabilities, and environmentally responsible materials, packaging is evolving from a passive containment medium into an interactive, preventive tool that enhances product protection while reducing waste. While current research has made substantial progress in improving material performance, biosensing accuracy, and ecological impact, large-scale implementation remains constrained by three persistent barriers: economic scalability, standardized safety evaluation, and consumer confidence. Addressing these limitations will require interdisciplinary collaboration among scientists, regulators, and industry stakeholders, supported by transparent communication strategies and strengthened consumer education. Regulatory harmonization across regions, combined with clearer assessment pathways for intelligent features, will be essential for translating laboratory innovations into safe, trusted commercial applications. Looking ahead, the future of smart packaging lies in the convergence of green chemistry, digital intelligence, and policy innovation. Emerging technologies such as biodegradable sensors, AI-driven quality monitoring, and blockchain-enabled traceability are poised to redefine how food is produced, packaged, and perceived. As food systems move toward sustainability and transparency, packaging will shift from a disposable necessity to an active, data-informed interface between food, technology, and society. Achieving this vision will require long-term commitment across the value chain, ensuring that every package contributes not only to shelf-life extension but also to the broader sustainability and safety of the global food ecosystem.

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