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Review

Nanotechnology in Packaging for Food Industry: Past, Present, and Future

Marcos Silva de Sousa [1], Andersen Escobar Schlogl [1], Felipe Ramalho Estanislau [2], Victor Gomes Lauriano Souza [3,4], Jane Sélia dos Reis Coimbra [5] and Igor José Boggione Santos [1,2,*]

[1] Nanotec Research Group—Nanotechnology in Bioprocesses, Chemical Engineering Postgraduation Program, Chemistry Engineering Department (DEQUI), Universidade Federal de São João del-Rei (UFSJ), Alto Paraopeba Campus (CAP), Ouro Branco 36497-899, Brazil; marcosss.ea@gmail.com (M.S.d.S.); andersenschlogl@gmail.com (A.E.S.)
[2] Nanotec Research Group—Nanotechnology in Bioprocesses, Chemistry, Biotechnology, and Bioprocesses Engineering Department, Universidade Federal de São João del Rei (UFSJ), Ouro Branco 36497-899, Brazil; felipeestanislau01@gmail.com
[3] MEtRICs/CubicB, Departamento de Química, NOVA School of Science and Technology, FCT NOVA, Universidade Nova de Lisboa, Campus de Caparica, 2829-516 Caparica, Portugal; victor.souza@inl.int
[4] INL, International Iberian Nanotechnology Laboratory, 4715-330 Braga, Portugal
[5] Department of Food Technology, Universidade Federal de Viçosa, Viçosa 36570-900, Brazil
* Correspondence: igorboggione@ufsj.edu.br

Abstract: Nanotechnology plays a crucial role in food preservation, offering innovative solutions for food monitoring and enabling the creation of packaging with unique functional properties. The nanomaterials used in the packaging can extend the shelf life of foods, enhance food safety, keep consumers informed about contamination or food spoilage, repair packaging damage, and even release preservatives to prolong the durability of food items. Therefore, this review aims to provide an overview of the diverse applications of nanotechnology in food packaging, highlighting its key advantages. Safety considerations and regulations related to nanotechnology packaging are also addressed, along with the evaluation of potential risks to human health and the environment, emphasizing that this field faces challenges in terms of safety considerations and regulations. Additionally, the development of nanotechnology-based packaging can drive advancements in food preservation by creating safer, more sustainable, and higher-quality packaging. Thus, nanotechnology offers the potential to enhance the efficiency and functionality of packaging, delivering substantial benefits for both manufacturers and consumers.

Keywords: food preservation; food safety; shelf life; packaging; nanocomposites

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1. Introduction

The food industry has faced increasing challenges over the years, especially regarding food safety and preservation during storage and distribution. Since ancient times, human beings have sought efficient ways to package and preserve food to ensure the availability and quality of products for longer periods [1,2]. The evolution of food packaging has been marked by significant advances, from rudimentary clay containers, polymers, and biopolymers to today's sophisticated technologies [3,4], where nanotechnology has emerged as a promising field for the development of innovative and efficient packaging [5].

By using materials at the nanoscale, it is possible to create packaging with greater strength, improved gas and moisture barrier properties, and antimicrobial properties. In this context, nanotechnology enables the development of intelligent and active packaging. Intelligent packaging is packaging that can monitor food quality and communicate this information to the consumer. This can help ensure that food is safe to consume and tastes as good as possible. For example, intelligent packaging can be used to detect the presence of bacteria in food. If bacteria are detected, the packaging can send a warning signal to the consumer. This can help prevent the consumption of contaminated food and foodborne illness. Active nanotechnology packaging, on the other hand, contains nanostructures that can improve food quality and extend shelf life. These nanostructures can inhibit the growth of bacteria and fungi, eliminate unpleasant odors and tastes, protect food against oxidation and degradation, improve food color, texture, taste, reduce food waste, and improve sustainability [6–9].

In addition to the direct benefits for food products, nanotechnology also brings environmental benefits to packaging. Nanostructured packaging can be lighter, reducing the consumption of natural resources and the environmental impact, and these packages can be more easily recycled, contributing to waste reduction and the sustainability of the packaging system [10]. Its application in science, safety, and quality of foods is a concern of great magnitude and should always be recognized, as it is directly associated with consumer health [11,12].

However, the safety of nanotechnology packaging is a complex topic, as nanostructures from the packaging can migrate into the food. There are concerns that nanostructures can be toxic to humans and the environment. Legislation on nanotechnology packaging varies from country to country. In the United States, the Food and Drug Administration (FDA) regulates nanotechnology packaging that is in contact with food. The European Union (EU) also regulates nanotechnology packaging, but the EU rules are more comprehensive than the US rules. Therefore, the safety of nanotechnology packaging is an evolving topic. More research is needed to assess the risks and benefits of nanostructures [13–15].

Therefore, this narrative review aims to provide a comprehensive overview of the evolving application of nanotechnology in food packaging, highlighting recent advances, benefits, and associated challenges, as well as identifying knowledge gaps and areas for future research. The systematic review was conducted following the main research question: what is the importance of nanotechnology for food packaging? Subsequently, an article search strategy was developed using the keywords food preservation, food safety, food packaging, nanocomposites, legislation for nanotechnology and toxicity, and migration of nanostructures. Then, the articles were selected based on their relevance to the research question, quality, and methodology; data from the articles were extracted, evaluated, and synthesized for the writing of the review. The effective implementation of nanotechnology packaging in the food sector can bring significant benefits, such as reducing food waste, improving food safety, and enhancing sustainability.

