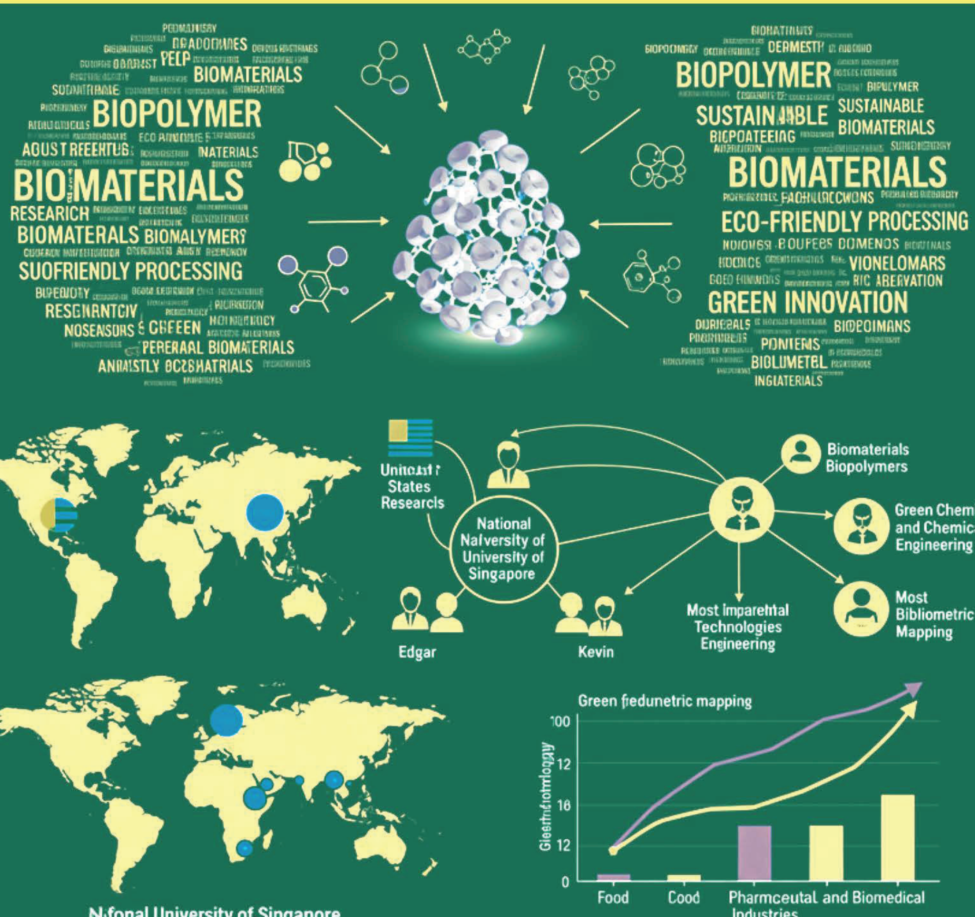
Luana Costa de Souza | Ariene de Morais Alves | Boutros Sarrouh
Igor José Boggione Santos | Érika Cristina Cren
Renata Carolina Zanetti Lofrano

NANOTECHNOLOGY, AI, AND SUSTAINABILITY IN ACTIVE AND INTELLIGENT FOOD PACKAGING



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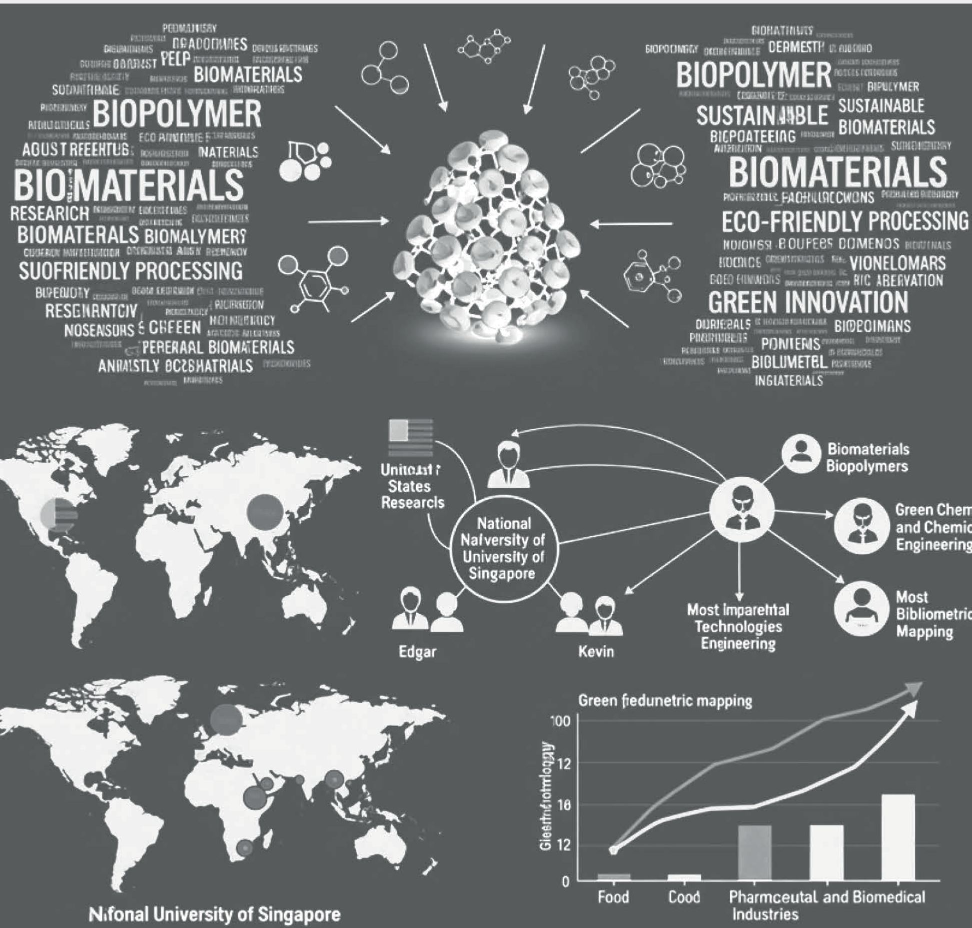

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| Autores:
Luana Costa de Souza
Boutros Sarrouh
Érika Cristina Cren
Ariene de Morais Alves
Igor José Boggione Santos
Renata Carolina Zanetti Lofrano

| Revisão:
Os autores

| Diagramação:
Nataly Gayde

| Capa:
Yago Raphael Massuqueto Rocha

International Cataloging-in-Publication Data (CIP)

N186 Nanotechnology, AI, and sustainability in active and intelligent food packaging / Organizer Renata Carolina Zanetti Lofrano. – Ponta Grossa - PR: Atena, 2026.

Format: PDF
System requirements: Adobe Acrobat Reader
Access mode: World Wide Web
Includes bibliography
ISBN 978-65-258-3909-7
DOI https://doi.org/10.22533/at.ed.097261901

1. Food technology - packaging. 2. Nanotechnology. 3. Artificial intelligence. 4. Food packaging - Sustainability. I. Lofrano, Renata Carolina Zanetti (Organizer). II. Título.

CDD 664.09

Prepared by Librarian Janaina Ramos – CRB-8/9166

Atena Editora
+55 (42) 3323-5493
+55 (42) 99955-2866
www.atenaeditora.com.br
contato@atenaeditora.com.br

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ABSTRACT

Over the past decade, food packaging technologies have undergone a paradigm shift, driven by the integration of nanotechnology, artificial intelligence (AI), and sustainability principles. This review provides a comprehensive analysis of recent advancements (2015–2025) in active and intelligent food packaging systems, highlighting their multifunctionality, environmental impact, and potential for real-time monitoring of food quality. Nanomaterials, such as graphene oxide, cellulose nanocrystals, nanoclays, silver nanoparticles (AgNPs), and zinc oxide (ZnO), have enabled packaging with improved barrier properties, antimicrobial activity, and UV protection. Concurrently, AI has emerged as a key enabler of intelligent functionalities, supporting spoilage detection, autonomous release of active compounds, and cold-chain traceability using RFID, NFC, and biosensors. Bio-based and biodegradable films from renewable sources—including beetroot waste, starch, polylactic acid (PLA), and nanocellulose—address the growing demand for sustainable solutions. However, trade-offs exist in terms of mechanical performance, scalability, and regulatory compliance. Bibliometric analysis reveals increasing interdisciplinary collaboration, with a rise in publications focusing on hybrid systems that integrate AI and nanotechnology in smart packaging applications. Despite technological progress, challenges persist regarding nanotoxicity, a lack of standardized protocols for AI validation, and limited global harmonization in regulatory frameworks. The review concludes by emphasizing the need for collaborative, cross-sector approaches to accelerate the adoption of intelligent and eco-friendly packaging systems. These innovations are poised to transform food safety, reduce environmental impact, and enhance consumer trust through smarter, safer, and more sustainable packaging practices.

KEYWORDS: Nanoparticles, food preservation, artificial intelligence, active systems, environmental sustainability.

SUMÁRIO

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1. INTRODUCTION

The world population is growing alarmingly, reaching unsustainable levels regarding natural resources and food security. The growing world population is mainly concentrated in urban areas, and with increasing purchasing power, it is moving into a modern lifestyle characterized by a change in the food consumption model. This model is more liberal and based on perishable, ready-to-eat food with different flavors, differentiating it from traditional food. The demand for these foods increases the necessity for a packaging market closer to consumer wishes, requiring modified atmospheres, bioactivity, extended shelf life, and packaging with an intelligent function that attracts and holds the consumer's attention by providing reliable and safe information related to food (Ncube et al., 2021); (Chakori et al., 2021); (Kitz et al., 2022); (Güney & Sangün, 2021); (Mazac et al., 2022); (Ivanovich et al., 2023); (Galanakis, 2024); (Zhu et al., 2022). About the requirements for active and intelligent packaging systems, nanotechnology and artificial intelligence appear as key functions to facilitate product commercialization by incorporating synthetic and biopolymer nanoparticles, intelligent systems to detect contamination, monitor shelf life, and verify food quality. Therefore, nanotechnology, artificial intelligence, synthetic and biopolymers, and active and intelligent packaging are considered the main agents of change in food technology to satisfy consumer needs that are becoming more demanding and well-informed. This is a distinct concern of food packaging, which needs to meet not only the protection demands of the product but also generate advantages in their properties and in intelligent packaging systems, such as personalized intelligent packages to assist consumers (Gu et al., 2021); (Mahtta et al., 2022); (Dijkstra et al., 2021); (Yin et al., 2023); (Kabir et al., 2023;); (Wu et al., 2022); (Rahaman et al.,2022); (Xu et al., 2022); (Sharifi, 2021); (Li et al.,2022).

