



## REVIEW ARTICLE

# Nanocomposites applications in food packaging- a review

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### Abstract

Most materials currently used for food packaging are non-degradable, causing environmental problems. Several biopolymers have been exploited to develop materials for environmentally friendly food packaging. However, the use of biopolymers is limited by their generally poor mechanical and barrier properties, which can be improved by forming reinforcing compounds (fillers) and composites. Most reinforced materials exhibit poor matrix-filler interactions, which will enhance with decreasing filler. Nanocomposites can be produced using fillers with at least one nanoscale dimension (nanoparticles). Nanoparticles have a proportionally larger surface area than their microscale counterparts, which favors filler-matrix interactions and the performance of the resulting materials. In addition to nano reinforcements, nanoparticles can perform other functions when incorporated into polymers, such as antimicrobial activity, enzyme immobilization, biosensing, etc. Significant types of nanoparticles that have been studied for use in food packaging systems, along with their effects and applications.

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## 1. Introduction

A nanocomposite is a complex material created by combining two or more elements, comprising a matrix (continuous phase) and a discontinuous Nanophase, with at least one dimension in the Nanoscale (i.e., less than 100 nm). Based on the number of Nanosized sizes, the Nano dimensional phase can be categorized into three groups: 0D Nano spheres or nanoparticles; 1D Nano rods or nanotubes; and 2D Nano sheets or Nanoplatelets. Nano spheres or nanoparticles possess three dimensions at the Nanoscale. Nano whiskers (Nanorods) and nanotubes have Nano metric dimensions, with nanotubes being hollow and Nano whiskers being solid. Lastly, Nanosheets or Nano platelets have only one Nanosized size [1].

Most Nanosized phases play a structural role, serving as reinforcement to enhance the mechanical properties of the matrix, typically a polymer. The matrix transfers stress through

the interface to the Nano reinforcement. Nano reinforcements are especially beneficial for biopolymers, which perform less effectively than conventional petroleum-based polymers. Integrating Nanosized reinforcements into biopolymers opens new possibilities for enhancing their properties and cost performance [2].

Beyond their mechanical and barrier enhancement role, Nano reinforcements and nanostructures contribute to various applications in food packaging. When incorporated into polymer matrices, these structures can interact with the food and its environment, conferring active or "smart" properties to packaging systems. When present in food packaging, such properties often relate to food safety or stability improvements or provide information about a product's safety or stability status.

The primary types of nanostructures will be discussed based on their principal functions and applications in food packaging

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systems. Some structures may have multiple applications, and in some cases, applications may overlap, such as certain immobilized enzymes that can function as antimicrobial components, oxygen scavengers, and nanosensors.

## 2. Nano reinforcements in food packaging materials

Polymer nanocomposites generally exhibit superior polymer/filler interactions compared to traditional composites [3]. The even dispersion of Nanofillers throughout a polymer matrix results in an extensive matrix/filler surface area, constraining the mechanical mobility of the matrix and enhancing mechanical, thermal (particularly glass transition temperature), and barrier properties. The aspect ratio, denoting the ratio of a filler's largest to smallest dimension, is a crucial factor influencing performance [4, 5]. Fillers with higher aspect ratios offer a larger specific surface area, imparting improved reinforcing effects. Beyond the impact of nano reinforcements, a reduced-mobility interphase region around each Nano filler contributes to a percolating interphase network in the composite, crucial for enhancing nanocomposite properties [6]. Maintaining a constant filler content and reducing particle size increases filler particle numbers, promoting closer proximity and overlapping interfacial layers, leading to more significant changes in mass properties [7].

