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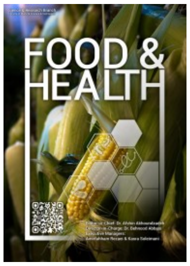

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Nanobiodegradable Packaging with Nanocomposites: Addressing Nanoparticle Migration and Sensory Impacts for Enhanced Food Preservation

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ABSTRACT

Nanotechnology has significantly advanced biodegradable food packaging by enhancing essential properties such as mechanical strength, barrier performance, and antimicrobial functionality. Traditional packaging materials, particularly plastics, pose significant environmental challenges due to their long-lasting resistance to degradation. This review highlights the integration of various nanomaterials, including nanocellulose, chitosan, and metal nanoparticles, into biodegradable packaging films to improve their functionality and sustainability. These nanomaterials not only extend the shelf life of food products by offering superior protection but also enhance food safety by minimizing microbial contamination. Despite these advantages, the widespread adoption of these innovations faces obstacles such as high production costs, regulatory challenges, and limited consumer acceptance. Addressing these hurdles is crucial for the successful commercialization of nano-enhanced biodegradable films. Future research is expected to focus on developing more sustainable nanomaterials, cost-effective production methods, and clear regulatory frameworks to facilitate the transition to environmentally friendly packaging solutions in the food industry.

1. Introduction

The need for sustainable food packaging has become increasingly urgent as the environmental impact of traditional packaging materials becomes more evident. The food industry has long relied on materials like plastics due to their versatility, durability, and effectiveness in preserving food. However, the environmental toll of synthetic polymers is undeniable, with plastics contributing significantly to pollution and waste accumulation (1). Plastics degrade slowly, often ending up in landfills or oceans, where they pose serious threats to ecosystems and biodiversity (2). Studies indicate that nearly 42% of global plastic production is dedicated to food packaging, making it a major contributor to plastic pollution (3).

This rising concern has accelerated the search for sustainable alternatives. Biodegradable polymers present a promising solution, with the potential to substantially reduce the environmental footprint of packaging materials (4). These materials, derived from renewable sources such as plants (e.g., cellulose, starch) or microbial processes, decompose through natural enzymatic activity into harmless byproducts like water and carbon dioxide. This degradation is more environmentally friendly, mitigating the long-lasting impacts of conventional plastics (5). Recent advances in polymer science have enabled the development of biodegradable materials with properties comparable to synthetic plastics, allowing them to perform effectively in food packaging applications (6).

One of the most exciting developments in this area is the integration of nanotechnology into biodegradable packaging. Nanomaterials, such as nanocellulose, Silver Nanoparticles (Ag NPs), and zinc oxide, can significantly enhance the mechanical and barrier properties of biodegradable films (7). These materials offer improved strength, flexibility, and protection against gases and moisture, making them particularly effective at extending the shelf life of food products (8). Additionally, some nanomaterials possess antimicrobial properties, which further contribute to food

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safety by reducing the risk of contamination and spoilage. As a result, nanocomposite biodegradable packaging materials are being recognized as a key innovation in the shift toward more sustainable packaging solutions (2).

While previous reviews have addressed aspects of nanotechnology in food packaging, this study is novel in its comprehensive exploration of nanoparticle migration and its impact on food safety, a critical but often underexamined area. Moreover, it highlights the sensory effects of nano-enhanced biodegradable films, such as their influence on taste, odor, and overall food quality, which are rarely addressed in existing literature. By delving into recent advancements in nanocomposites, this review demonstrates how these materials enhance mechanical, barrier, and antimicrobial properties while ensuring sustainability. It also identifies the regulatory, commercialization, and environmental challenges that hinder widespread adoption of nano-biodegradable films, highlighting the need for further innovation and research to bridge these gaps.

Despite the clear benefits, challenges remain in bringing these sustainable packaging materials to the mainstream market. Regulatory hurdles, high production costs, and limited consumer acceptance remain major barriers to widespread adoption. Governments and industry leaders are beginning to implement stricter regulations on plastic use and are advocating for the adoption of biodegradable and recyclable materials. The European Union, for example, has introduced stringent measures aimed at reducing plastic waste and encouraging the use of sustainable packaging (5). These regulatory changes, coupled with increasing consumer awareness, are driving innovation in the packaging industry (8).

In conclusion, the demand for sustainable food packaging is reshaping the industry. The development of biodegradable polymers, particularly those enhanced with nanotechnology, presents a viable alternative to conventional plastics. These innovations offer significant environmental benefits while maintaining the protective qualities needed for food preservation. However, to fully realize their potential, continued research, regulatory advancements, and market adaptation will be essential.