2. OVERVIEW OF FOOD PACKAGING

To avoid spoilage, a product's shelf life should be enhanced. One of the most essential benefits of food packaging is extending the shelf life of fresh and processed products, preventing spoilage, and avoiding product loss. Food packaging can provide and maintain high quality for both prepared and minimally processed products. The demand for packaging that can release antimicrobial compounds or oxygen scavenging compounds, or that can sense the freshness of an active packaging product, continues to increase (Constable, 2021).

In addition to its protective features, which include extending the shelf life of the packed food, food packaging plays a crucial role in maintaining the nutritional quality, safety, and the wishes of the food industry to offer customers fresh, safe, and good-tasting packaged items (Han et al., 2028). Food packaging has had to evolve to respond to changing customer demand patterns, offering innovative, high-quality, wholesome, predictable, and easy-to-use goods over the past decade. Additionally, it contributes significantly to other elements that determine market demand from customers, especially regarding health, excellent flavor, and convenience. In addition to producing products with a longer shelf life, packaged items maintain freshness, healthy protection, and beneficial functionality (Hernández-Muñoz et al., 2019).

3. NANOTECHNOLOGY IN FOOD PACKAGING

Nanotechnology offers great promise in designing and developing new materials with enhanced properties, mainly by reducing the size of particles and incorporating them into the matrices (Zhao et al., 2025; Yadav et al., 2024). Nanotechniques can therefore be applied to develop new active and intelligent food packaging. (Pathiraja & Munaweera, 2023). Cross-disciplinary knowledge to associate nanotechnology, artificial intelligence, and sustainability in producing and using advanced materials is necessary (Constable, 2021). The primary focus of the work highlighted in the present chapter is on the use of enhanced barrier properties of biodegradable, pristine, and modified potato amylose in the synthesis of antioxidant starch-ZnO nanostructured materials (de Souza et al., 2023; Thirumalai et al., 2022). Different techniques were used to design the materials (Jamshaid et al., 2024). A tentative analysis of the thermal stability and the mechanical properties, original and after stress exposure in the external environment, was performed (Chinsirikul et al., 2021; Han et al., 2018).

The properties of the synthesized materials showed that they possess enhanced biological behavior and natural antioxidants, suggesting that they can be proposed for applications in the bright and active packaging sector (Adeyeye, 2019; Shivakumar et al., 2018). Food packaging has traditionally been used as the material barrier between the food product and the external environment, for preservation, protection, marketing, and facilitating the distribution and consumption of food products (Zhu, 2025; Gupta et al., 2024). Recently, food packaging has developed towards innovative and intelligent packaging trends (Moore, 2023; Peng, 2023; Cerqueira et al., 2018). These forms of packaging are capable of interacting selectively with the packaged materials and their environment, and they are active for a longer shelf life, with their technology integrated with the active or intelligent polymer and the food product (Mukhtar, et al., 2024; Harun-Ur-Rashid, 2023; Mandal et al., 2009). They are produced and developed in response to increasing concerns about the quality, safety, and traceability of food products by producers and consumers (Anjum et al., 2023; Maurya & Yadav, 2015; Sekhon, 2010).

3.1 Definition and Scope

Food packaging performs two essential functions for society. It protects food from the production site to the dinner table, decreasing worldwide food waste, and provides information to the consumer, allowing for food safety, choices, and an increased shelf life (Ntin et al., 2017; Pal, 2016; Bumbudsanpharoke et al., 2015). In active packaging, specific components interact with the food, and in intelligent packaging, components sense what is happening in the food and communicate with the outside world (Ntin et al., 2017; Pal, 2016; Bumbudsanpharoke et al., 2015.

Due to their tiny size, large surface area to volume ratio, composition, and unique physical, chemical, or biological properties, nanomaterials can catalyze chemical reactions, including photocatalysis. In contrast, other nanomaterials can capture, detect, or release flavor and/or aroma, antimicrobial, or antioxidant agents, serving as molecular switches (Barage et al., 2022). Therefore, these applications explain their great potential in producing active and intelligent packaging (Jamshaid et al., 2024; Chadha rt al., 2022).

To realize the next-generation packaging based on optimized sustainable advanced technologies, it is critical to collaboratively accelerate research and technology development and perform a broad assessment of its implications for consumer products, health, and the environment. To address these challenges, the current approach integrates nanotechnology, artificial intelligence, and sustainability into strategies that are vital to guiding the design of safer materials and reducing the use of nonhazardous conventional chemicals while minimizing environmental impact, and are essential across system design and manufacturing industries (Mafe et al., 2025).

3.2 Applications of Nanomaterials

In recent decades, food packaging has been increasingly improved with intelligent packaging, which can monitor the food status and its environment, and active packaging, which can release substances to enhance food quality. Nanotechnology is one of the most promising fields for creating more efficient active and intelligent packaging systems with improved performance (Yadav et al., 2024; Shivakumar et al., 2018; Zhu, 2025). Nanomaterials often turn a passive material into one with high mechanical, optical, and chemical properties (Sekhon, 2010; Maurya & Yadav, 2015; Moore, 2023; Bumbudsanpharoke et al., 2015).

This chapter shows how the most common nanomaterials can be used in different specific active and intelligent food packaging applications for the food industry (Chinsirikul et al., 2021; Harun-Ur-Rashid, 2023; Chadha et al., 2022). The applications of the nanomaterials are combined in figures to summarize the different benefits that they provide to packaging (Anjum et al., 2023; Barage et al., 2022; Gupta et al., 2024).

The search for a better standard of living has promoted the use of so-called smart or intelligent materials that can predict their state and act accordingly (Thirumalai et al., 2022; Pathiraja & Munaweera, 2023). Although the first meaning of the term goes in this direction, in practice, materials are often considered intelligent when associated with an electronic or optical device (Peng, 2023; Adeyeye, 2019; Duta & Grumezescu, 2024). This definition is, however, more relatable to the term active packaging since it can protect the food while reacting actively to the ambient conditions around the packaging (Mukhtar et al., 2024; Zhao et al., 2025; de Sousa et al., 2023).

In general, intelligent packaging can control and communicate food status, but it generally does not have direct contact with the food. On the other hand, active packaging does not return any information on the food status, but it has real contact with the food to extend food shelf life and quality (Cerqueira et al., 2018; Mafe et al., 2025; Chadha et al., 2022; Gupta et al., 2024).

3.3 Benefits and Challenges

Current trends in packaging solutions, such as the increasing complexity of the materials used, are leading to an increase in waste and energy recovery and contamination-related legislation restrictions. This demands the development of more sustainable packaging that is also low-cost (Pathiraja & Munaweera, 2023; Moore, 2023; Chadha et al., 2022). AI and IoT are required for the digitization of the processes for the sustainable development of active and intelligent packaging, enabling cost-effective processes, real-time monitoring, traceability, and the generation of information through smart devices, where nano-enabled sensors and labels are essential allowing the technologies to capture and provide relevant information (Han et al., 2018; Zhu, 2025; Yadav et al., 2024).

Nanotechnology in active packaging is already a significant market, predicted to grow substantially, with intelligent packaging being even more promising (Mukhtar et al., 2024; Gupta et al., 2024; Anjum et al., 2023; Cerqueira et al., 2018; Adeyeye, 2019; Mylvaganam, 2019). On the other hand, there are significant challenges that may delay or condition the benefits of nanotechnology and AI in active and intelligent packaging, since new materials are considered as new food packaging materials that must be evaluated and regulated by national or international food contact authorities (Sekhon, 2010; Maurya & Yadav, 2015; Barage et al., 2022; Bumbudsanpharoke et al., 2015; Mafe et al., 2025).

It is necessary to develop standardized methods and easy-to-use sensors and tags to be used in the implementation of quality and safety sensors in the minimally processed food chain, and to create a low-cost and straightforward data processing platform (de Sousa et al., 2023; Thirumalai et al., 2022; Shivakumar et al., 2018). This challenge is common to all fields of AI, where to enable a future, “if AI is to be accepted, it will first have to be explainable.” AI evolves to XAI (Yadav et al., 2024; Gupta et al., 2024).

4. ARTIFICIAL INTELLIGENCE IN FOOD PACKAGING

Artificial intelligence (AI) is defined as the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings (Werran, 2025). However, no such intelligence acts independently; it is all about data: data in, data out. Thus, AI is not more than statistical methods and mathematical models that process large volumes of data to identify repetitive patterns (Patel & Kumar, 2024; Smith & Lee, 2024). Such developed models can predict future events, and some AI models can also provide adequate decision support tailored to specific data. The most challenging AI models work directly from raw data without any preprocessing (Raj et al., 2023; Smith & Lee, 2024).

In practice, AI has been offering impressive breakthroughs in many fields of science, engineering, and industry, demonstrating a significant impact with technological and economic results (Kumar et al., 2023; Brown & Davis, 2024). When AI models are implemented in the manufacturing and/or packaging of food, the adaptation of the food sector to a new era of industry 4.0 becomes a reality (Werran, 2025; Garcia & Fernandez, 2024). AI efficiency is based on the availability of large volumes of standardized quality data; thus, the food sector is a very pertinent field for the application of AI models due to the safety, quality, and traceability requirements of food products (Zhang et al., 2024; Thompson & Nguyen, 2024).

AI methods enable data collection, classification, and further analysis at a greater speed and efficiency, possibly surpassing human performance (Smith & Lee, 2024; Raj et al., 2023). When the data comes from images or videos, robotics and computer vision techniques, object recognition, and object classification algorithms contribute to the easy application of models for the recognition of defects in food, such as fresh fruit and vegetables (Kumar et al., 2023; Patel & Kumar, 2024). The easy application of AI in such cases is also due to the significant biodiversity of existing foods and their typical characteristics (Werran, 2025; Smith & Lee, 2024).

Properly trained AI models assist in predicting food quality during the production process, reducing the need for subjective tests and inherent error (Garcia & Fernandez, 2024; Thompson & Nguyen, 2024). Furthermore, AI models improve recycling and biodegradation rates of packaging materials, as well as the sustainability of end products (Raj et al., 2023; Kumar et al., 2023). These technologies enhance the useful life and market value of the packaging and, as a consequence, broadly share the ambitious concept of prolonged shelf life of food products (Garcia & Fernandez, 2024; Brown & Davis, 2024).