### 2.1 Nano clays (layered silicates)

Nano clays stand out as the most extensively researched Nano fillers owing to their widespread availability, cost-effectiveness, commendable performance, and ease of processing. The inception of Polymer-Nano clay composite applications in food packaging dates back to the 1990s [8]. Typically, the clays employed for nanocomposites are two-dimensional platelets with minimal thickness (often approximately 1 nm) and lengths extending a few micrometers. In contrast to the conventional tactoid structure of micro composites, where polymer and clay tactoids remain immiscible [9, 10], the interaction between layered silicates and polymers gives rise to two distinct types of nanoscale composites (Figure 1): intercalated nanocomposites, formed by polymer chain penetration into the interlayer region of the clay, resulting in an ordered multilayer structure with alternating polymer/inorganic layers [11]; and exfoliated nanocomposites, characterized by extensive polymer penetration, causing the delamination of clay layers distributed randomly in the polymer matrix [12]. Exfoliated nanocomposites are renowned for their exceptional properties due to optimal clay-polymer interaction [13, 14]. Montmorillonite (MMT) stands out as the most studied clay, featuring a chemical formula of  $\text{MX}(\text{Al}_4\text{-XMgX})\text{Si}_8\text{O}_{20}(\text{OH})_4$ . MMT represents a 2:1 layered phyllosilicate, with platelets comprising two layers of tetrahedral silica sheets filled with a central octahedral alumina sheet [11]. MMT possesses a moderately negative surface charge critical for defining interlayer spacing, and this charge imbalance is

compensated by exchangeable cations (typically  $\text{Na}^+$  and  $\text{Ca}^{2+}$ ). Weak electrostatic forces connect the parallel layers, and MMT acts as an excellent reinforcing filler, boasting a high surface area and an aspect ratio ranging from 50 to 1000 [15].

The inherent hydrophilicity of clay surfaces poses challenges for dispersion in organic matrices [16]. Organ clays have gained prominence in polymer nanocomposites resulting from interactions between clay and organic compounds. Effective organophilization is crucial for successful clay exfoliation in most polymeric matrices, reducing clay energy and enhancing compatibility with organic polymers [17]. For instance, organomontmorillonite (oMMT) is produced by exchanging MMT's inorganic cations with organic ammonium ions, enhancing MMT compatibility with organic polymers [18, 19]. This process leads to a more orderly layer organization and reduces water uptake in the resulting nanocomposite [20].

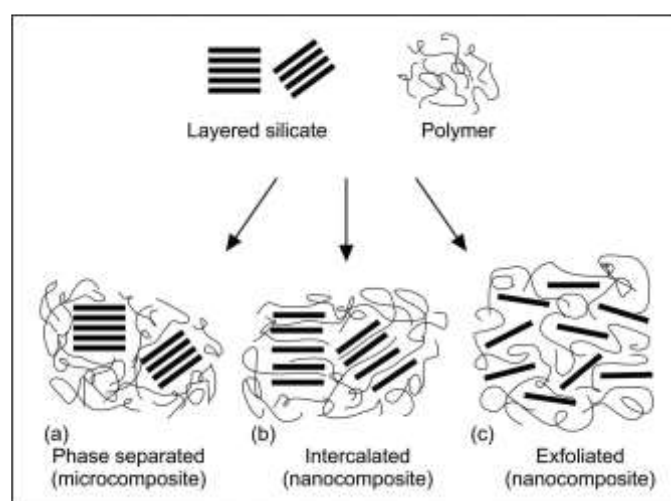


Figure 1: Types of compositions of polymer-clay interactions (Alexandre & Dubois, 2000).

The enhanced barrier properties in polymer-clay nanocomposites arise from an increased tortuosity in the diffusive path for permeants (Figure 2), compelling them to traverse a more extended route through the film. Nielsen (1967) initially formulated this theory, which was subsequently corroborated by other researchers [13]. The elongation of the diffusion path is contingent upon the clay's aspect ratio and the volume fraction of the filler in the composite. Nielsen's model, effective for predicting permeability in systems with clay loadings below 1%, encounters discrepancies at higher loadings. Addressing this, Beall (2000) introduced a new model that considers the polymer-clay interface as an additional determinant influencing the tortuous path, offering a correction factor to Nielsen's model [21]. Besides their impact on permeability, clays have been noted to enhance the mechanical strength of biopolymers [22], although concurrently diminishing polymer elongation.

## 2.2 Cellulose Nano reinforcements

Cellulose Nano reinforcements (CNRs) present a compelling option for crafting cost-effective, lightweight, and robust nanocomposites. Synthesized in living organisms, predominantly plants, cellulose chains manifest as microfibrils or nanofibers—bundles of elongated molecules (2–20 nm in diameter, micrometric in length) stabilized by hydrogen bonds.