2. Overview of biodegradable polymers in food packaging

2.1. Definition and classification of biodegradable polymers

2.1.1. Natural biopolymers (e.g., cellulose, chitosan, starch)

Biodegradable polymers are materials that break down through natural biological processes, typically involving microbial activity, into non-toxic products such as water, carbon dioxide, and biomass. Natural biopolymers are sourced from renewable biological origins like plants, animals, or microorganisms. Cellulose, one of the most abundant natural polymers, is derived from plant materials and is widely used in food packaging due to its film-forming ability, biocompatibility, and biodegradability. Chitosan, derived from the shells of crustaceans, possesses antimicrobial properties, making it valuable for packaging that requires preservation of food quality over longer periods. Starch is another widely used natural polymer due to its biodegradability and availability from plant sources such as corn and potatoes. However, starch-based materials often require modifications to improve their water resistance and mechanical properties (9,10).

2.1.2. Synthetic biodegradable polymers (e.g., PLA, PBS)

Synthetic biodegradable polymers, unlike their natural counterparts, are designed through chemical processes and are often tailored to exhibit specific properties required for packaging applications. PLA is one of the most extensively studied and used synthetic biodegradable polymers. Derived from lactic acid, which is produced by fermenting carbohydrates from renewable sources like corn, PLA has excellent transparency, mechanical strength, and biodegradability. However, it has limitations in moisture and heat resistance, which necessitates further modification for use in food packaging. PolyButylene Succinate (PBS) is another synthetic biodegradable polymer with good mechanical properties and biodegradability. PBS is flexible and heat-resistant, making it suitable for various packaging applications (11-13).

2.2. Advantages and limitations of biodegradable polymers

2.2.1. Benefits of using biodegradable polymers in food packaging

The primary advantage of using biodegradable polymers in food packaging is their ability to reduce the environmental impact of packaging waste. As they break down naturally through microbial activity, biodegradable polymers help in minimizing landfill waste and marine pollution compared to conventional plastics, which can persist in the environment for hundreds of years. Moreover, many biodegradable polymers, especially those derived from renewable sources, have a lower carbon footprint during production. They can also help extend the shelf life of food products by offering properties such as antimicrobial activity (in the case of chitosan) and oxygen barriers (in the case of cellulose) (14,15).

2.2.2. Challenges such as mechanical weakness and moisture sensitivity

Despite their advantages, biodegradable polymers face several challenges that limit their widespread adoption in food packaging. One major drawback is their mechanical weakness. For example, natural polymers like starch and cellulose often exhibit brittleness and poor mechanical strength when used alone, making them unsuitable for applications that require high durability. Moisture sensitivity is another significant limitation. Many biodegradable polymers, such as starch-based materials, are highly susceptible to water absorption, which can degrade their structure and compromise their barrier properties. These limitations necessitate blending biodegradable polymers with other materials or incorporating additives, such as plasticizers or nanomaterials, to improve their mechanical and moisture resistance (16,17).

These issues highlight the importance of continued research to optimize biodegradable polymers for broader application in the food packaging industry. Researchers are working on innovative approaches such as nanocomposite materials, where nanoparticles are incorporated into biopolymer matrices to enhance their mechanical, thermal, and barrier properties without compromising biodegradability (17,18).

3. Nanotechnology in biodegradable films

3.1. Introduction to nanotechnology in food packaging

Nanotechnology is a cutting-edge approach used to enhance the performance of biodegradable food packaging films. Nanomaterials, due to their nano-scale dimensions, provide large surface areas and unique properties that significantly improve the mechanical strength, barrier properties, and antimicrobial activities of packaging materials. Incorporating nanoparticles into biodegradable matrices addresses (19). limitations such as poor mechanical strength and high sensitivity to moisture in conventional biodegradable polymers. Nanotechnology helps in improving the overall functionality of biodegradable films, thus prolonging food shelf life and ensuring better food quality and safety during storage (20,21).

3.2. Types of nanomaterials used

3.2.1. Metal nanoparticles (e.g., ZnO, Ag)

Metal nanoparticles, particularly Zinc Oxide (ZnO) and silver (Ag), are well known for their antimicrobial properties and are widely used in biodegradable films. AgNPs have strong antimicrobial effects against a broad spectrum of bacteria and fungi, making them ideal for food packaging that aims to extend the shelf life of perishable goods. These nanoparticles also enhance the mechanical and barrier properties of the packaging, reducing the permeability of gases like oxygen and moisture, which are key factors in food spoilage (22). ZnONPs also exhibit antimicrobial activity and provide UV protection, which helps maintain food quality by preventing oxidative degradation caused by light exposure (23,24).