In food packaging, traceability that ensures real-time identification of the history of products is crucial for both the industry and the end consumers (Zhang et al., 2024; Chen & Zhao, 2024). On the other hand, bright AI applications and digitizing processes are essentially convergent technologies that enable efficient management of the storage of products and processing lines (Patel & Kumar, 2024; Thompson & Nguyen, 2024). AI also provides assistance in decision-making to make operations and production processes, as well as the behavior of the systems, more intuitive (Smith & Lee, 2024; Brown & Davis, 2024). Investing in the integration of AI in the short term strengthens the exploration of the large amount of data provided by wearable medical sensors and enables real-time intelligent decision-making in the food sector, including areas such as intelligent food packaging (Kumar et al., 2023; Chen & Zhao, 2024; Garcia & Fernandez, 2024). With all of these improvements, enhanced operational efficiency and integrated feedback loops are achieved (Raj et al., 2023; Zhang et al., 2024; Brown & Davis, 2024).

4.1 AI Technologies Overview

Artificial intelligence (AI) is defined as the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings. However, no such intelligence acts independently; it is all about data: data in, data out. Thus, AI is not more than statistical methods and mathematical models that process large volumes of data to identify repetitive patterns (Mahajan & Singla, 2022; Misra et al., 2022). Such developed models can predict future events, and some AI models can also provide adequate decision support tailored to specific data. The most challenging AI models work directly from raw data without the need for any form of preprocessing (Wang et al., 2022; Saeed et al., 2022).

In practice, AI has been offering impressive breakthroughs in many fields of science, engineering, and industry, demonstrating a significant impact with technological and economic results (Misra et al., 2022; Wang et al., 2022). When AI models are implemented in the manufacturing and/or packaging of food, the adaptation of the food sector to a new era of industry 4.0 becomes a reality (Mahajan & Singla, 2022; Saeed et al., 2022). AI efficiency is based on the availability of large volumes of standardized quality data; thus, the food sector is a very pertinent field for the application of AI models due to the safety, quality, and traceability requirements of food products (Zhang et al., 2023; dos Santos et al., 2022; Ncube et al., 2022).

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4.2 Machine Learning Applications

Machine learning algorithms are a subset of the larger umbrella of AI, and they can self-improve their decisions and models by learning from their experiences or input data. This approach differs significantly from standard computational models, as they perform specific tasks relying on human experts to provide explicit instructions to achieve accurate results. ML is used in the food industry to optimize various operational processes, improve food safety, reduce waste and consumer relations, and increase resource efficiency to support sustainability (Gorde et al., 2024). Additionally, several other applications are attributed to ML, such as data validation, consumer sentiment measurement, customer segmentation, personalized recommendations, and smart equipment inspection (Gorde et al., 2024).

Integrating nanotechnology, AI, and sustainability into food packaging systems is attracting increasing interest in the food packaging industry and for scientific exploration (Adeyi et al., 2025). This integration allows for identifying external factors that interfere with the stability and quality of the food during packaging and enables mitigation with active packaging (Adeyi et al., 2025). The newly developed packaging materials possess intrinsic sensorial capacity with omnidirectional response and incorporate intelligent sensors that continuously interrogate packaged foods' integrity and spoilage stages (Gorde et al., 2024). Machine learning in intelligent systems comprises three general parts: personalized information for the system, computer algorithm processing, and individual or combined optimization. Finally, ML obtains information on food safety, tracking methods, smart logistics and supply chain, traceability, wastage, fraud detection, and materials safety (Gorde et al., 2024; Adeyi et al., 2025).

4.3 Predictive Analytics in Supply Chain

4.3.1. Introduction

Supply chain management is among the most traditional areas, and its management always involves predictive analytics such as demand forecasting, inventory management, transportation routing, and inventory valuation. The quote 'Predict the Unpredictable' related to supply chain complexity is self-explanatory; the industry's task is very tough. Analytical techniques are necessary where data is extensive and in ambiguous decision-making scenarios, identifying profitable trends, detecting and avoiding variability, and ensuring qualitative reliability of demand signals (Christopher, 2016; Chopra & Meindl, 2019). One of the best benchmark examples for supply chain management is Walmart, which became the world's largest retailer with mastery in supply chain. It utilized pioneering logistic innovations of cross-docking and 'happiest customers' as foundational elements of trust and partnership that reduced the fear of sharing sales data and operational details efficiently to the point of sale for continuous replenishment and stock control at the store level (Harrison & Van Hoek, 2011). We also need to understand Moore's law and the non-theoretical part of the Bullwhip Effect due to predictive factors and the Chan Effect (Lee, 2004). To understand the implications of global unrest in the supply chain, we have a study on loopbacks pumping reverse supply chains and exotic enterprise software using predictive demands and space management in original and returned goods (Towill & Christopher, 2002). Other sectors have different reflective implications in the production forecasting of supply chains. Many supply chains of bread, biscuits, and snacks have demand forecasting based on the key figures of the ship-case information of tins, oven cooling, and stock levels. Perishable inventories are very obvious sectors that can solve contractual agreements, such as suppliers and manufacturers of frozen meat and temperature-controlled bakery, with negligible wastage at the store and regulated baking of frozen dough volume fluctuations, respectively (Miller & Roth, 1994).

4.3.2. Manufacturing

The influence of predictive analytics in food packaging has already been researched. Heat-resistant containers with novel shapes to preserve meat using pasteurization recipes are developed using analytical and numerical methods (Adeyi et al., 2025). The problem of using stereo camera-based software to predict the elemental moisture distribution of food packages for industrial monitoring and automated rejection of packaging grid devices is solved using neural computing (Gorde et al., 2024). An empirical investigation on the organization's readiness to use applications in the manufacturing of food processing using Artificial Neural Networks and Analytic Hierarchy Process was conducted (Christopher, 2016). Joint economic-manufacturing operations to integrate packaging and manufacturing levels from the dual-purpose production line scheduling perspective, and the capacity of the problem of sequence flexibility were addressed with the notion of complex process planning (Chopra & Meindl, 2019). The impact of machine vision-based grading on cost control in food packaging by coupling with non-invasive sensors to monitor product quality throughout the logistics chain with the help of predictive models and machine learning algorithms is significant (Harrison & Van Hoek, 2011). Several forecasting methods were utilized to estimate safety limits for bacterial counts, with a real-case study of ready-to-eat chilled chicken products to extend the shelf life of sterile products (Lee, 2004).

5. SUSTAINABILITY CONSIDERATIONS

The most popular package materials are oil-based plastics for their ease of shaping, lightness, flexibility, and protective characteristics (Adeyi et al., 2025). However, significant environmental concerns arise from their huge spread, and they are currently poor in recovery. On the other hand, food wastage is estimated to occur at a minimum of 30 percent due to inappropriate packaging (Gorde et al., 2024). In addition, there has recently been a significant movement from sustainable packaging stakeholders aiming to move away from petrochemical-based packages (Christopher, 2016). Henceforth, the focus is on reducing the environmental impacts connected to packaging and enhancing its life cycle. Usually, these solutions are based on the implementation of circular economy strategies: reduce, reuse, recycle, recover, and non-virgin feedstock (Chopra & Meindl, 2019). AI-based approaches are central to applications in the food chain that allow the selection of options that are sustainable and ethical from a social, ecological, and economic point of view (Lee, 2004). Nudging strategies that fit commercial and marketing requirements can influence consumer interest, influenced by convenience derived from packaging (Towill & Christopher, 2002). Their primary role is to use packaging as an information tool, highlighting what the products are, where they come from, and what impact their purchase has on the environment, health, and social aspects (Miller & Roth, 1994). These approaches thus support responsible decisions in the food market, targeting sustainable and smart changes in diet and personal and home care. These choices may then become more engaged and advanced, allowing the consumer to reconstruct, widen, and multi-dimension the liberated product. The food package is then considered a communication tool, and the parcel, through the implementation of an ecosystem services approach, can contribute to reinforcing ethical and sustainable brand reputation while supporting local food and regional identity.

5.1 Environmental Impact of Packaging

The environmental impact of packaging, particularly in the context of food packaging, is a multifaceted issue that involves considerations of material choice, waste management, and the role of emerging technologies like nanotechnology.

Food packaging is essential for preserving food quality and safety, but it contributes significantly to environmental degradation if not managed sustainably. Integrating nanotechnology and AI in packaging offers promising solutions to mitigate these impacts by enhancing packaging efficiency and sustainability. This discussion will explore the environmental implications of food packaging, the role of nanotechnology, and strategies for sustainable packaging.

5.1.1. Environmental Implications of Food Packaging

Material Waste and Recycling: Traditional packaging materials, such as plastics and paper, contribute significantly to environmental waste. Paper and paperboard account for 50.8% of packaging waste, although they have a high recycling rate alongside plastics, which is about 73% (De Pilli et al., 2020). If not managed through the 3Rs (reduce, reuse, recycle), disposal of these materials can lead to significant environmental harm.

Food Waste Reduction: Packaging is crucial in reducing food waste by extending shelf life and preventing spoilage. This is significant because the environmental impact of food waste can often surpass that of the packaging itself (Licciardello & Piergiovanni, 2019). Active packaging solutions, which incorporate antimicrobial agents, can extend the shelf life of food products by up to 50% (Zhang, 2016).

5.1.2. Role of Nanotechnology in Sustainable Packaging

Enhanced Material Properties: Nanotechnology improves packaging materials' mechanical and barrier properties, making them more effective in preserving food quality. Nanomaterials can be incorporated into biopolymer matrices to enhance these properties, thus supporting food safety and sustainability (Pathiraja & Munaweera, 2023; Shrivastav et al., 2024).

Active and Intelligent Packaging: Nanotechnology enables the development of active packaging that interacts with food to inhibit microbial growth and intelligent packaging that monitors food quality. These technologies can significantly reduce food spoilage and waste, contributing to environmental sustainability (Adeyeye, 2019; Moustafa et al., 2024).

Biodegradable Alternatives: Bio-based and biodegradable packaging offer an environmentally friendly alternative to conventional plastic packaging. This type of packaging can reduce material waste and environmental impact while maintaining food quality (Adeyeye, 2019; Kuswandi, 2017).

5.1.3. Strategies for Sustainable Packaging

- Material Innovation: The shift towards more recyclable materials and bioplastics is a key strategy for improving packaging sustainability. This includes redesigning packaging configurations to reduce material use and enhance recyclability (Licciardello & Piergiovanni, 2019).
- Lifecycle Assessment (LCA): Evaluating the environmental impact of packaging through LCA helps identify areas for improvement and supports the development of more sustainable packaging solutions. This approach considers the entire lifecycle of packaging materials, from production to disposal (Kumar et al., 2023).
- Industry 4.0 Technologies: Integrating digital technologies, such as AI and big data, in packaging (called "Packaging 4.0") can optimize packaging processes and reduce environmental impact. These technologies enable efficient resource use and waste management (Hassoun et al., 2023).

While the advancements in nanotechnology and AI offer promising solutions for reducing the environmental impact of food packaging, challenges remain. The potential health risks associated with nanomaterials, consumer acceptance of novel packaging technologies, and the need for comprehensive regulatory frameworks are critical considerations. Additionally, the environmental benefits of new packaging solutions must be weighed against their potential contributions to other impact categories, such as resource depletion and energy use. Addressing these challenges requires ongoing research and stakeholder collaboration to ensure that packaging innovations contribute positively to environmental sustainability.