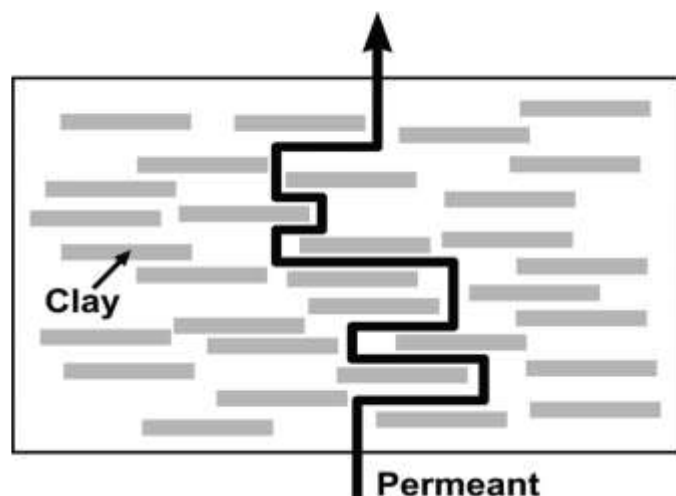


Figure 2: Winding path for a permeant through a polymer-clay nanocomposite, according to Nielsen's model [13].

Our investigation delved into the impact of cellulose nanofibers on the physical properties of mango puree edible and chitosan films [23]. Varying concentrations of cellulose

nanofibers were incorporated into edible films with mango puree and homogenized at 6500 rpm for 30 minutes. A control film sans nanofibers was also prepared. Film-forming dispersions were vacuum degassed, cast onto leveled glass plates, and dried for 16 hours at 22°C and 42% RH. Tensile properties were assessed using an Instron Model 55R4502, while water vapor permeability (WVP) was determined via the gravimetric modified cup method (Standard Method E96-80). Adding at least 10% CNRs notably reduced WVP, aligning with findings by Paralikar et al. (2008), suggesting favorable interactions between CNRs and mango polysaccharides enhancing the water vapor barrier [24]. CNRs also enhanced tensile strength and Young's modulus, with a slight reduction in elongation at concentrations exceeding 10%. Numerous studies echo these positive effects on tensile properties, particularly modulus, though extension tends to decrease. Helbert et al. (1996) attribute the significant impact of CNRs on modulus not only to filler geometry and stiffness but also to forming a fibrillar network within the polymer matrix, possibly linked by hydrogen bonds. In essence, CNRs emerge as influential modifiers, shaping the physical characteristics of nanocomposites through intricate interactions, thus offering the potential for diverse applications in material engineering. These microfibrils, with crystalline and amorphous regions, yield nanocrystals or Nano whiskers upon isolation through methods like acid hydrolysis, their aspect ratio dependent on cellulose origin and processing conditions [4]. Microfibrils harbor structural defects, considered as whiskers linked by amorphous domains.

Table 1. Physical properties of mango puree films with different concentrations of CNRs

CNR (%)*	TS (MPa)	EB (%)	YM (MPa)	WVP (g.mm/ kPa.h.m2)
0	(4.07 ± 0.10)d	(44.05 ± 0.94)a	(19.82 ± 0.48)e	(2.63 ± 0.05)a
5	(4.56 ± 0.19)c	(41.76 ± 0.41)b	(30.90 ± 1.25)d	(2.14 ± 0.02)b
10	(4.89 ± 0.11)c	(43.15 ± 1.71)ab	(40.85 ± 1.38)c	(2.01 ± 0.9)b
18	(5.51 ± 0.06)b	(39.4 ± 0.50)b	(78.79 ± 5.02)b	(1.87 ± 0.03)bc
36	(8.73 ± 0.10)a	(31.50 ± 2.26)c	(322.01 ± 19.38)a	(1.63 ± 0.8)c

The provided data, based on a dry basis, illustrates various physical properties of nanocomposite films, namely tensile strength (TS) in MPa, elongation at break (EB) in percentage, Young's modulus (YM) in MPa, and water vapor permeability (WVP) in g.mm/kPa.h.m2. Distinct letters in the same column signify significant differences at  $p > 0.05$ . In a subsequent study, nanocomposite films were created from a chitosan matrix incorporating Cellulose Nano reinforcements (CNRs). Employing an essential composite design with two variables—CNR concentrations (0–20%) and glycerol concentrations (0–30%) [23]—, the experiment involved preparing a 3% chitosan solution in a 1.5% acetic acid solution. CNRs and glycerol were added to the chitosan solution and homogenized at 4500 rpm for 30 minutes using a Polytron PT 3000. The subsequent degassing, casting, drying, and analysis procedures mirrored those for mango puree films. Contour plots in Figure 3 depict the physical properties of nanocomposite chitosan films

concerning CNR and glycerol concentrations. Notably, the Nano fillers bolstered the overall tensile properties of the films while diminishing elongation. The water vapor barrier was reinforced, evident in the reduced WVP with increasing CNR concentrations. Additionally, CNRs raised the films' glass transition temperature ( $T_g$ ). Favorable responses, except for elongation, were thus associated with high CNR concentrations and low glycerol content.