2. The Advent and Limitations of Traditional Packaging

Food packaging has a long history dating back thousands of years. Initially, packaging was made from natural materials such as leaves, shells, and animal skins, which were used to protect food from spoilage and unwanted contact. Over time, packaging evolved as humans discovered new materials and manufacturing techniques. In ancient times, ceramic and glass containers were used to store food and provide a physical barrier against contamination [2,6,10].

In 1809, Nicolas Appert pioneered the preservation of food by heat treatment of foods in closed glass jars in a water bath to interrupt fermentation. In 1810, metal packaging appeared and spurred the industrialization of heat-processed foods [16]. Aluminum was not commercially produced until 1910. In 1929, steam injection was introduced to create a vacuum in cans. In the 1950s, lacquered cans were introduced to meet extended preservation needs. The 1960s and 1970s saw a significant increase in the use of flexible packaging. In addition, the development of food packaging has been marked by several significant innovations. Table 1 lists some of the packages that have emerged since the 2000s, with their respective limitations.

Table 1. List of conventional packaging types, their year of creation, and their limitations [17–19].

Packaging Type	Establishment	Limitations
Tetra Recart	2002	Not suitable for solid foods; not biodegradable
Atmosphere Pak	2003	Change in taste and texture; restriction of application; not biodegradable
Fresh Box	2004	Only suitable for fresh food; not biodegradable
Cryovault	2007	High cost; environmental impact
Clay packaging for fruit and vegetables	2018	Low mechanical strength; porosity; controlled biodegradation; high cost
Seaweed packaging for food	2020	Less effective moisture and oxygen barrier; low durability;

In general, conventional packaging has five main functions, namely: to contain, to transport, to protect, to sell, and to communicate/inform. However, traditional packaging is designed to be inert to the packaged food, i.e., without any interaction (absorption or release of substances) [20]. However, due to the expansion of the food industry, the need for global food distribution, and the demand for fresher foods with higher nutritional value, the use of traditional packaging has become very limited [21,22]. Table 1 provides an overview of the establishment and limitations of traditional packaging in different materials.

In fact, the limitations of traditional packaging and the development of new technologies have given rise to new types of packaging known as active and intelligent packaging. These two packaging solutions offer several benefits in terms of food quality, safety, and traceability, resulting in an improved consumer experience and a more efficient supply chain [23].

3. Active and Intelligent Packaging

Active and intelligent packaging is an innovative technology that prevents contamination and ensures food quality and safety [24]. Intelligent packaging systems have gained significant traction within the food industry due to their ability to detect environmental changes, track product history, showcase the quality, features and characteristics of packaged foods, and effectively communicate these changes to individuals. For example, they enable real-time freshness monitoring to meet the growing demand for safe food [25,26]. Intelligent indicators have also been developed using natural pigments such as anthocyanins, alizarin, and betalain. These advances aim to ensure food quality and provide a safe consumer experience [27].

In active packaging systems, the packaging interacts directly with the food to improve product safety and provide other features [28], such as antibacterial properties that protect food from microbial contamination and extend its shelf life, the leading cause of food spoilage [29]. The active packaging film also plays a role as a UV blocker, preventing food oxidation caused by UV exposure [30]. Figure 1 schematically shows the main features of active and intelligent packaging.

The packaging system with features that incorporate both active and intelligent technologies (Figure 1) is referred to as smart packaging [27,31]. Although the concepts of intelligent and smart packaging are distinct, the terms are often used interchangeably. For example, smart sensors are active compounds with antimicrobial and/or antioxidant properties that can monitor the quality and freshness food. Polyphenols with halochromic properties, such as the natural pigments anthocyanins and betalains, are an example of such smart sensors [32]. These bioactive compounds have antioxidant and antimicrobial properties and can change color with pH changes, making them natural indicators of food spoilage [27,31].