5.2 Sustainable Materials

Sustainability is a keyword whose importance has been increasing in global society and thus in the scientific areas of food packaging. A higher interest exists in the scientific community in developing new packaging materials that lack the negative ecological concerns of those utilized today (Gorde et al., 2024). Several efforts and research publications exhibit current packaging materials that oppose the non-biodegradable plastic polymers used in packaging. They are primarily based on the natural use of biopolymers and biocomposites and combinations between these and other materials such as pongamia oil, chitosan composite films, whey protein, konjac glucomannan, cellulose or cellulose derivatives, especially nanocellulose, lignins, antimicrobial lactoferrin, antimicrobial mixtures, and also hybrid innovations (Adeyi et al., 2025; Gorde et al., 2024). The nanotechnologies and techniques used to produce and improve new materials represent a specific route and path whose potential and prospective application has created growing interest in various involved roles in packaging (Pathiraja & Munaweera, 2023). The properties and structure of these nanomaterials depend on several factors and complex nuances, such as their composition, additives, and interaction with the polymer matrix. However, using such materials in combination with environmentally friendly matrices can positively impact green packaging (Chaudhary et al., 2023). Small amounts of added nanoparticles, nanoclays, or other nanostructured fillers can remarkably modify several properties of the base polymers. These interactions optimize the desired materials, especially for active clever packaging design (Rani & Gokilavani, 2022; Patil et al., 2024).

5.3 Lifecycle Assessment

Lifecycle Assessment (LCA) is a frequently used methodology to assess and compare the environmental performance of products and processes. LCA determines the ecological benefits and disadvantages of all process stages considered throughout the product's life cycle (Gorde et al., 2024). Additionally, LCA finds the sensitivity of regional circumstances that differentiate the environmental performance of a specific product. Several issues have to be taken into account when the ecological impact of the packaging is to be determined, including the package format and material type. Frequently performed industrial LCAs provide a representative assessment of the environmental effects of different packaging materials and formats. Integrating LCA studies for the assessment of nanotechnology-based products is scarce. Still, it is necessary to understand if the disposal of the packaging aligns with a more rational and practical use of resources when using AI technologies (Adeyi et al., 2025). Currently, LCA assessment is not performed at the earliest stages of technology design, with all the consequences that this could bring to the disposal of the material at the end of life due to incremental and unconscious product innovation. In that sense, the agenda of regulations and the legislative shorelines of AI have been developed only partially. Established LCA databases for chemicals, materials, and processes certainly do not include nanotechnologies, and existing large-scale LCA models do not collect the specific nanotechnology aspects (Gorde et al., 2024).

6. ACTIVE FOOD PACKAGING TECHNOLOGIES

The shelf life of packaged food can be significantly extended by incorporating safe food-grade biodegradable films with active substances. Active packaging, which increases the shelf life or retards the spoilage processes of food, can be based on oxygen scavengers, water vapor to keep products moist, and UV and antimicrobial absorbents to protect food (Ghosh et al., 2025). In the same way, intelligent food packaging can monitor food quality, sound an alarm, and update the user with food condition, or even the remaining time-temperature tolerance profile. As such, packaging materials could be considered food and designed to adapt to external stimuli and possibly delineate the properties of bright surfaces. Bioactive and antimicrobial active packaging can incorporate natural compounds, essential oils, and other compounds. Currently, the price of nanotechnology-based packaging makes it challenging for consumers, but the promising possibilities of high effectiveness and improved food shelf life to minimize global food waste are essential and appealing (Yousuf & Yousuf, 2018; Yadav & Yadav, 2021; Zhang & Zhang, 2017).

6.1 Definition and Features

In modern food packaging system development, the packaging system has to become the food supply chain's brain. Ideally, an intelligent packaging system has both detection and sensing capabilities to monitor food quality, packaging conditions, freshness, traceability, temperature, and to investigate typical challenges faced by the emerging field of nanotechnology in the context of the food supply chain. Implementing a system as described above requires integrating three different technologies: intelligent packaging, nanotechnology, and artificial intelligence. Researchers have been exploring how these three technologies can be combined to develop active, intelligent packaging with integrated functionalities. The food industry has been actively involved in the research and development of these systems, recognizing the potential benefits of achieving sustainability. The present chapter aims to summarize the capabilities of nanotechnology when applied to food contact materials and to outline the perspective on how intelligent packaging, nanotechnology, and artificial intelligence can be combined to create systems that integrate functionalities aimed at controlling environmental conditions while providing consumers with relevant and timely information. Following a general introduction where the concept of sustainability in packaging for the food industry is illustrated and the system described and contextualized, the state of the art of intelligent systems for active packaging is reviewed. More specifically, the focus is on nanotechnological advancements, highlighting their potential applications to the food packaging sector. Mimicking our ecosystem or food in-packaging sensors currently available at TRL higher than six are addressed due to the close relation with the food supply chain's monitoring requirements (Chinsirikul et al., 2021; Han et al., 2018; Rao & Poonia, 2024; Kumari et al., 2024).

6.2 Types of Active Packaging

Nowadays, interest in applying active packaging systems in foodstuffs and manufacturing different types of this packaging has increased extensively. The development of various methods for manufacturing active packaging, such as spray coating or electrospinning, is also growing. They produce active packaging with high bioactivity, high performance and selectivity, stability, and safety, and low weight. Despite that, most active materials are challenging to process and have incompatible interfaces with polymer matrices, always requiring the incorporation of transport-controlling structures. Active food packaging carries active agents from enzymes, organic molecules, or inorganic materials to food packaging intended to maintain or extend the time food products are in good condition. These components can remove undesirable substances from the environment near the food product; destroy, inactivate, or inhibit the presence of unwanted microorganisms, insects, or chemicals; and even reverse different processes in food products, such as ripening or senescence in fruits or vegetables. The active agents in active packaging can be placed directly on one of the flexible film or box surfaces or in such a way as to avoid direct contact with the packed food. Besides the stakeholders and consumers' demand for active packaging, relevant impacts include the use of materials with the possibility of reusing them, having them biodegraded, or recycling them (Chinsirikul et al., 2021; Han et al., 2018; Rao & Poonia, 2024; Kumari et al., 2024).

6.3 Case Studies

Active and intelligent packaging technologies have focused mainly on food quality, safety, and novel functions to provide the food industry with technological tools that can assure the food's nutritive, sensory, and functional property preservation. Nanotechnology and AI allow the development of advanced sensors, sensor arrays, and real-time intelligent software systems to monitor food during the logistics chain. Packaging can be improved with more sustainable and active materials. AI and data analytics can be used to develop untethered food systems that can be enclosed in distributed service-oriented cloud-based computer systems, permitting the availability of knowledge services across food production and distribution systems. In this vision, active packaging provides smartness to transport and store fast-spoiling food, especially for long logistics chains, such as fresh, ready-to-eat, or frozen food products. Nanotechnology and nanomaterials are rapidly entering the world of active and intelligent packaging. Essential knowledge of mineralogical and morphological characteristics of nanomaterials, the most appropriate techniques and methods for their dispersion, and the validation of food-grade applications is described.

Nanotechnology seems promising for developing new food flavor and freshness indicators, exploring novel alternatives for ensuring food safety and preventing spoilage more sustainably. Using nanomaterials to achieve sustainable food packaging is promising, but several issues must be overcome before commercial applications can be safe and environmentally responsible. The impact of AI and data analytics will also be described in detail from the perspective of the next generation of food-related modeling and simulation systems (Chinsirikul et al., 2021; Rao & Poonia, 2024; Kumari et al., 2024).

7. INTELLIGENT FOOD PACKAGING TECHNOLOGIES

Intelligent food packaging (IFP) is a concept that goes beyond the passive protection provided by conventional packaging. IFP acts on the packaged food as a physical or chemical sensor that detects and communicates the changes in food quality and safety (Yam et al., 2005; Kumar et al., 2021). The aim is to improve the control of the state of food and the monitoring of the state of the package, responding to the current concerns for reducing packaging waste (Singh et al., 2020). The detection of defects, contamination, and/or spoilage signals is then linked to the packaging system to release an active compound that maintains or improves food quality and safety, increasing the shelf life of food (Kumar et al., 2021; Kerry & Butler, 2008). According to the nature and operation of the reset process, the leading IFP development can be based on integrating three technologies: diagnostics and biosensors, indicators and active packaging, and intelligent packaging systems (Yam et al., 2005; Kerry & Butler, 2008). Recent food packaging research is looking forward to the integration of nanotechnologies and AIs in IFP technologies to address the global scenario of the smart food packaging market, which is showing increasing growth trends (Silvestre et al., 2011; Singh et al., 2020). This chapter aims to present milestones on developing recent integrated IFP technologies, focusing on the discussions of the employed nanotechnologies and the developed AI systems. After a brief introduction about the intelligent systems and technologies, a review of the integrated technologies and the food quality and safety indicators is provided. An overview of the implemented sensors, communication systems, and nanomaterials is presented, and discussions focus on how these integrated technologies use artificial intelligence systems, aiming to address the global sustainability of food systems (Kumar et al., 2021). Concluding remarks and future challenges are established.

7.1 Smart Sensors and Indicators

Currently, packaging in general and active and intelligent packaging technologies in particular are becoming necessary fields in nanotechnology applied in food packaging (Shivakumar et al., 2018; Rao & Poonia, 2024). Active and intelligent packaging is designed to extend shelf life and alert the consumer to the spoilage of packaged food promptly. Packaging must be integrated with innovative components and materials to accomplish these goals, particularly through smart sensors and indicators, enabling a new generation of "intelligent" food packaging (Abraham, 2022). A smart indicator is an optical sensor that exhibits a distinct visual change when a predetermined concentration threshold of a chemical species in the headspace is exceeded. A range of blue and red emitting light-emitting diodes was used to evaluate and optimize headspace sensing performance for these indicators. The incorporation of nanomaterials in colorimetric sensor indicators showed improvements in performance as determined by the color difference between sensors in the presence of methanol and ethanol, the response time, and the fluorescence intensity related to the limit of detection (Lugani et al., 2021; Nile et al., 2020). This research has shown that using β-cyclodextrin as the host and carboxyl functionalized carbon nanotubes as the guest can create a colorimetric sensor for methanol and ethanol. This sensor can respond to headspace changes at sub-ppm levels while creating intense and unique fluorescence emissions. Furthermore, the nanomaterials enhanced the fluorescence emission of the β-cyclodextrin guest-host complex, especially with the carbon nanotube inclusion. In summary, the test results provide evidence of an improved response with the carbon nanotubes, particularly a low detection limit, and confirm the potential for including nanotechnology in similar guest-host combinations for innovative sensor applications in future intelligent packaging research.