3.2.2. Biopolymer-based nanoparticles (e.g., nanocellulose, chitosan nanoparticles)

Nanocellulose, derived from renewable plant sources, has excellent mechanical properties, making it a preferred additive for enhancing the tensile strength of biodegradable films. The high aspect ratio of nanocellulose also improves the barrier properties, reducing the transmission of water vapor and gases, which is critical for food preservation. Chitosan nanoparticles, known for their biodegradability and antimicrobial effects, are another key biopolymer-based nanomaterial. When incorporated into packaging films, chitosan nanoparticles offer both physical protection and active preservation of food by preventing microbial growth (25,26)

3.2.3. Other nanostructures

Other nanostructures, such as carbon-based nanomaterials and nanoclays, are also utilized in the development of nano-enhanced biodegradable films. Nanoclays, in particular, are layered silicate materials that improve the film's barrier properties by creating a tortuous path for gas and moisture molecules. This layered structure makes the films more resistant to the passage of oxygen and water vapor, thereby extending the shelf life of packaged foods. Carbon nanotubes, due to their extraordinary strength and conductivity, are used in some packaging applications to improve the mechanical and thermal properties of films (27,28)

Table.1. Overview of nanoparticles used in biodegradable packaging films.

Nanoparticle	Main Benefits	Applications	Challenges	References
Silver (Ag)	Strong antimicrobial properties	Perishable goods (e.g., meat, dairy)	Risk of migration, cost of production	(22,29,30)
Zinc Oxide (ZnO)	UV protection, antimicrobial activity	Fresh produce	Potential toxicity, regulatory concerns	(23,24,31)
Nanocellulose	Enhanced mechanical strength, moisture barrier	All types of food packaging	Sensitivity to moisture	(27,32)
Chitosan	Biodegradable, antimicrobial	Meat and dairy, dry goods	Brittle, needs blending with other polymers	(33-35)
Carbon Nanotubes (CNTs)	High mechanical strength, thermal conductivity	High-performance packaging	Expensive, potential environmental concerns	(29,36,37)
Nanoclays	Improved gas and moisture barrier	Fresh produce, meat products	Layer alignment, processing complexity	(36,38)
Graphene Oxide	Enhanced moisture resistance, antimicrobial, thermal stability	High-barrier food packaging	Cost, potential toxicity	(39,40)

3.3. Advantages of nano-enhanced biodegradable films

3.3.1. Improved mechanical, barrier, and antimicrobial properties

The incorporation of nanomaterials into biodegradable films offers several significant advantages. Firstly, mechanical properties are considerably improved. Nanoparticles like nanocellulose and silver enhance the tensile strength and flexibility of the films, which is crucial for maintaining the integrity of packaging during transportation and storage. Secondly, the barrier properties of the films are enhanced, reducing the permeability to gases such as oxygen and carbon dioxide as well as to water vapor. This improved barrier function is key to preventing spoilage and maintaining the freshness of food products (36,37).

Another important benefit is the antimicrobial activity provided by nanomaterials like silver, chitosan, and ZnO. These nanoparticles actively inhibit the growth of pathogenic bacteria and fungi, reducing the risk of contamination and spoilage. This antimicrobial effect is particularly useful for packaging perishable food products, extending their shelf life and reducing food waste. Overall, nano-enhanced biodegradable films represent a promising advancement in sustainable packaging solutions, combining environmental friendliness with improved functionality (32,38,41).

3.3.2. Advantages of nano-enhanced biodegradable films

The integration of nanomaterials into biodegradable films significantly enhances their performance, offering benefits such as improved mechanical strength, antimicrobial properties, and barrier functions. However, each nanomaterial exhibits unique properties, applications, and challenges, which may also influence food safety and sensory attributes. Table 2 provides a detailed comparison of the key nanomaterials used in food packaging, highlighting their benefits, specific applications, challenges such as nanoparticle migration and toxicity, and their sensory impacts on food products.

Table.2. Comparative overview of nanomaterial properties in nano-biodegradable films.

Nanoparticle	Benefits	Applications	Challenges	Sensory Impacts	References
Silver (AgNPs)	Antimicrobial, mechanical strength	Perishable goods (meat, dairy)	Migration, cost	Metallic taste in food	(22,29,30)
Zinc Oxide (ZnO)	UV protection, antimicrobial activity	Fresh produce, dairy products	Toxicity concerns, regulatory	Subtle changes in taste/smell	(23,24,31)
Nanocellulose	Mechanical strength, barrier function	All food types	Moisture sensitivity	Generally neutral	(27,32)
Nanoclays	Gas and moisture barrier	Fresh produce, meat products	Processing complexity	Minimal impacts	(36,38)