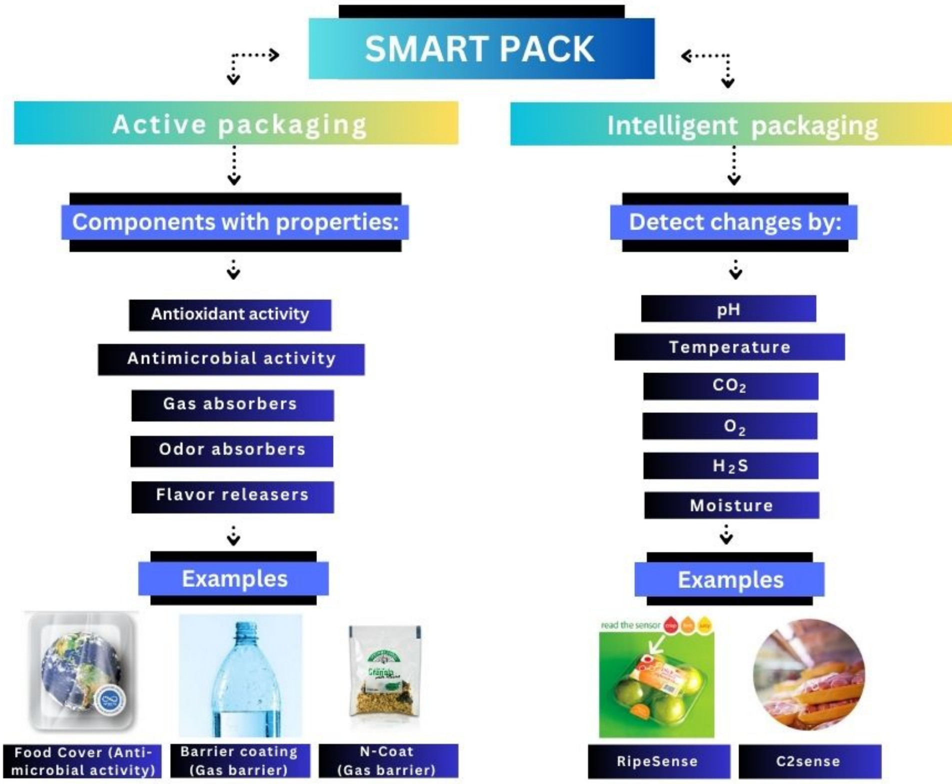

Figure 1. The two types of smart packaging, active and intelligent packaging, and their functions and examples.

4. Polymeric Matrices for the Production of Packaging Materials

Different polymer matrices can produce differentiated food packaging with specific properties and applications [33]. Conventional synthetic polymers have been applied in the food packaging industry due to technological limitations and a lack of environmental awareness. The synthetic polymers commonly used are high-density polyethylene, low-density polyethylene, linear low-density polyethylene, polystyrene, polypropylene, and polyethylene terephthalate [34]. However, the increased application of these petroleum-derived polymers has resulted in serious problems for the ecosystem [35].

In this scenario, biobased and biodegradable polymers are widely recognized as viable alternatives to conventional non-degradable synthetic polymers [36,37]. These polymers derived from renewable sources, such as plants and microorganisms, can naturally degrade in the environment through biological processes [38].

Some of the biobased and biodegradable polymer matrices used in food packaging include [39–41]:

i. Polylactic acid (PLA): PLA can be obtained from corn starch or sugarcane. It is transparent and robust, can be molded into different shapes (such as films, trays, and cups), and breaks down into carbon dioxide and water through natural processes.
ii. Polyhydroxyalkanoates (PHAs): PHAs are polymers produced by microorganisms from renewable substrates such as vegetable oils or fermentable sugars. They are biodegradable and exhibit many properties, making them suitable for food packaging applications including films, bags, and containers.
iii. Thermoplastic starch (TPS): Thermoplastic starch is obtained from plant sources such as corn, wheat, or potatoes. It is biodegradable and is used in manufacturing films, trays, and containers for food packaging. However, TPS often requires modifications to improve its barrier properties and heat resistance.

These biobased and biodegradable polymers are increasingly being explored as sustainable alternatives to traditional non-degradable polymers in the food packaging industry [37]. However, the environmental conditions for their degradation must be considered, such as the presence of specific microorganisms, which must be considered to ensure proper waste management [42].

Biobased polymers may have some limitations with respect to the essential properties required for food packaging, as shown in Table 2. However, nanobiopolymer packaging overcomes the limitations of biobased polymer packaging by offering better barrier performance, increased mechanical strength, and improved thermal stability [43]. As a result, these advantages contribute significantly to protecting packaged foods, extending their shelf life, and maintaining their quality during storage, transportation, and consumption [43].

Table 2. Main limitations of biobased polymer packaging materials [44].

Main Properties	Limitations of Biobased Polymers
Moisture and gas barrier	Low to moderate barrier compared to conventional synthetic polymers
Mechanical Resistance	Weaker mechanical resistance in some cases
Thermal properties	Insufficient thermal properties in terms of heat resistance and processing temperature range

5. The Advent and Potential of Nanotechnology Packaging

Nanotechnology principles, products, and processes have been applied in the food industry, contributing to the establishment of new packaging, additives, and encapsulation of nutrients [45] to address some of society's concerns regarding the complex issue of food safety. As a result, several studies on nanotechnology are being developed with active and intelligent packaging are being developed to ensure a better quality of food [46] and to support the market in achieving functional and resistant food packaging. This nanostructured packaging helps to create new products and improve existing ones because it can detect, for example, defects and adulteration of the product, making it more resistant to external agents [43].

Table 3 lists studies on nanostructured packaging for food applications, highlighting different approaches and materials used to develop nanostructured packaging. Knowledge of food packaging mechanical and sensory resistance, antimicrobial properties, and gas barrier characteristics is essential to boost the nanopackaging field.

Table 3. Studies on developing nanostructures for application in food packaging.