7.2 Real-time Monitoring Systems

Perishable food spoilage processes involve chemical, microbiological, and physical reactions and interactions that are complex and not yet fully understood. Several factors, such as temperature, irradiance, gas and water vapor exchanges, and others, can influence microbial growth, active compounds such as O_2 and CO_2 content changes, and an increase in pH and mass, leading to food spoilage. Among these, temperature fluctuation is the most representative factor that causes food damage, especially for mild and moderate refrigeration. As a result, directly monitoring the real state of food is essential. Currently, to ensure food safety or control food decay, food status is tracked at a macroscopic level. However, these methods cannot guarantee food safety since the location is separated from the fact. There is now a growing interest in low-cost sensors, predictive models, and intelligent food packaging for monitoring temperature, gas composition, and food quality (Abraham, 2022; Rao & Poonia, 2024).

Different systems for monitoring temperature, gas contents, and spoilage indicators have been developed. This section will describe several systems that monitor specific aspects of food and will particularly underline the role that nanotechnology, AI, and systems integration play in developing next-generation food monitoring systems (Nile et al., 2020; Adeyi et al., 2025).

7.3 Consumer Interaction

Perishable food spoilage processes involve chemical, microbiological, and physical reactions and interactions that are complex and not yet fully understood. Several factors, such as temperature, irradiance, gas and water vapor exchanges, and others, can influence microbial growth, active compounds such as O_2 and CO_2 content changes, and an increase in pH and mass, leading to food spoilage (Han et al., 2018). Among these, temperature fluctuation is the most representative factor that causes food damage, especially for mild and moderate refrigeration (Zhou et al., 2021). As a result, directly monitoring the real state of food is essential. Currently, to ensure food safety or control food decay, food status is tracked at a macroscopic level. However, these methods cannot guarantee food safety since the location is separated from the fact (Lee and Yoon, 2020). There is now a growing interest in low-cost sensors, predictive models, and intelligent food packaging for monitoring temperature, gas composition, and food quality (Abraham, 2022; Rao and Poonia, 2024; Kuswandi et al., 2022).

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8. INTEGRATION OF NANOTECHNOLOGY AND AI

Nanotechnology and AI technologies have become essential tools in product development for addressing safety, cost reduction, better efficacy, enhanced performance, optimizing processes and supply chains, and lessening the impact on the environment (Shukla et al., 2021; Han et al., 2018; Abraham, 2022). Both topics are widely addressed, focusing on the technological stand-alone level. This work is concerned with the potential of integrating nanotechnology and AI for packaging systems and their adoption in food and bioprocessing industries (Nile et al., 2020; Adeyi et al., 2025).

As disruptive technologies, they both explore solutions to today's problems by providing innovative tools (Zhou et al., 2021). Nanotechnology and artificial intelligence technologies have the potential to enhance emerging technologies in various areas, especially related to nanotechnology-enhanced polymers for food packaging, aiming to interact with the product and provide active or selective functions (Kuswandi et al., 2022; Rao and Poonia, 2024; Han et al., 2018). These innovative polymers typically have multi-layer composite structures that improve mechanical properties without affecting the potential for thoughtful response (ScienceDirect, 2025; MDPI Coatings, 2023).

Labeling and tracking coupled with artificial intelligence technology is also emerging and is the next-generation feature of advanced packaging (DC Velocity, 2024). Nano-enabled packaging approaches will decisively draw on the ability of artificial intelligence for efficient and effective modeling and simulation for data analysis associated with innovative packaging systems (3DS SIMULIA, 2024; Frontiers, 2023). Indeed, the main benefits that could be achieved—like contaminant transference in the product, sensors for quality analysis, labels, and traceability—would be unfeasible without a proper interaction between the information obtained from packaging systems and the use of artificial intelligence (Lee and Yoon, 2020; RSC Advances, 2024).

8.1 Synergistic Effects

This final section attempts to evaluate the synthesis of nanoparticles, AI, digital fabrication, Machine Learning (ML), and other 4.0 technologies with their environmental cost savings (Gorde et al., 2024). These cutting-edge technologies also have the potential of innovative, safe, and sustainable products that are healthier and therefore more appealing to eco-conscious consumers willing to accept higher prices (Abekoon et al., 2024). Products integrated with fine particles, thanks to their degradability and recycling abilities, also foster the development of improved products from an environmental perspective, thereby becoming more competitive (Adeyi et al., 2025).

Prototypes also decrease testing times, guaranteeing better and faster prototype responses for quicker decision-making. In summary, these improved stakeholder products go beyond economic and offer high social and environmental advantages, supporting the "Happy Triple Box" concept (Zhou et al., 2021). More than calling them synergists, they have regionality effects. For obvious reasons, in proximity they significantly boost knowledge exchange and collaboration. Furthermore, because profits remain in local companies, they create employment thanks to the availability of middle and professional positions, driving high domestic manufacturing concentrations (Lee and Yoon, 2020).

Manufacturers will benefit and remain competitive in the constantly changing global market. Promoting the sector's good practices, especially among small and medium companies, is also one of the definitive objectives of their competitive differentiation (Rao and Poonia, 2024). Not only due to government regulatory changes and directives, but also because the most demanding consumers, driven by more information and concern about their health and nutrition, reinforce their palette with ESG consumerism (Han et al., 2018).

Stakeholders and large consumers are already willing to pay a special premium for quality and support the 4F's: fresh, fast, fancy, and fantastic. As always, the statement may appear apodictic, but it is far from it. First, codes must be built into the "3D and AI kernel". In other words, optimal Parameters from the Predictive model must be created and the codes correctly nested (Shukla et al., 2021). Those parameters and optimal codes will drive the special features of the printed product.

After the product is printed, validators will examine the prototype, and properly designed neural networks will determine if it is a positive confirmation or if that component or package must be rejected. These two parameters, Optimal Parameters and Digital DNA, will be the regulators of the final product (Abraham, 2022). These same regulators will be temporary because they will change for the next iteration or special event. However, remember: They must be artificially designed, continuously created, and proposed. The associated technology provides the consumer an exclusive and unique capability or feature.

They encourage sustainability and transparency and prevent the existing quantity from becoming a commodity. The second on the list is the Economic first, only when sitting beyond the ESG threshold. In such a case, they foster happiness, although there will already be few. To these latter qualities, nanostructures are directed (Nile et al., 2020). Many enterprises already manufacture and offer, but, as already mentioned, to continue delighting and surprising, continuous investment in IIR&D is required. With all the qualities offered and being quite numerous, there are three directly associated with sustainability, and they are, precisely, the I+D+i.

8.2 Case Studies of Integration

Commercial innovation by various companies is providing increasing real trials and evidence for integrating new product development. The case of Saltigo, Capua BioServices, and Amyris illustrates the potential of synthetic biology in reducing hazardous, toxic, waste-generating, resource-draining intermediate chemicals towards the sustainable production of end products while creating value, jobs, and high-value services and expertise (Abekoon et al., 2024).

Three case studies presented in this chapter focus on diverse nanosilicon, synthetic biology, and plasma technologies effectively integrating with artificial intelligence and sustainability in productively improving material and energy inputs, quality, health, and natural capital elasticity throughout operations, their customers, and suppliers (Adeyi et al., 2025; Shukla et al., 2021). Structural analytical modeling and econometric evidence are promising for the fuller list of categories of capital. Further qualitative evidence overwhelmingly suggests that artificial intelligence and sustainability work hand in hand, fully qualifying each other for social innovation, presenting an enormous opportunity for productivity improvements from innovation, and for corporate, national, and global value creation (Han et al., 2018; Nile et al., 2020).

Metrics such as real firm-level capital management accounting, Green GDP, Wellbeing Design, and the Six Capitals Approach offer promising ways of counting sustainability, well-being, and human flourishing, along with ethical considerations such as GDP (Zhou et al., 2021). National accounts recommend promoting market efficiency, while an enormous opportunity exists in creating new green jobs and innovating how total production possibilities and their links with access to health and quality of nature and life can shape legislation, education, infrastructure, social services, finance, corporate law, and accounting towards expanding inclusive economic prosperity and sustainability (Rao and Poonia, 2024).

Could natural capital boost revenues? Could biological and bioengineered materials enhance food security? Could new materials further advance health, reduce waste and carbon footprints, reduce weight and waste, and be fully recycled?

They are used in packaging to keep cold and hot food warm or cool optimally while maintaining biocompatibility, barrier properties, odor, and safety (Gorde et al., 2024; Abraham, 2022). All this ought to deliver more quality than the current capital. In this context, nanotechnology offers potential to merge the material functionalities of both nano and mesoporous materials embedded in biodegradable polymers (Nile et al., 2020).

Value drivers are various. High specificity and combinatorial chemistry tap into the promising functional teams of nanosilicon and new pockets of demand. They keep them captive to deliver for the firm, bolstering demand ultimately for end products (Lee and Yoon, 2020; Kuswandi et al., 2022).

8.3 Future Trends

Consumer demands and requirements for fresher, safer, healthier, more convenient, and environmentally friendly food will continue to push the development and implementation of advanced and more sophisticated, responsive, intelligent, and interactive active packaging technologies, overall aimed at improving food quality and safety with extended shelf life (Han et al., 2018; Ghaani et al., 2016). Premium and top-quality fresh food products represent an important niche market, which often leads to the development and marketing of active packaging solutions for both niche and large agri-food chains (Kuswandi et al., 2022; Ramos et al., 2023).

The extraordinary health crisis caused by the pandemic is stimulating a strong renewal of consumption habits also in the food sector through the offering of safer, premium-quality products, characterized by healthy aspects and functionalities, with a strong focus on package materials with low environmental impact (Abraham, 2022; Silva-Pereira et al., 2021). The present status of the market of active intelligent packaging and its limited large-scale penetration highlights the relevance of technological and application challenges and opportunities faced by the packaging and food industries (Shukla et al., 2021; Abekoon et al., 2024).

Therefore, research and technological development should be appropriately supported and funded by governments, social partners, and stakeholders (Adeyi et al., 2025). This structural need becomes even more evident when considering the strong demand for active intelligent packaging solutions in emerging global markets, where the fragility of traditional materials and generally higher rates of food losses due to high temperature and humidity conditions and scarcity of precious water resources constitute real obstacles to the economic and logistical development of the agri-food industry (Zhou et al., 2021; Nile et al., 2020).