Research on CNR effects in starch systems indicates that CNRs mitigate water sensitivity and reduce starch brittleness. The impact on starch brittleness aligns with transcrystallization, where semi-crystalline matrix crystals orient perpendicular to cellulose microfibrils. Furthermore, some studies note increased the  $T_g$  of starch with CNR incorporation. However, Mathew & Dufresne (2002) reported inconsistent effects of cellulose whiskers on starch matrix  $T_g$ , observing an initial increase up to 10–15 wt% whisker content,

followed by a decline. These findings underscore the nuanced influence of CNRs on the physical properties of nanocomposite films, emphasizing the need for a careful balance in formulation to achieve optimal outcomes.

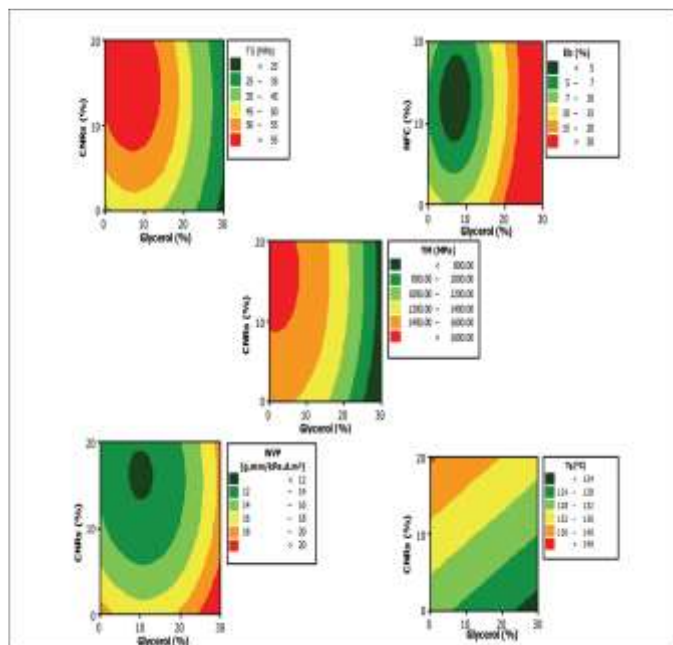


Figure 3: Physical properties of chitosan films incorporated with cellulose nanofibers and glycerol TS: tensile strength (MPa); Eb: Increase on break (%); YM: Young's Modulus (MPa); WVP: water vapor permeability (g.mm/kPa.h.m<sup>2</sup>); Tg: glass transition temperature (°C).

The glass transition temperature (Tg) elevation of up to 15% of whiskers was attributed to heightened matrix crystallinity and restricted mobility of amorphous amylopectin chains induced by physical crosslinks during crystallization. The subsequent Tg decline above 15 wt.% whiskers suggests that sorbitol, during crystallization, may have been partially expelled from crystalline domains, concentrating in amorphous regions. This phenomenon competes with the Tg-increasing effect of whiskers, likely dominating at higher loading levels and leading to a Tg decrease. Like nanoclays, cellulose Nano reinforcements augment the tortuosity of the diffusivity path for permeants, reducing polymer permeability. Numerous studies highlight the enhanced barrier properties of polymers with cellulose Nano reinforcements. Improved barriers result when the filler is less absorbent, well-dispersed, and possesses a high aspect ratio. The overall properties of polymer composites with cellulose Nano reinforcements are closely tied to filler dimensions, aspect ratio, and nanostructure orientation [Chen et al., 2009].