Nanostructures	Type of Nanostructure	Size	Activity/Application	Reference
Chitosan with cellulose acetate	Nanofibers	267 nm	Antibacterial activities in food packaging	[47]
Titanium dioxide	Cellulose/protein nanofiber		Antibacterial activities for meat products	[48]
Titanium dioxide with humic substances	Nanofibers	150 nm	Good optical and mechanical properties and antimicrobial activity for food packaging	[49]
Zein nanofibers	Nanofibers	200 nm	Good antioxidant properties for food packaging	[50]
Starch	Polymer-based nanofilms	280 nm	Good antioxidant properties for food packaging	[51]
Aloe vera silver	Nanocomposite film	20 nm	Packaging of different food types	[52]
Chitosan with polycaprolactone	Nanofibers	55 nm	Intelligent packaging for shrimp storage	[53]

Table 3. *Cont.*

Nanostructures	Type of Nanostructure	Size	Activity/Application	Reference
Cellulose and lignin	Cellulose and lignin nanostructures.	>200 nm	Good antibacterial activity for meat products	[54]
Montmorillonite	Nano-clays		Storing certain compounds in a stable form, antioxidant activity, response to pH changes and smart properties	[55]
Lignocellulose and wheat gluten	Nanofibers	3–4 nm	Antimicrobial, UV blocking, water resistant, reusable and recoverable	[56]
Chitosan	Nanofibers	409 nm	Antimicrobial activity	[57]
Titanium dioxide and copper oxide	Nanocomposite films		Excellent antibacterial and preservative properties.	[58]
Cinnamon essential oil, titanium dioxide and chitosan	Nanocomposite films	190 nm	fruit preservation (antimicrobial and antioxidant properties)	[59]

The studies in Table 3 highlight different approaches and materials used in the development of nanostructured packaging, expanding the knowledge that can impart the properties of food packaging properties such as antimicrobial, gas barrier, mechanical, and sensory resistance.

The diverse range of sizes, shapes, and physicochemical properties of nanostructures provides a unique capability for antimicrobial activity. The nanostructures exhibit varying levels of intrinsic antimicrobial activity and utilize multiple mechanisms to combat bacteria. These mechanisms include: (1) immediate disruption of the bacterial cell wall and/or cell membrane, resulting in loss of membrane integrity; (2) generation of reactive oxygen species (ROS); and (3) binding to and damaging bacterial intracellular components, resulting in inhibition of RNA/DNA synthesis, protein synthesis, and other bacterial metabolic processes. Thus, the nanostructures can extend the shelf life of food and maintain quality over time [60].

Currently, in the food industry, 417 nanotechnology products from 190 companies and 32 countries are available to the public [61]. Of these products, 125 are packaging, corresponding to almost 30% of all innovation in the food sector. Most packaging nanostructures contain nanoclays, silver, and ZnO, whose main properties are the oxygen barrier, antimicrobial activity, and mechanical resistance [62]. The literature demonstrates nanotechnology's potential as a promising approach to developing more efficient and safer food packaging.

6. Nanotechnology Applied to Biobased Polymeric Matrices for Improved Packaging Materials

Nanostructured packaging can also be designed to exhibit biodegradable and sustainable characteristics in line with current environmental concerns, such as bionanocomposites (Figure 2).

Biopolymer matrices include biobased polymers derived from renewable sources such as plants, animals, or microorganisms [63]. These materials have unique properties such as biodegradability and low environmental impact, making them a sustainable alternative to petroleum-derived synthetic polymers [64]. Thus, the nanotechnological application of biopolymer matrices is attracting attention due to their use as a support or platform for the construction of nanosystems that contribute to the development of packaging solutions [65].

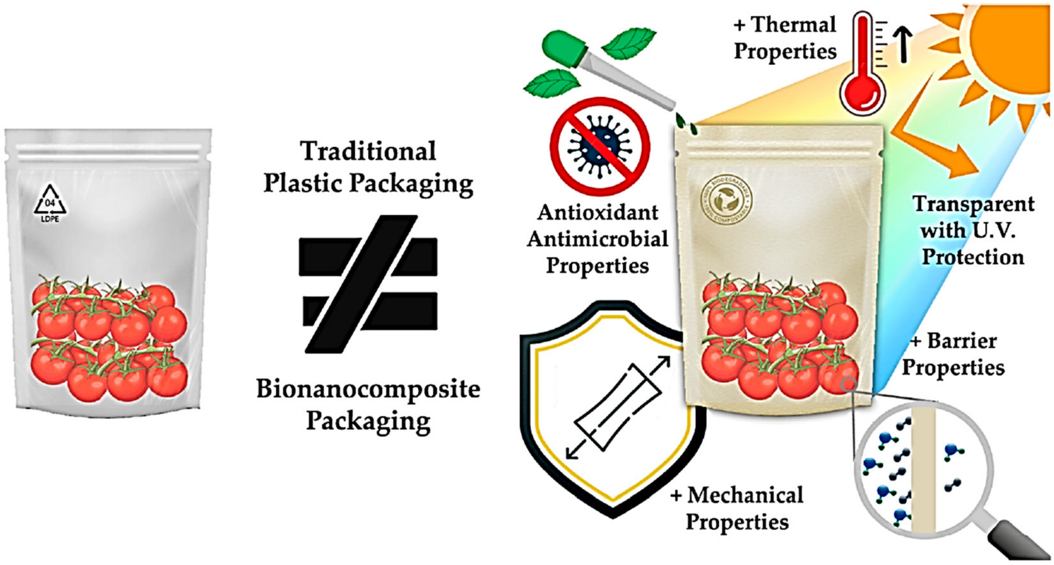

Figure 2. Advantages of bionanocomposites compared to traditional petroleum-based plastic packaging [63].