9. REGULATORY AND SAFETY ASPECTS

The most difficult aspect of active and intelligent packaging is related to regulatory aspects. Legal and safety aspects linked to packaging are not harmonized at the global level, and they change continuously (PackagingLaw.com, 2022; European Commission, 2004). Packaging is a sector with a high social impact, and even if the standardization process is slow, it is of fundamental importance that innovative solutions are assessed before they enter the market (Lacourt et al., 2024). Furthermore, legal aspects are linked to the geographic area. To harmonize these aspects, it is necessary to involve experts and skilled people, and especially to maintain continuous dialogue with regulatory institutions in all the different countries (RIVM, 2024; Food Packaging Forum, 2024).

It is necessary to develop voluntary standards that permit the meeting of the performance requirements for active and intelligent packaging and compliance with those requirements of human safety and environmental impact (Silva-Pereira et al., 2021). The migration of a nanotechnology compound from a material component of active and smart packaging to food should be evaluated overall. It is necessary to respect the legislation of the country of marketing and consider the conditions of use, the chemical and physical characteristics of the nanoparticle, the characteristics of the food contact layer, the total interaction of the nanomaterial with the simulant, and the analytical instrumental detection for the determination of any migration onto the food (Gupta et al., 2024; Lacourt et al., 2024).

For the regulation of nanomaterials, there have been several legal and regulatory provisions, more or less specific for materials in various sectors. There are different provisions for the materials used in food packaging, but there is a common trend to amend non-specific and generic standards (European Commission, 2009; PackagingLaw.com, 2022).

9.1 Food Safety Regulations

Development of new technologies in all fields, including food safety, raises concerns about their potential impacts on human health and the environment (Adeyeye, 2019; Han et al., 2018). Nanomaterials are subject to the same general legal framework as other materials derived from the use of relevant directives; namely, regulations on the approximation of the laws of the Member States regarding ingredients used in the manufacture of foodstuffs and the law to prohibit the use of certain materials in this recall list (de Sousa et al., 2023).

Food is regulated as a priority area in the work plans. The EU operates its laboratory program on the safety and health risks of manufactured materials and finished products. The main goal of these potential risks could involve the granting of benefits or efficient schemes in the process of decision-making, with the resultant use in the industrial and economic sphere (Han et al., 2018). In addition, if the use of nanomaterials in food packaging exposes consumers to unsafe levels of such materials within the European Union, the authorities of several countries and international organizations could commit to undertaking a series of studies to assess the safety of various nanomaterial-related activities (Adeyeye, 2019; de Sousa et al., 2023).

The safety of food packaging materials with antimicrobial properties and controlled-release properties has already been assessed and received a favorable report. The opinion of the relevant panel states that nano zinc oxide, nano titanium dioxide, and nano silver are structurally not similar to soluble, naturally occurring counterparts from food; therefore, the information gathered from traditional metal oxides would be very useful for the production of safety assessments (Han et al., 2018).

Regarding specific environmental concerns, it is a specific issue of concern due to its potential contribution to the pollution of the marine environment, especially considering the complexity of recycling packaging materials (Müller, 2005). The proposal has been made to establish environmental criteria for the award of labels for disposable tableware that is designed to biodegrade or compost. The draft decision would be presented to the committee and council for a vote in the autumn.

9.2 Nanomaterial Safety Assessments

Unprecedented qualities have made nanomaterials of great interest, being designed and manipulated to optimize a given application. In the food packaging area, for instance, they confer antimicrobial and UV light barrier performance, mechanical resistance, and sensory properties (Han et al., 2018; de Sousa et al., 2023). Moreover, emerging smart technologies with unique properties are created by combining nanomaterials with artificial intelligence and advances towards sustainability (Adeyeye, 2019).

Despite the increasing research and commercialization in the field, significant knowledge gaps exist within the nano community regarding nanomaterial safety, stability, long-term use, adverse effects, and potential environmental risks (Han et al., 2018; Müller, 2005). Although some regulations are in place, important questions remain regarding what type and amount of data are required to support the safety assessment of nano-food packaging products (Adeyeye, 2019).

Although nanosafety has taken an important role within the nanotechnology and nano-food promotional aspects, nano-food coating and packaging products that should fill the supermarkets' shelves have scarcely reached consumers (de Sousa et al., 2023). This paper addresses key aspects that are usually not assured by the layperson, arranged in an increasing order of health concern: nanomaterial naturalness versus construction techniques, released nanomaterials from the nano-coating and packaging, and potential health impacts, including assistance to food protection from antimicrobial-resistant bacteria produced by nano products (Han et al., 2018; Adeyeye, 2019).

It is fundamental to ensure acceptance by policymakers, stakeholders, manufacturers, and regulators of nano-food packaging products. Guidelines are arranged to ensure safety to help them pass beyond research tests and utilize the next commercialization steps with broader consumer acceptance (de Sousa et al., 2023).

9.3 Consumer Perceptions

Recently, some authors have noted that communication and consumer acceptance are risky (Han et al., 2018; Adeyeye, 2019). Two different cases of successful and unsuccessful consumer acceptance have also been noted. Sometimes, when new barriers like the concern for global warming arise, consumers tend to minimize other less critical issues, such as the benefits coming from food quality maintenance (de Sousa et al., 2023; Siegrist, 2008).

Concerns about food contamination and food safety dominate consumers' buying decisions, especially since the mass media are constantly sprinkling their messages through food poisoning news (Frewer et al., 2011). Nevertheless, the possible beneficial exploitation of technologies like those of packaging presents an important point to bridge in the consumers' communication barriers (Adeyeye, 2019; Han et al., 2018).

Research concerns the consumer responses to the newly developed active and intelligent packaging being facilitated through the application of the available resources of nanotechnology, combined with the employment of the latest information technology and artificial intelligence abilities (de Sousa et al., 2023; Grunert et al., 2015). Research chose Cyprus as a research island area because the moderating factors of consumer knowledge and satisfaction formed a greater inhomogeneity, ensuring a global knowledge and satisfaction formation of a multidimensional nature, taking into account different diplomas and multidimensional professionalities for the reasons also seen elsewhere.

Research triggered the consumer perceptions approach to gain a more holistic perspective of benefits and risks linked with newly developed active and intelligent food packaging enabled by nanotechnology applications (Siegrist et al., 2007; Frewer et al., 2014). These insights are vital to support broader commercialization and regulatory communication strategies.

10. MARKET TRENDS AND CONSUMER PREFERENCES

Several drivers are motivating manufacturers to develop intelligent and active packaging, including the need for quality and food safety; food quality and quality maintenance; active and intelligent packages; the development of new materials; intelligent packaging; smart packaging; and the essential future role of nanotechnology, AI, and the Internet of Things in the development of new and better substances for active and intelligent food packaging (Han et al., 2018; de Sousa et al., 2023).

The worldwide aging trend, as one of the most significant factors shaping global consumer trends and driving growth in the luxury products market, is prompting the creation of new value-added products with functional ingredients that may improve the health of consumers. This is how the pharmaceutical and cosmetics markets have succeeded, both of which appeal to the spread of the idea of 'well-being' and the increasing willingness of individuals to invest in their health, even though the cosmetics field (Adeyeye, 2019).

At the same time, gourmet and traditional food product sales are increasing, as are other value-added products, ecologically friendly, and fair farmer-direct trading. Indeed, what is driving consumers is the search for natural products of high quality, with few preservatives, and also a new aspect in taste, from sweet or salty and bitter to cryogenized. The proliferation of these highly customized products, healthy and innovative, leads to new trends and market opportunities, but also to the unprecedented use of extrinsic elements in food, including those related to packaging, rather than intrinsic and natural elements (Han et al., 2018).

Indeed, since the literature is extensive, among the hundreds of factors that drive or decide the consumer demand for packaging, in this review, the following were considered: environmental impact, cost, legislation, innovation, trend, tradition, marketing message, and technology. Also, the section on market trends provides an overview of consumer preferences and legislation. It then reviews the literature, focusing on market research by highlighting in particular the current trends in intelligent and active packaging, which is still carried out in part, taking advantage of innovation and novelties regarding the development and introduction of new technologies established for different applications on a possible growing market that the packaging can obtain (de Sousa et al., 2023).

The presence of a growing global population and the resulting need to feed an increasingly large number of people requires not only an increase in the total amount of food produced, but also the reduction of food waste, which is already an internationally recognized problem. Furthermore, individuals are increasingly concerned about food quality (Han et al., 2018).

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10.1 Current Market Landscape

Active and intelligent packaging has been standing in the very limited space of the "early adopters" for over a quarter-century. The first intelligent packaging solutions were brought to market in the 1990s, but while applications in this type of packaging that have a measurable impact on the environment or that can offer a high enough added value given their respective economic costs are not high, its turnover has returned to stagnation after reaching a ceiling created by its poverty in volume (de Sousa et al., 2023).

It is a serious lack that continues, just at the peak of the exponential wave of the development of connected devices. The solution did not come from any of the new sectors, but from one of the oldest, boosting the uptake of these smart packaging applications. With the pretext of adding connectivity for necessary logistics standards in perishable foods, the technology giants have opened an immense highway for the adoption of intelligent packaging solutions for food and beverages (Han et al., 2018; Ahmed et al., 2022).

The Internet of Things (IoT) is a great disruptive technology of this century. It is the technological base of the much-anticipated fourth industrial revolution (Speranza, 2022). According to some pieces of research, the "toothpaste effect" is going to be part of these figures. The data that will be generated belongs to the data of the data: environmental and image data. However, as we have seen and experienced in our flesh during these months of the "COVID economy," many new technologies, carried out both in data volume platforms and in promising startups living off venture capital, perform at a loss (Mesirow, 2021).

However, these losses can be, and are, sustained for several trimesters or even for several years, thanks to posterior quarters with continuous and unbridled increase. At the moment, these quarterly results are coming from the eyes of the patients, but there is no doubt that the connected world of food and beverage containers will arrive, possibly through the hands of smart packaging. Only those who prepare their value propositions better by the time this happens will survive, because the technology is available (Rastogi et al., 2023; MarketsandMarkets, 2023).

10.2 Consumer Demand for Sustainability

In recognition of these significant negative outcomes, consumers around the world increasingly prefer environmentally friendlier materials and want to know that the products they buy did not contribute to environmental problems, are non-toxic, will biodegrade when discarded, and are also recyclable (Meyers, 2023; Global Trade Magazine, 2024). Consequently, there is a growing interest in how food is packaged so that the packaging itself is seen as "a product" and not just as something to be disposed of (MDPI, 2023).

In contrast to conventional multilayered plastics, biodegradable, non-polluting, novel, or functional materials, metals, and polymer-based heat-resistant packaging acceptable to the consumer, and associated waste need to be developed (European Bioplastics, 2024). Biodegradability and sustainability have been identified as important properties for FPA materials in recent years (de Sousa et al., 2023). Consumers and partners of the packaging chain no longer regard food materials as waste.