The hydrophilic nature of cellulose surfaces fosters satisfactory interactions with hydrophilic matrices. Conversely, incorporating cellulose Nano reinforcements into hydrophobic matrices often leads to weak filler-matrix interactions and filler aggregation through hydrogen bonding [25]. The hydrophilic character of cellulose Nano

reinforcements also poses challenges due to their high water absorption capacity, which is undesirable in many applications. Mitigating these issues involves modifications, such as hydrophobization, on cellulose surfaces through reactions with hydroxyl groups, including esterifications and acylations with fatty acids. These modifications enhance compatibility with hydrophobic matrices, diminishing aggregation and improving overall application performance.

In essence, understanding the intricate interplay between cellulose Nano reinforcements and matrices is crucial for optimizing the performance of nanocomposites. The balance of factors, including loading levels, filler-matrix interactions, and surface modifications, dictates these materials' overall properties and applicability in diverse fields.

### 2.3 Other Nano reinforcements

Carbon nanotubes exhibit one-atom-thick single-walled structures or multi-walled nanotubes with multiple concentric layers, offering exceptionally high aspect ratios and elastic moduli. Adding carbon nanotubes to various polymers, including polyethylene naphthalate, polyvinyl alcohol, polypropylene, and polyamide, has enhanced tensile strength and modulus [26]. As indicated by Brody (2006), research from Natick revealed that polylactic acid not only improved its tensile properties through carbon nanotubes but also saw a significant 200% decrease in water vapor transmission rate.

Silica nanoparticles (nSiO<sub>2</sub>) have demonstrated the ability to enhance the tensile properties of polypropylene, starch, and starch/polyvinyl alcohol while simultaneously reducing water absorption in starch and improving the oxygen barrier in polypropylene. Jia et al. (2007) researched nanocomposites of polyvinyl alcohol with nSiO<sub>2</sub>, demonstrating enhanced thermal and mechanical properties compared to pure polyvinyl alcohol. These enhancements were attributed to robust interactions between nSiO<sub>2</sub> and the polymer matrix, facilitated by covalent bonding through radical copolymerization of vinyl silica nanoparticles and vinyl acetate [27].

Chitin or chitosan nanostructures have also been explored for their impact on polymer properties. Including chitin fibers significantly enhanced the tensile properties and water resistance of soy protein isolate thermoplastics. Furthermore, the incorporation of chitosan-tripolyphosphate nanoparticles into hydroxypropyl methylcellulose films significantly improved the tensile and barrier properties of the films. Other nanostructures, such as starch nanocrystals (SNCs), have also been identified as effective reinforcing agents. In pullulan films, SNCs increased tensile strength, modulus, and glass transition temperature (Tg) while decreasing elongation [26].

Overall, incorporating nanomaterials, including carbon nanotubes, silica nanoparticles, and chitin or chitosan nanostructures, has proven effective in enhancing various mechanical and barrier properties of polymers. These advancements offer promising opportunities for developing high-performance polymer composites with improved strength, modulus, and resistance to environmental factors. The nuanced effects of different nanostructures on polymer

properties underscore the importance of tailoring these materials to specific applications for optimal performance.

### 3. Nanocomposite active food packaging

Traditional food packaging primarily serves as a passive barrier, shielding food from the external environment. In contrast, active food packaging goes beyond mere isolation, engaging with the food intentionally. This interaction involves releasing specific compounds, such as antimicrobial or antioxidant agents, or eliminating harmful factors like oxygen or water vapor. The outcomes of these interactions often lead to enhanced food stability. Active nanocomposite food packaging, combining nanotechnology with operational packaging functionalities, exemplifies this approach. These systems can release beneficial agents or mitigate detrimental elements, improving food safety and shelf life. Integrating nanocomposites in active packaging represents an innovative and dynamic avenue for advancing the capabilities of food packaging systems.

#### 3.1 Antimicrobial systems

Antimicrobial food packaging systems have become a focal point in the quest to control the proliferation of pathogenic and spoilage microorganisms on food surfaces, mitigating potential health risks associated with microbial contamination. The exploration of antimicrobial nanocomposite systems introduces a compelling dimension to this pursuit, capitalizing on materials at the nanoscale for heightened efficiency.

Nanoscale materials, characterized by an elevated surface-to-volume ratio compared to their microscale counterparts, exhibit enhanced effectiveness in attaching copies of microbial molecules and cells. This efficiency is attributed to their ability to interact at the molecular level, showcasing potential applications as growth inhibitors, killing agents, or antibiotic carriers.