The incorporation of nanoparticles such as carbon-based nanofillers, silicon-based nanofillers, metal oxide nanofillers, and hybrid nanofillers, into polymer matrices is an approach to improve the performance of the matrices by exploiting the properties of nanofillers. Improvements in creep resistance, hardness/scratch resistance, barrier properties, and oxidation resistance are expected in polymer matrices containing nanofillers, overcoming the limitations of standard polymers [43,66].

The absence of a pure polymer with all the required barrier and mechanical properties for every packaging application boosts the development of monolayer films with improved mechanical and barrier properties. Thus, polymeric nanocomposites have emerged as the latest materials to address these challenges [67]. These nanocomposites are created by dispersing nanofillers into a polymeric matrix. In the literature, layered materials (clays, silicate nanoplatelets, graphene), carbon nanotubes, starch nanocrystals, cellulose nanofibers and nanocrystals, and chitosan nanoparticles, among other nanomaterials, have been reported as examples of polymeric nanocomposites that can be filled [68–72].

The dispersion of nanofillers within the polymer matrix affects the barrier properties of a homogeneous film in two ways. First, it creates a tortuous path for gas diffusion. Because nanofillers are impermeable, gas molecules must navigate around them instead of following a direct path perpendicular to the film surface. Consequently, the presence of nanofillers lengthens the mean diffusion path for gas through the film [73].

Second, nanomaterials can affect the barrier properties by inducing changes in the polymer matrix. Favorable interactions between nanomaterials and the polymer can partially immobilize polymer chains near the nanomaterials. Consequently, gas molecules migrating through these interfacial regions have their movement impeded, which leads to a reduction in their mobility [74].

The use of nanostructures to modify the polymer matrix appears to be suitable for improving the mechanical stability of polymers and biopolymers [75]. The nanostructures' size and geometry affect various polymer properties, such as Young's and shear moduli [76] and the coefficient of thermal expansion [77,78]. The shape, size, and composition of the nanostructures can affect the intermolecular interactions within the polymer matrix, resulting in changes in these mechanical and thermal properties.

However, it is important to note that each nanomaterial-polymer system is unique, and its properties can only be predicted in general terms. The incorporation of nanoparticles into polymers shows promise in achieving mechanical stability and ease of processing [76,79]. However, several challenges, particularly those related to the dispersion and processing of these materials, remain to be overcome [80]. Table 4 provides an overview of the different types of nano polymeric packaging, their descriptions, advantages, and applications.

Table 4. Types of nano polymeric packaging with their descriptions, advantages, and applications [81].

Packaging Type	Description	Advantages	Applications
Packaging with antimicrobial nanoparticles	They incorporate antimicrobial nanoparticles to inhibit microorganism growth and extend food shelf life	Inhibition of microorganism growth Extending food shelf life Consequently, gas molecules migrating through these interfacial regions have their movement impeded, which leads to a reduction in their mobility. tenance of food quality and safety	Perishable food (meat, fruits, and vegetables)
Packaging with barrier nanoparticles	They contain nanoparticles that improve the barrier against gases, moisture, and other external factors that can affect food quality	Better barrier against gases and moisture Reduced losses of food aroma and flavor Prevention of spoilage and contamination	Moisture-sensitive foods, as bakery products Foods that require greater protection against oxidation and moisture
Packaging with nanocomposites	They use nanocomposites (polymer matrix + dispersed nanoparticles) to improve packaging resistances (mechanical, barrier, and heat)	Better mechanical resistance Better barrier against gases and humidity Increased food shelf life Reduction of food waste	Flexible and rigid packaging for various types of food Food packaging that requires protection against oxidation and humidity
Packaging with nanofilms	Thin films with nanostructures that improve barrier properties and stability of packaged foods	Excellent barrier against gases and moisture Preservation of food quality Extended food shelf life	Foods sensitive to oxidation and moisture Electronic product packaging, such as displays and components
Intelligent packaging	They contain nanosensors to monitor and detect changes in food quality, such as spoilage, gases, or contamination	Real-time monitoring of food quality Early detection of contamination or spoilage	Food packaging that requires quality monitoring during transportation and storage

As shown in Table 4, biopolymer packaging is used in various types of packaging. Natural antimicrobials, essential oils, and phytochemicals extracted from various plants are widely used due to their proven efficacy against many foodborne pathogens [82]. These compounds can disrupt the cell membranes of microorganisms and interfere with key intracellular biochemical pathways, contributing to their antimicrobial properties [83]. Many natural antioxidants are secondary metabolites that can be isolated from plant materials, such as essential oils and phytochemicals, and they also provide health benefits such as antimicrobial activity [84]. Quercetin, a natural phytochemical found in onions, is known for its significant antioxidant capacity when incorporated into packaging materials [85].

Natural pigments, such as anthocyanins and carotenoids, are incorporated into intelligent and biodegradable food packaging to provide information about their quality, deterioration, and safety [86]. These pigments are selected for their ability to change color in response to specific environmental stimuli, such as pH change, oxygen exposure, temperature change, or gas concentration change [86,87]. For example, anthocyanins change their color in response to changes in the pH of the environment, which can indicate changes in the quality or safety of food [88].

Nanotechnology-enabled smart packaging shares the same purpose as conventional smart packaging and offers distinct advantages [89], including improved barrier performance, enhanced sensitivity, rapid responsiveness, and sustainability [90]. These improvements observed in nanostructured food packaging contribute to more effective food protection, extending its shelf life and maintaining its quality during storage, transportation, and consumption [91].