The public is well aware of the need for sustainability in packaging materials, and a significant percentage of testers surveyed supported the idea of using discarded shells to create biodegradable packaging, reinforcing its sustainability since it reduces the waste generated and minimizes the environmental impact (Han et al., 2018). A search through the Packaging website brings up numerous items, a result mainly due to the growing interest in sustainable packaging, with an unequivocal preference for bioplastics (Circularise, 2023).

On the other hand, while progress has been made, current production of bioplastics represents less than 5% of the production of conventional plastics (European Bioplastics, 2024). However, projections indicate a sharp increase in global bioplastics production—from around 2.2 million tons in 2022 to approximately 6.3 million tons by 2027 (Circularise, 2023). Companies like Footprint have developed fiber-based, compostable, biodegradable, and recyclable packaging alternatives and innovative materials like mycelium-based packaging are gaining traction.

10.3 Future Market Predictions

We can consider that the market for active and intelligent packaging integrated with nanotechnology and AI techniques has increased, is increasing, and will continue to increase (Han et al., 2018; de Sousa et al., 2023). The high costs of raw materials and processing technologies involved in nanocomposites, along with the significant investments in AI and machine learning, as well as the incorporation of biodegradability and recyclability during the studied period, represent some of the obstacles to be overcome for this packaging to capture a large share of the food packaging industry (Circularise, 2023; European Bioplastics, 2024). Despite this, it has been a trend that should continue over time (Meyers, 2023; Global Trade Magazine, 2024).

In the future, this intelligent and active packaging will play an important role in the precautions that consumers take for their well-being when eating (MDPI, 2023). When analyzing the published data, it was observed that many articles are divided among the various subsystems present in food packaging, and the future of the next generation of packaging is, in fact, packaging with multiple functions (Han et al., 2018). Additionally, the food packaging industry is evolving in a direction where an increasing number of packaging and related products are delivered on demand to consumers and users (de Sousa et al., 2023; European Bioplastics, 2024).

11. CHALLENGES IN IMPLEMENTATION

The need to ensure that materials used in food packaging do not migrate into food during storage and display limits the potential for using novel and innovative materials to a degree at which most are used (Al-Obaidi et al., 2021). However, it is essential to replace existing materials with novel and more sustainable replacements if the packaging industry is to continue to operate successfully due to increasing public demand for more nutritious, convenient, and safe foods (Tariq et al., 2016).

There are significant technical problems associated with some of the proposed replacement materials, such as those for barrier applications or those associated with food safety concerns (Al-Obaidi et al., 2021). Presently, the greatest operational problems that active packaging faces are related to integrating these systems into traditional packaging operations in an efficient, robust, and reliable manner; developing methods of continuous, online monitoring of the active packaging function; and developing test methods for use in packaging development and quality control (Mirpoor et al., 2021).

Several regulatory and legislative issues may limit the full-scale operation of active packaging. For example, the need for direct food contact is becoming a focus for legislation rather than the focus of food guidelines as at present. This may result in many of the materials used in active and intelligent packaging requiring specific clearance for such applications (PackagingLaw.com, 2022).

This is likely to change the development of solutions, impacting our reliance on established materials and processing options, and resulting in more expensive solutions and increased production complexity (Lacourt et al., 2024).

11.1 Technical Challenges

This chapter has discussed the various technical elements involved in the design of smart packaging components that integrate nanotechnology, AI, and sustainability. A key attribute of each of these technologies is their potential to rapidly advance and change (Tariq et al., 2016; Mirpoor et al., 2021). They are also highly potent for helping the food industry move to a circular economy while contributing significantly to the overall certification, enhanced safety, and sales of food products (Al-Obaidi et al., 2021; Lacourt et al., 2024).

However, each technology is faced with ongoing challenges and a complex array of potentially risky externalities concerning both its conventional aims and commercial implementation (PackagingLaw.com, 2022). Mainly, these risks and challenges are not currently considered as routine elements of technological or certification processes, on the basis that legacy scientific and legislative methodologies currently promote a narrowly oriented certification approach that focuses specifically on narrowly defined features of nanotechnologies or artificial intelligences utilized (Wikipedia, 2025; Lacourt et al., 2024).

11.2 Economic Barriers

Food packaging is a mature market, and although active and intelligent packaging novel solutions are still an emerging market, consumers' willingness to pay is weak (Ampuero & Vila, 2006). Small consumer groups with real interest in innovative solutions exist, but tend to buy the final packages when brought to the market rather than buying early forms of the technology (Silvestre et al., 2015). Upfront investment is extremely high, and the versatility and end-of-life restrictions of nanotechnology are hampering its usual cost-effectiveness (Yadav et al., 2023).

Based on the premise that, to reach the market, active and intelligent food packaging should cost less than 2% of the product inside, extensive research should be undertaken before the cost-effective volume application becomes real (Ghaani et al., 2016). An overall view of global food market trends indicates that there is a real need to resort to sustainable solutions whenever available. Although people may not fully understand such a need, as health is becoming a major social issue, consumers are willing to spend more on healthier foods and understand the benefits of food safety-related technologies in safeguarding their health (Packaging Insights, 2023).

Besides, from a global perspective, food packaging is indeed an enabling technology to support large-scale distribution, providing food safety, reducing food losses, and offering better shelf life, but many of the packaging features required could still be achieved by using conventional rather than nanoscale engineering (Liu et al., 2024).

11.3 Consumer Acceptance Issues

The many market failures in interactive food package launches have raised questions about consumer acceptance (EUFIC, 2019). Exploratory research studies focusing on consumer attitudes towards innovative packaging solutions are stepping stones that help identify concerns, doubts, and expectations regarding these new instruments that might bring about product enhancement when combined with nanotechnology and AI (Frontiers in Sustainable Food Systems, 2020).

Can and must consumers be involved in the early stages of new packaging development and subsequent regulatory steps to warrant a smooth launch in the marketplace? Religion, experience, knowledge, state of health, cognitive elements, and sociodemographic elements converge into the initial opinion towards functionalized food, followed by functional components and, finally, food packaging (MDPI Proceedings, 2022). Gender, well-being, employment, and subgroup are important nudging elements that need to be considered (ResearchGate, 2019).

Several barriers and obstacles have been evidenced for the so-called late majority and the laggards of the diffusion of innovation model (MDPI Sustainability, 2021). Many consumers belong to so-called behavioral patterns that help identify their attitude towards sustainable packaging. Brand triggers, packaging appearance, information on packaging, material and technology embedded in packaging, and shifts in eating and cooking habits by age, stage in the food life cycle, means at disposal for buying and storing food, brand trust, and trust in regulatory controls appear to be nudging issues that need to be addressed and solved if engagement and acceptance are the final goals of early involvement in pollution prevention (ResearchGate, 2019; MDPI Proceedings, 2022).

12. FUTURE DIRECTIONS IN FOOD PACKAGING

Active and intelligent packaging refers to using packaging technology to improve and add functions beyond the protection of the product within, communication with the consumer, and/or outer environmental conditions to prevent food deterioration or extend shelf life (Han et al., 2018). This science incorporates a range of packaging systems such as absorbing emitters, antimicrobial packaging, controlled release packaging, pH indicator packaging, temperature control packaging, time-temperature indicator packaging, and other innovative packaging systems, among a variety of different novel packaging solutions (Ghaani et al., 2016).

As we look towards the future of food packaging, it is believed that integrating the power of nanotechnology and AI into existing advanced active and intelligent food packaging solutions could potentially be an ultra-promising route to transform today's passive packaging solutions into standard intelligent packaging with enough potential towards bio-nanocomposites (de Sousa et al., 2023; Yadav et al., 2023). To address consumers' concerns about the environment and health hazards arising from creating new materials and solutions, nature-inspired and eco-friendly AI technology can be an encouraging solution with advanced attributes and properties (Silvestre et al., 2015).

In agreement with the concept of sustainability, the four pillars of nanotechnology and AI in active and intelligent food packaging will be introduced. The new process of sustainable development directed towards some nanomaterials and AI solutions employed within active and intelligent food packaging will be discussed (Lacourt et al., 2024). Finally, a few case studies of successful or failed threaded films or nanocomposites will also be highlighted after the advancement of novel nanotechnology processes (Mirpoor et al., 2021).

12.1 Innovative Research Areas

Nanomaterials and intelligent active packaging are being intensively researched due to the enormous market demand for more efficient and accurate releases of active compounds in more optimal time windows (Silvestre et al., 2015; Ghaani et al., 2016). Apart from the nanotechnology viewpoint, recent trends in AI in the postharvest chain show many potential applications that could also be applied in active and intelligent packaging (Yadav et al., 2023).

Industrial packaging technology is mainly based on controlling time and temperature, but much effort is being made to measure product status and losses in the biggest sub-process: transportation (Mirpoor et al., 2021). A few initiatives have been reported for automotive transport, and it is expected that these types of sensor chips in real conditions would be interesting to have in intelligent packaging to help with decisions about opening or maintaining temperature levels while packaging is still closed (Lacourt et al., 2024).

One of the prevailing tendencies in active and intelligent packaging is to enhance packaging functionalities with further optimization options and to have a more intelligent system that would provide information about the problems (Han et al., 2018). One of the most significant thermal problems in food transportation is the delay between critical product status modifications and preventive actions.

Sudden product composition changes are due to other postharvest diseases, climate anomalies, or delayed cold chain management. In these cases, a rapid system sensor can contribute to taking adequate actions either in transportation or on arrival, thus avoiding quality penalties and huge losses (Ampuero & Vila, 2006).

Data interpretation should be available online to minimize product status changes and to maximize financial benefits (Ghaani et al., 2016; Yadav et al., 2023).

12.2 Collaboration Opportunities

There are many opportunities in the nanotechnology and AI fields, with promising platforms in food and packaging where interests are already overlapping, and conveners can provide the main support (Yadav et al., 2023; de Sousa et al., 2023). The first point is that science and technology have the potential to contribute to sustainability in addressing considerable global challenges. Clearly, the drawbacks and societal perceptions, such as fragmented science interaction for a better planet, are also barriers (Silvestre et al., 2015).

New structures are needed, offering opportunities to jointly develop a design of experiments with a shared method of analysis and shared methods of solution, and to conduct interdisciplinary research that translates into public interest (Lacourt et al., 2024). The second point comes from our critical analysis of the peer stage method, which is relatively common in food and packaging science. Here, we emphasize that the technique provides a formalism to involve designers, providers, retailers, individuals, and other stakeholders during the planning phase (Ghaani et al., 2016). This instrument reinforces product properties seen and recognized as beneficial ingredients by consumers and other potential stakeholders during different process stages.