Silver nanoparticles, known for their potent toxicity to a broad spectrum of microorganisms, are prevalent in antimicrobial nanocomposite films for food packaging. Their effectiveness surpasses larger silver particles due to the increased surface area available for interaction with microbial cells. Mechanisms underlying their antimicrobial activity include adhesion to cell surfaces, degradation of lipopolysaccharides, penetration into bacterial cells causing DNA damage, and the release of antimicrobial Ag<sup>+</sup> ions through nanoparticle dissolution. The latter mechanism, releasing Ag<sup>+</sup> ions, is particularly vital, binding to electron-donating groups in biological molecules containing sulfur, oxygen, or nitrogen.

Beyond their antimicrobial attributes, silver nanoparticles exhibit additional benefits, such as the absorption and decomposition of ethylene. This dual functionality contributes to extending the shelf life of fruits and vegetables. Nanostructured calcium silicate (NCS) is another noteworthy antimicrobial agent that can adsorb Ag<sup>+</sup> ions from a solution. The resulting NCS-Ag complex exhibits effective

antimicrobial activity at low silver levels, making it a potential candidate for incorporation into food packaging.

Titanium dioxide (TiO<sub>2</sub>), widely recognized for its photocatalytic disinfection properties, has been employed in surface coatings for antimicrobial food packaging. TiO<sub>2</sub> photocatalysis induces peroxidation of phospholipids in microbial cell membranes, leading to the inactivation of food-associated pathogenic bacteria. Metal doping, particularly with silver, enhances the visible light absorption of TiO<sub>2</sub>, increasing its photocatalytic activity. This synergistic effect was observed in a polyvinyl chloride nanocomposite with TiO<sub>2</sub>/Ag<sup>+</sup> nanoparticles, demonstrating effective antibacterial activity.

Chitosan nanoparticles, derived from chitin, showcase antibacterial properties attributed to interactions between positively charged chitosan and negatively charged cell membranes. These interactions increase membrane permeability, causing rupture and leakage of intracellular material. Notably, chitosan nanoparticles exhibit limited efficacy at pH levels below 6, emphasizing the importance of considering environmental conditions.

Additional antimicrobial mechanisms proposed for chitosan include chelation of trace metals, inhibiting microbial enzyme activities, and penetration through fungal cell walls and membranes to bind DNA, inhibiting RNA synthesis. Carbon nanotubes, characterized by antibacterial properties, have been shown to kill *E. coli* through direct contact, potentially due to their piercing action on microbial cells. However, concerns arise regarding their cytotoxicity to human cells, particularly for individuals involved in nanotube processing stages.

Understanding the potential health effects of ingesting carbon nanotubes becomes crucial once they are incorporated into food packaging materials. Overall, exploring antimicrobial nanocomposite systems reflects a multifaceted approach, where each material contributes unique attributes to combat microbial threats, ensuring food safety and extending shelf life. Thorough consideration of these nanocomposite systems' mechanisms, potential risks, and applications is essential to strike a balance between technological advancements and consumer well-being.

#### 3.2 Oxygen scavengers

Oxygen (O<sub>2</sub>) plays a pivotal role in diverse forms of food deterioration, ranging from direct oxidation reactions leading to browning and rancid flavors to indirect actions causing spoilage by aerobic microorganisms. Incorporating oxygen scavengers into food packaging systems to mitigate these effects proves beneficial, allowing for maintaining deficient oxygen levels in various applications. In addressing this need, Xiao-e et al. (2004) successfully developed oxygen-scavenging films by integrating TiO<sub>2</sub> nanoparticles into different polymers. These nanocomposite materials serve as packaging films for various oxygen-sensitive food products. The key advantage lies in the ability of TiO<sub>2</sub> to function through a photocatalytic mechanism. However, it's essential to note a potential limitation—the requirement for UVA light to activate the photocatalytic process. Utilizing nanocomposite



films with TiO<sub>2</sub> nanoparticles presents an innovative solution to oxygen-related food deterioration. By harnessing the scavenging capabilities of these materials, the packaging effectively maintains low oxygen levels, extending the shelf life and preserving the quality of oxygen-sensitive food products. Despite the need for UVA light, this approach represents a valuable advancement in food packaging technology with broad applications in the food industry.