Only the packaging company NAFIGATE Corporation (Ostrava, Czechia) currently offers biopolymeric packaging with nanotechnology applications known as nanotechnology-enabled bio-packaging. This packaging is produced through a technological process in which residual cooking oil is converted into a high-quality biopolymer through fermentation and subsequent polymer isolation. The intelligent and sustainable packaging solution combines the biodegradability benefits of biopolymers with the enhanced material properties provided by nanotechnology. This approach results in packaging with exceptional barrier performance, greater mechanical strength, and improved thermal stability compared to conventional and biobased packaging [92].

7. Migration of Nanostructures from Packaging Materials into Food Matrices

Packaging or coating for use in the food segment requires the evaluation of an additional factor; the migration rate. Food packaging migration occurs when the analyzed additive diffuses from the polymeric matrix of the film, or coating, towards the foodstuff or food simulant, as evaluated in [93]. Depending on the substance migrating, this process may be or may not be desirable. For active and intelligent packaging, in most cases, the migration of the active compound to the food packaging is expected, once it will be responsible to protect the food packaged; thus, in this case, the migration rate is associated with the transfer of a beneficial compound (such as the nutraceutical omega-3, natural antimicrobials, extracts, and essential oil, to name a few) [94]. On the other hand, harmful chemical compounds that are harmful to human health may also migrate, in which case they are considered contaminants because they have not been intentionally added to the food (e.g., monomers, oligomers, alkanes, phthalate plasticizers, processing aids, photoinitiators, nanoparticles, slipping agents, flame retardants). Several factors influence the migration process: time of contact with the food during storage, temperature (storage or in the preparation step-heating), type of contact, characteristics of the migrating substances/migrants (molecular weight, volatility, and polarity), and food properties (composition, e.g., fat content and properties) [93,95,96]. Moreover, the level of migration achieved also plays a role in determining the toxicity of nanostructures, as more concentrated nanoparticles are associated with more toxic effects [97,98]. Figure 3 illustrates the migration of a nanostructure from a contact surface to food [99].

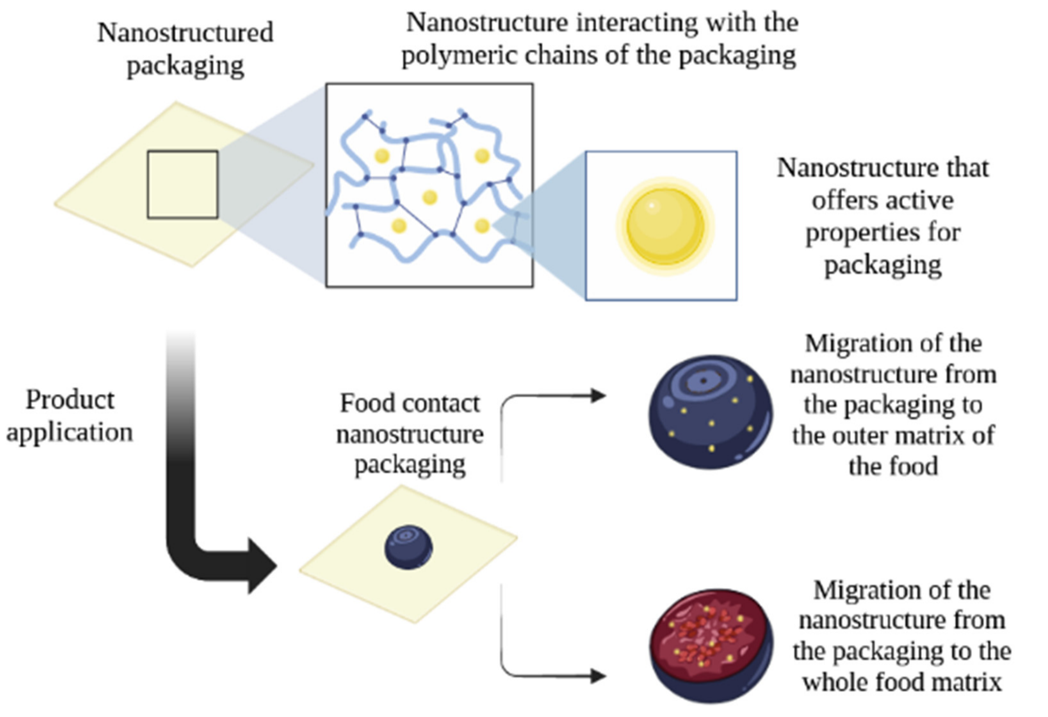

Figure 3. Migration of a nanostructure from a packaging surface to food. Created in BioRender.com.

The nanostructures present in packaging materials can migrate into food matrices in different ways, depending on the properties of the materials and the storage and processing conditions. Some of the migration mechanisms include [4,100–102]:

i. Diffusion: Migration of nanostructures can occur through diffusion, which is the process by which particles move from an area of high concentration to an area of low concentration. This process is influenced by temperature, humidity, pH, and chemical composition of the materials.
ii. Interaction with lipids: Nanostructures can interact with lipids present in food, which are fat-soluble molecules. This interaction can lead to the incorporation of nanostructures into lipid micelles, which are small spherical structures formed by lipids.
iii. Interaction with proteins: Nanostructures can also interact with proteins present in food, which are water-soluble molecules. This interaction can lead to the formation of protein-nanostructure complexes, which can be absorbed by the digestive system.
iv. Permeation: Migration of nanostructures can also occur through permeation, which is the process by which particles pass through the packaging material's barrier. This process is influenced by the nature of the packaging materials and storage and transportation conditions.