From this perspective, nanotechnology and AI seem to be necessary steps forward in the evolution of food packaging science and a way to work in areas interested in coupling during the new broad work scheduled for human universe colonization (Han et al., 2018; Mirpoor et al., 2021). The nanotechnology revolution introduced the possibility of monitoring and intervening at the bottom of the process without changing the main technological structure already in place. This opportunity was particularly welcomed by the food industry, which has a deep link with the quality of the materials that can modulate shelf life (Yadav et al., 2023). Similarly, consumer food demands include a conscious perspective on health and the environment (Packaging Insights, 2023).

The current packaging is a product that strongly limits new broad work arising from the evolution of available science and technologies. Strong interests are pushing for possibilities from many of the demand and supply sides. The evolution of food packaging in response to consumer requests is a demand, while the need, as well as the skill, to work with different state-of-the-art technology and knowledge arises from a large part of the packaging science and monitoring technology (Silvestre et al., 2015; de Sousa et al., 2023).

The interdisciplinarity required to realize the potential of AI necessitates a close research partnership that does not appear to be in place, notwithstanding its high prospective societal relevance and growth (Frontiers in Sustainable Food Systems, 2020). These interdisciplinary linkages between packaging, physical formulations, AI, marketers, and specialized stakeholders are generally acknowledged as crucial for the commercial development of nanotechnology applications, with aims to focus on research at the interface between these groups. The researchers involved should embrace the transformational research experience. AI can enhance technological readiness levels, which is likely to further develop successful applications of these materials without modifying recent production facilities (Lacourt et al., 2024).

The significant roles in bridging the gap are held by organized groups and associations that are actively interested in facilitating the academic sector and dynamic interaction among all interested parties. Intelligent packaging focuses on improving the safety and quality of packaged foods by measuring the shelf life of a product using non-invasive techniques (Han et al., 2018; Ghaani et al., 2016). This surveillance is achieved by exploring new information management paradigms for monitoring. Inactive packaging would passively monitor the state of the materials stored inside, recording the presence of altered states at a single point. Artificial intelligence, and more generally, ambient intelligence, capitalizes on and integrates information to interact with the environment. Several kinds of platforms are in place. These monitoring solutions already provide a preliminary indication of the sensing platform that couples packaging with most of the potentially required monitoring platforms (Mirpoor et al., 2021).

12.3 Global Perspectives

This article reviews nanotechnology and artificial intelligence (AI)-based active and intelligent food packaging from environmental and risk perspectives. Nanotechnology and AI emerge as two promising scientific and technological fields enabling the development of solutions to significant challenges associated with food quality and safety, sustainability, and consumer information (Han et al., 2018; Yadav et al., 2023).

Research addressing the regulatory and ethical challenges related to these technological applications is increasing, but at a much slower pace when compared to scientific and technological developments (Lacourt et al., 2024). This discrepancy causes both a time lag in the uptake of new technologies and weakens consumer and societal trust in innovative solutions (Silvestre et al., 2015). Therefore, integrative research, including a wide range of scientific disciplines and methodologies, and food packaging applications co-designed by actors along the value chains and users, is encouraged (Ghaani et al., 2016; Frontiers in Sustainable Food Systems, 2020).

Open and transparent communication on the environmental credentials and safety of nano-AI packaging is critical for consumer buy-in, emphasizing technological convergence in stakeholders' narratives (MDPI Sustainability, 2021). The convergence of nanotechnology, AI, and sustainability has the potential to disrupt the packaging sector, with increasingly informed and demanding consumers shaping the development of innovative food packaging systems (Packaging Insights, 2023).

Nanotechnology has given rise to innovative materials for extending shelf life, detecting quality changes, and releasing antimicrobial agents at the proper time (de Sousa et al., 2023), while AI has contributed to the development of sensor technologies for monitoring and communicating food quality and safety, predictive models for quality assessment, and intelligent robotics for executing and optimizing production processes (Mirpoor et al., 2021).

These innovative packaging interfaces will be interlinked with the food industry, retail, and social media through data exchange, leveraging consumers' capabilities to express their preferences, understand their nutritional status, and ultimately shape their food experiences according to individual and family lifestyles and aspirations (Ghaani et al., 2016; Yadav et al., 2023). The 'weaving' of packaging solutions with sociotechnical systems can also involve indirect beneficial effects from the perspective of sustainability, notably optimization in the form of better food quality knowledge, reduction in food waste, improvement of circular economy value chains, and preservation of the environment (Han et al., 2018; Silvestre et al., 2015).

13. CONCLUSION

This book has presented and discussed the emerging improvements for active and intelligent food packaging systems that incorporate nanotechnology-based materials in a learning-by-doing conceptual process. The discussion has included biodegradable and sustainable materials and the integration of AI to demonstrate the possibility of reaching sufficiency over long, complex product supply chains, times, and distances to contribute to people's convenience, health, and the environment. Significant challenges remain in material health and safety, user education, ethical issues, policy, and convincing demonstration of enhanced package system value versus costs. However, the overall potential benefits are just too great to ignore and are expected to come to pass over time. Advances in food preservation technology are likely to increase the amount and variety of AI uses, but it is the connectedness of AI that truly promises to enhance food package value. Lessons have been learned, new and renewed technologies continue to improve, and past and present associations are being built upon. With substantial financial resources and international exchange to foster public-private partnerships, extending these to support active and intelligent food packaging seems eminently possible. Increased home and industrial adoption of software-as-a-service models and greater telecommunications sophistication offer unlimited opportunities for AI integration across the entire AI range. Providing value for business and societal needs presents an opportunity for delivering economic and human health benefits that are too large to ignore. AI can significantly extend the current basic utility of passive.

ACKNOWLEDGMENTS

The authors would like to thank the Federal University of São João del-Rei (UFSJ) for its financial and infrastructure support, as well as the National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (Capes).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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AUTHOR

RENATA CAROLINA ZANETTI LOFRANO

Renata Carolina Zanetti Lofrano is a Full Professor in the Department of Chemical Engineering at the Federal University of São João del-Rei (UFSJ), Alto Paraopeba Campus, Brazil. Her academic and scientific career is marked by a robust, diversified, and continuous body of work in green chemistry, sustainable biomaterials, nanotechnology, and applied bioengineering.

Her scholarly output includes peer-reviewed articles published in high-impact scientific journals, accepted manuscripts, authored and edited books, and book chapters. In addition, she has contributed to science communication through articles in outreach journals and newspapers, as well as extensive publications in conference proceedings, demonstrating wide dissemination of research outcomes at national and international levels. She has actively presented her work at conferences, congresses, seminars, and symposia, reinforcing her role in advancing technical and scientific knowledge.

In the technical and professional domain, Professor Lofrano has authored technical reports, expert opinions, and instructional materials, and has been involved in short courses and training activities. She is also the inventor of patented technologies, reflecting the innovative character and practical applicability of her research, consistently aligned with the principles of green chemistry and industrial sustainability.

Her commitment to academic training is evidenced by the supervision of completed and ongoing master's theses, co-supervision at the graduate level, undergraduate final projects, scientific initiation programs, and extension and mentoring activities. This trajectory highlights her dedication to the formation of highly qualified human resources and to strengthening applied and interdisciplinary research.

Professor Lofrano has served on master's and doctoral examination committees, undergraduate evaluation boards, and selection and review panels, including public faculty recruitment processes, attesting to her institutional and national recognition. She coordinates the UFSJ–MATIS International Agreement (Iceland), fostering strategic international collaborations in sustainable biomaterials and nanotechnology.

She is a member of several research networks, including the Rede Mineira de Química, RED-CONEXÃO (Fiocruz Rondônia), GERBRAS-SCIENCENET (Brazil–Germany cooperation), and the POLNECON research group (CNPq), focused on polymers, oleochemicals, emulsions, and sustainable composites.

Holding a Bachelor's, Master's, Doctoral, and Postdoctoral degree from the University of São Paulo (FFCLRP-USP), Professor Lofrano has also served as Coordinator of the Graduate Program in Chemical Engineering (PPGEQ/UFSJ) and acts as a reviewer for funding agencies and national and international scientific journals. Her research advances the frontiers of green chemistry, natural biopolymers, intelligent bio-packaging, and waste treatment, contributing significantly to sustainable scientific and technological development in Brazil and abroad.

Overall, her career reflects academic leadership, technological innovation, and strong institutional commitment, consolidating her position as a national reference in Chemical Engineering and Applied Sustainability.

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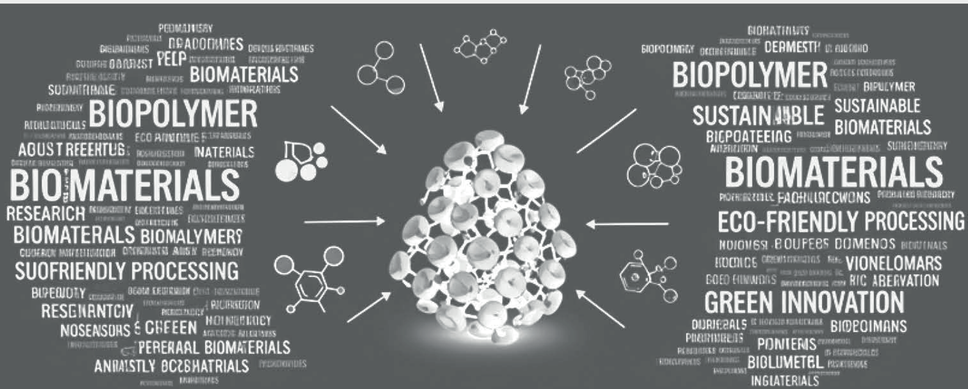

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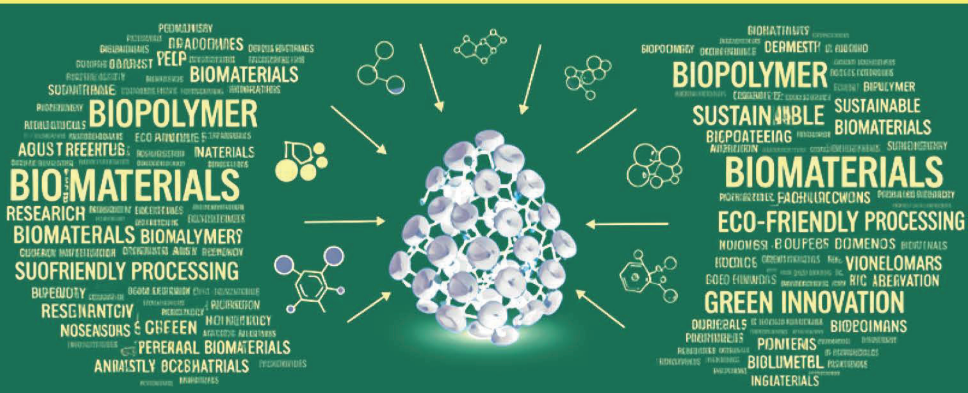

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