### 3.3 Enzyme immobilization systems

Enzymes are crucial in diverse applications within the food industry, contributing to flavor development, preservation, and nutritional enhancement. However, their applicability can be constrained by sensitivity to processing conditions or enzyme inhibitors. Immobilization effectively enhances enzyme stability against pH and temperature variations, resistance to proteases, and exposure to denaturing compounds. Moreover, it provides a conducive environment for controlled release or frequent use. Enzyme immobilization finds application in packaging, addressing consumer needs and elevating the value of food products. For instance, incorporating enzymes such as lactase or cholesterol reductase into packaging meets the requirements of consumers with specific enzyme deficiencies. Nanoscale enzyme immobilization systems hold promise for superior performance compared to conventional counterparts, attributed to their significantly higher surface contact area and enhanced mass transfer rates—crucial factors influencing efficiency. In nanotechnology, approaches involving enzyme adsorption in polymer-incorporated nanoclays gain attention. Nanoclays exhibit a notable affinity for protein adsorption, making them potential carriers for enzymes. This approach enhances the effectiveness of enzyme immobilization systems. Additionally, conductive polymers, such as poly(aniline-co-fluoroaniline), have been explored as matrices for immobilizing biomolecules. Sharma et al. (2004) reported the successful immobilization of glucose oxidase on films of this conductive polymer. SiO<sub>2</sub> nanoparticles were also modified to immobilize glutamate dehydrogenase and lactate dehydrogenase, showcasing excellent enzyme activity post-immobilization.

These advancements in enzyme immobilization, especially within nanoscale systems, address the limitations associated with direct enzyme addition and open avenues for innovative applications in food packaging. The improved stability and performance of enzymes contribute to developing value-added food products, catering to consumer preferences and nutritional requirements.

## 4. Nanocomposite smart food packaging

An intelligent food packaging system is characterized by its ability to "sense" specific attributes of the packaged food. It utilizes mechanisms to register and transmit current quality or safety status information. In this context, nanostructures are pivotal as reactive particles integrated into packaging materials, serving as Nanosensors. These sensors have the

potential to respond to various environmental changes during storage, such as temperature fluctuations, variations in relative humidity, exposure to oxygen, degradation products, or microbial contamination.

Traditionally, food expiration dates are determined based on estimated distribution and storage conditions, which may not accurately reflect the real requirements to which the food product is exposed. For instance, foods requiring a cold chain may experience temperature abuse, and packaging system defects can result in unexpected exposure to oxygen. Nanosensors embedded in food packaging systems can actively detect changes associated with spoilage, the presence of pathogens, and chemical contaminants. This real-time monitoring eliminates the need for unreliable expiration dates, accurately assessing food freshness.

Several nanocomposite applications in innovative packaging systems showcase the versatility of this technology. By leveraging Nanosensors, these systems enhance food safety and quality assurance. Integrating nanotechnology in food packaging exemplifies an innovative approach to address challenges in the food industry, promoting more accurate assessments of food conditions and minimizing the risks associated with inadequate expiration date estimations.

### 4.1 Time-temperature integrators

Time-temperature indicators (TTIs) play a crucial role in monitoring and interpreting food products' temperature history to ensure their consumption safety, especially when stored under suboptimal conditions. When food is expected to be frozen, TTIs indicate whether it has been exposed to higher temperatures for an inadequate duration. TTIs are categorized into three main types: abuse indicators, partial temperature history indicators, and total temperature history indicators.

Abuse indicators, also called critical temperature indicators, signal whether a reference temperature has been reached. Partial temperature history indicators track when the temperature surpasses a predetermined critical value. Total temperature history indicators provide a comprehensive record of temperature changes over time. These indicators typically communicate information through color development, linked to the temperature-dependent migration of a dye through a porous material or a color change triggered by a temperature-dependent chemical reaction or physical transformation. For instance, Timestrip® has introduced the iStrip system for refrigerated foods, utilizing gold nanoparticles. These nanoparticles exhibit a red color above freezing temperatures. In accidental freezing, irreversible aggregation of the gold nanoparticles occurs, resulting in the loss of the red color. This visual change serves as a clear and irreversible indication of temperature history, allowing consumers and stakeholders to make informed decisions about the safety and quality of the food product. TTIs provide an additional layer of transparency and assurance in the food industry, particularly when maintaining specific temperature conditions is critical.