Furthermore, the detection and characterization of nanomaterials in the food chain are necessary due to the potential risks they pose to consumers, as they have the ability to migrate from packaging materials into food. In light of this, specific techniques are required to assess and analyze nanomaterials. To measure nanomaterials in complex matrices, analysis techniques must clearly distinguish between nanoparticles and other matrix components [103,104]. Moreover, the employed techniques should be sensitive enough to detect low concentrations of materials and provide comprehensive information regarding the concentration, composition, and physicochemical properties of the nanomaterials in the samples. For this purpose, there are several methods available for the detection of nanomaterials, including [103,105]:

Microscopic Methods [106,107]:

i. Transmission Electron Microscopy (TEM): Allows for direct visualization of nanoparticles at high resolution, revealing their morphology, size, and distribution.
ii. Scanning Electron Microscopy (SEM): Provides surface images of nanoparticles, enabling detailed analysis of their morphology and size.
iii. Atomic Force Microscopy (AFM): Enables analysis of surfaces at the nanoscale, providing detailed information about the topography, roughness, and mechanical properties of nanoparticles.

Quantitative Analysis Methods [108]:

i. Atomic Absorption Spectrometry (AA): Used to determine the concentration of elements present in nanoparticles.
ii. Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES): Allows for quantitative analysis of elements in nanoparticles.
iii. Inductively Coupled Plasma Mass Spectrometry (ICP-MS): Used to determine the concentration of metallic elements in nanoparticles.
iv. Trace Element Analysis (TEA): Employed for the detection and quantification of trace elements in nanoparticles.

Spectroscopy Methods [109,110]:

i. UV-Vis Absorption Spectroscopy: Used to analyze the absorption of light by nanoparticles and determine their concentration.
ii. Raman Spectroscopy: Enables identification and characterization of the vibrational properties of nanoparticles, providing information about their structure and composition.
iii. Photoluminescence Spectroscopy: Used to analyze the emission of light by nanoparticles and obtain information about their optical properties.

iv. Infrared Spectroscopy (IR): Allows for identification and characterization of the chemical bonds present in nanoparticles, aiding in determining their composition.

Several studies have demonstrated that the migration rate of packaging materials depends on a wide range of factors, such as the density of remaining segments, thickness of additives, food composition in contact with nanoparticles, solubility of materials in the food, as well as the duration and temperature of contact between packaging materials and food [103]. Other factors that can affect the migration of packaging materials into food include food acidity, fat content, presence of antioxidants, pressure, humidity, and temperature during storage. Additionally, the interaction between nanoparticles and food components such as proteins and lipids can impact migration [111,112].

The migration of packaging materials into food can have implications for food safety and quality. Some nanoparticles may be toxic to humans, depending on their composition, size, and shape. Therefore, it is important to conduct migration testing of materials to assess the safety of food [113].

8. The Legislation, Safety, and Toxicities of Nanotechnology Packaging

Nanotechnology is a powerful tool for formulating new materials, packaging, and coating, and for improving intelligent or active materials [114]. However, one question remains: how safe are nanostructures? Are the new nanomaterials loaded with unsafe structures? Are there laws or standards approved by food regulator agencies to commercialize these products? What tests must these products undergo to be considered safe?

The toxicology of a polymeric packaging or coating is directly related with the polymer matrix and the additives. The influence of both factors in packed food has been evaluated over the past decades, and some countries have established standards and legislation for polymers and additives in packaging.

Each country has agencies to regulate and inspect the production, use, and trade of food products and materials inside their territories. For example, the European Union has the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) list developed and updated by the European Chemicals Agents (ECHA) in compliance with EC 1907/2006 and EC 1935/2004 of the European Parliament and Council and EU 10/2011 of the Commission Regulation. The United States has a list of foods generally recognized as safe (GRAS) developed by the regulatory public health agency Food and Drugs Administration (FDA) in sections 201(s) and 409 of the Federal Food, Drug, and Cosmetic Act. China presents the Inventory of Existing Chemical Substances in China (IECSC) list. The Agency of National Health Surveillance (ANVISA) of the Ministry of Health exists in Brazil. These agencies regulate the use and trade of products and materials in their respective countries [13]. Thus, nanotechnology's advent creates or improves some norms and legislation to regulate nanostructured materials' production, uses, and handling. In fact, in 2021, the European Food Safety Authority (EFSA) released a "Guidance on the risk assessment of nanomaterials to be applied in the food and feed chain: human and animal health" [115].

The incorporation of nanostructures into polymeric matrices and biopolymers will result in changes in the properties of the packaging produced, which will vary depending on the nanostructure and concentration used. The changes can modify the material's physicochemical properties, such as viscosity, tensile strength, elastic modulus, water solubility, thermal conductivity, electrical conductivity, thermal stability, and opacity. Or they may add new properties to the packaging, such as antimicrobial activity to enlarge the food protection. The Table 5 lists the changes in biopolymer matrices caused by the inclusion of different nanostructures [116,117].