#### 4.2 Detection of gases produced by food spoilage

Food spoilage, often instigated by microorganisms emitting detectable gases during their metabolic processes, can be effectively identified and monitored by applying nanosensors. These sensors, designed to translate chemical interactions into reaction signals, commonly rely on metal oxides or, more recently, conductive polymer nanocomposites for gas detection. Conductive polymer-based nanosensors consist of conductive particles embedded in an insulating polymer matrix. Notably, these sensors exhibit resistance changes that generate distinctive patterns resembling the gas under scrutiny. Conductive polymers, including polyene and polyaromatic variants like polyaniline, polyacetylene, and polypyrrole, offer significant advantages due to their diverse electrical, electronic, magnetic, and optical properties linked to their conjugated electron backbone. The electrochemical polymerization of conducting polymers is particularly interesting, enabling a seamless transition between conducting oxidized (doped) and insulating reduced (undoped) states. This inherent capability forms the foundation for various applications. Arshak et al. (2007) demonstrated the effectiveness of nanosensors incorporating carbon black and polyaniline in detecting and identifying three foodborne pathogens. The sensors produced distinct response patterns for each microorganism, showcasing the potential of nanosensors in enhancing food safety by providing rapid and specific identification of spoilage-related microorganisms.

#### 4.3 O<sub>2</sub> sensors

There is a growing interest in developing non-toxic and irreversible oxygen sensors, particularly for oxygen-free food packaging systems like those involving vacuum or nitrogen packaging. Lee et al. (2005) introduced a UV-activated colorimetric O<sub>2</sub> indicator utilizing TiO<sub>2</sub> nanoparticles to photosensitize methylene blue (MB) reduction by triethanolamine within a polymer encapsulation medium. Under UV irradiation, the sensor becomes colorless until exposed to oxygen, where its original blue color is restored. The rate of color recovery is directly proportional to the level of oxygen exposure. Gutiérrez-Tauste et al. (2007) employed liquid phase deposition (LPD), a soft chemical technique, to deposit MB/TiO<sub>2</sub> nanocomposite thin films on glass, offering a potential method for creating an O<sub>2</sub> indicator packaging system for various oxygen-sensitive foods. In another approach, Mills & Hazafy (2009) utilized nanocrystalline SnO<sub>2</sub> as a photosensitizer in a colorimetric O<sub>2</sub> indicator. This system comprised a sacrificial electron donor (glycerol), a redox dye (MB), and an encapsulating polymer (hydroxycellulose). Exposure to UVB light triggered the activation of the indicator (photobleaching) and the photoreduction of MB by SnO<sub>2</sub> nanoparticles. The films' color changed with O<sub>2</sub> exposure, transitioning from a bleached state when unexposed to a blue hue when exposed. These advancements in nanocomposite-based O<sub>2</sub> indicators ensure oxygen-sensitive foods' integrity during packaging and

storage.

#### 5. Final considerations

Nanotechnology holds significant promise for transformative advancements in the food packaging industry. Incorporating nano reinforcements into biodegradable polymers, forming nanocomposites, represents a notable development. This enhancement contributes to elevating the overall performance of biopolymers, rendering them more competitive in a market predominantly characterized by non-biodegradable materials. Nanocomposites extend beyond passive protection, offering an avenue to introduce desirable properties into food packaging systems actively. These properties may encompass antimicrobial effects, oxygen scavenging capabilities, enzyme immobilization, or indicators reflecting exposure to adverse conditions such as insufficient temperatures or oxygen levels. Consequently, nanocomposites have the potential not only to safeguard food against environmental factors but also to enhance its stability or indicate its unsuitability for consumption.

However, adopting nanotechnology in food packaging also raises significant safety concerns. While the properties and safety of bulk materials are generally well understood, nano-sized counterparts exhibit distinct properties due to their small size, allowing them to move more freely through the body. Additionally, their increased surface area enhances reactivity. More scientific data is needed regarding the migration of nanostructures from packaging materials to food. Despite their tendency to form large aggregates, the possibility of migration cannot be ruled out. Evaluating the risks associated with these microscopic, potentially biologically active particles in the human body or the environment is a critical area requiring further research. Addressing potential toxicity and ensuring the environmental safety of nanotechnology products is imperative, emphasizing the need for comprehensive scientific investigations in this evolving field.

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