Table 5. Changes in biopolymer matrices caused by different nanostructures.

Nanostructure	Effect on Biopolymers Matrices	Reference
ZnO	Reduce photo-oxidative degradation Increase the glass transition Increase in thermal stability Decrease in tensile strength Increase the absorbance of UV radiation Antimicrobial activity	[115–117]
Zirconium Phosphate	Antifungal activity Increase the tensile strength Increase the strain at break Increase the water resistance Decrease thermal stability	[116]
Copper	Increase the tensile strength Antimicrobial activity Increase the antioxidant activity Increase the thermal stability Increase the barrier high UV light	[115,116,118]
Gold	Increase the tensile strength Antimicrobial activity Increase the antioxidant activity Increase the thermal stability Increase the electrical conductivity Increase the optical property Increase the barrier high UV light	[115,116,119]
Silica	Increase tensile strength Increase water resistance Decrease of both water solubility Decrease of water uptake Increase the strain at break Increase the melting temperature	[116]
Carbon nanotubes	Increase the tensile strength Increase the strain at break Increase the Young's modulus Decrease in water uptake Decrease the flexibility Increase the thermal stability Increase the electrical conductivity	[115,116]
Cellulose	Decrease the toughness Decrease the strain at the break Increase the Young's modulus Increase the tensile strength Increase the moisture barrier Increase the tortuosity Decrease the solubility of water Decrease the permeable	[115,116,120]
Chitosan	Increase the tensile strength Increase the elastic modulus Increase the water resistance	[115,120]

Knowledge in the field of nanostructure toxicology is still being developed. The toxicology of nanostructures can be influenced by the nanostructure's size, geometry, morphology, and content [96]. Therefore, determining the toxicology of a nanostructure is a complex task. The literature is contradictory regarding the toxicity of some nanostructures [63] because some authors reported toxicity for particular nanostructures, while others described no toxicology for identical nanostructures and conditions of analysis [121–124].

Due to the complexity of toxicological analysis, there is still no uniform legislation on the use of nanostructures. In 2009, the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) organized an international conference to discuss the risks of unintended use of nanostructures and the applications of nanostructures in the food and agriculture segments [125] since nanotechnology made possible the creation of numerous new products, new solutions to market difficulties, and food improvements. However, misuse of nanostructured materials can cause health problems such as colon cancer, kidney complications, dermatitis, and vasculitis, depending on the type and conditions of the nanostructure used [126].

Furthermore, as discussions on the safety of nanostructures progress, each country is already preparing a list of allowed or prohibited nanostructures for use as packaging additives, with a stipulation of maximum concentration allowed in food. In the United States, aluminum, carbon black, nanoclay, silver, and zinc oxide nanostructures are approved for sale. The European Union has authorized the utilization of titanium nitride, silicon dioxide, and carbon black nanostructures, with respect to EC 10/2011. In Brazil, the use of titanium nitride nanoparticles, copolymers in nanoforms, and ZnO nanoparticles coated or not with [3-(methacryloxy)propyl]trimethoxysilane are allowed by RDC No. 326 as of 3 December 2019 [114,127]. Nanotechnology-enabled packaging and coatings are already being inserted into society, and gradually each federal agency is compiling a list of tests and standards for the application of nanostructures in their respective countries [14].

9. Outlook and Final Considerations

Nanotechnology is revolutionizing global technologies; therefore, its influence is observed in the food segment, packaging, and coatings. Nanotechnology-based industrial processes will make it possible to produce safer food with a longer shelf life, generate less industrial waste, and produce food with higher nutritional value. Packaging with nanostructures promotes (i) the production of new intelligent packaging, e.g., packaging that carries information about the product, such as the condition of the packaged food, time and temperature control, and detection of pathogenic microorganisms and harmful chemical agents using nanosensors; (ii) the production of new active packaging, e.g., those that contain molecules that give new properties to the packaging, for example, those with antimicrobial properties; (iii) improving the physicochemical properties of packaging and coatings, such as thermal resistance or conductivity, tensile strength, and polymer elasticity; and (iv) using nanostructures as drug carriers, e.g., as vectors for the release of nutraceuticals, vitamins, nutrients, thus enabling active foods with better nutritional value. Nevertheless, studies are still needed to find safe and appropriate conditions for each nanostructure to ensure the safety and well-being of humans and the environment when using packaging with nanotechnology. Thus, new standards, legislation, and tests are needed for the application of nanostructures in food as the trend is the increasing use of nanotechnology in different industrial segments.

Currently, there are few specific regulations for nanotechnology applied to food. However, it is important to mention the REACH legislation from the European Union that aims to ensure the safety and risk assessment of chemical substances used in the industry, including nanostructures. The registration and prior evaluation of chemical substances are needed, guaranteeing that manufacturers and importers must conduct tests and provide information on associated risks before placing them on the market. The FDA from the United States regulates nanotechnology in the food packaging sector, and it is responsible for assessing the safety and risks associated with nanomaterials used in food packaging to protect consumers' health. In Brazil, there is no specific regulation for using nanotechnology in food. However, standards developed by the International Organization for Standardization (ISO) are used as a reference for evaluating nanomaterials. These standards establish guidelines for the characterization, measurement, risk assessment, and safety of nanomaterials in products.

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