4. Key biopolymers used in nano-biodegradable films

4.1. Cellulose-based films

Cellulose-based films are among the most widely researched and applied biodegradable materials in food packaging due to their excellent film-forming capabilities, abundance, and biodegradability. Nanocellulose, derived from natural cellulose sources, offers significant advantages, including high tensile strength, flexibility, and transparency, which make it an ideal material for packaging applications. These films provide effective barriers against oxygen and oils, which are essential in maintaining food freshness. Additionally, nanocellulose-based films are often combined with other materials or nanoparticles, such as silver or ZnO, to improve their antimicrobial properties, further enhancing food preservation capabilities. One limitation of cellulose-based films is their sensitivity to moisture, which affects their performance under high-humidity conditions. To address this, researchers are exploring the incorporation of hydrophobic coatings or blending cellulose with other biodegradable polymers (33,42).

4.2. Starch-based films

Starch-based films have gained attention as a sustainable alternative to synthetic plastics due to their biodegradability and availability from renewable sources such as corn, potatoes, and cassava. These films are typically inexpensive to produce and possess good film-forming properties. However, starch films have several limitations, including brittleness and high-water sensitivity, which can compromise their mechanical and barrier properties in moist environments. To overcome these challenges, researchers are incorporating nanoparticles like nanoclays or using plasticizers to improve flexibility and moisture resistance. Blending starch with other biopolymers, such as polyvinyl alcohol or cellulose, has also shown promise in enhancing its mechanical properties and water resistance, making starch-based films more suitable for food packaging applications (34,43).

4.3. Chitosan-based films

Chitosan, a biopolymer derived from chitin, is well known for its antimicrobial properties, biocompatibility, and biodegradability, making it highly suitable for use in food packaging. Chitosan-based films form a natural barrier against microbes, extending the shelf life of perishable food products by inhibiting the growth of bacteria and fungi. Additionally, these films exhibit good oxygen barrier properties, which help prevent oxidation in packaged foods. However, chitosan films tend to be brittle, and their mechanical properties can be improved through the incorporation of plasticizers or blending with other polymers. Recent studies have also explored combining chitosan with nanoparticles, such as ZnO or AgNPs, to further enhance its antimicrobial and mechanical properties (35,44).

4.4. Other biopolymer matrices (e.g., pectin, gelatin)

Other biopolymers like pectin and gelatin are also widely used in the development of biodegradable films for food packaging. Pectin, extracted from plant cell walls, is commonly used for its film-forming abilities and biocompatibility. Pectin-based films exhibit good gas barrier properties, making them ideal for preserving the freshness of packaged foods. However, pectin films can be sensitive to moisture and often require blending with other polymers or the addition of plasticizers to improve their durability and water resistance. Gelatin, derived from collagen, is another biopolymer known for its excellent film-forming properties and flexibility. Gelatin-based films are commonly used for their transparency and mechanical strength, but they are also sensitive to moisture. To address this issue, researchers have experimented with adding nanomaterials, such as nanoclays, to enhance the moisture resistance and mechanical properties of gelatin-based films (31,45).

Table.3. Comparative overview of nanomaterial properties in nano-biodegradable films.

Nanoparticle	Benefits	Applications	Challenges	Sensory Impacts	References
Silver (AgNPs)	Antimicrobial, mechanical strength	Perishable goods (meat, dairy)	Migration, cost	Metallic taste in food	(22,29,30)
Zinc Oxide (ZnO)	UV protection, antimicrobial activity	Fresh produce, dairy products	Toxicity concerns, regulatory	Subtle changes in taste/smell	(23,24,31)
Nanocellulose	Mechanical strength, barrier function	All food types	Moisture sensitivity	Generally neutral	(27,32)
Nanoclays	Gas and moisture barrier	Fresh produce, meat products	Processing complexity	Minimal impacts	(36,38)

5. Properties and performance of nano-biodegradable films

5.1. Mechanical properties

The mechanical properties of nano-biodegradable films are significantly enhanced by the incorporation of nanomaterials such as nanocellulose, nanoclays, and metal nanoparticles. These nanomaterials act as reinforcing agents, improving the tensile strength, flexibility, and elongation at break of the films. For example, the addition of nanocellulose to biodegradable matrices has been shown to increase tensile strength and modulus while maintaining film flexibility. This makes the films more durable and resistant to mechanical stress during food packaging, transportation, and storage. Additionally, nanoclays incorporated into the matrix of biodegradable films enhance not only the mechanical strength but also thermal stability, making the films suitable for a wider range of food packaging applications (32,46).

5.2. Mechanical properties

Barrier properties, particularly the ability of the film to block gases such as oxygen, water vapor, and carbon dioxide, are crucial in food packaging to prevent spoilage. Nano-enhanced biodegradable films typically exhibit improved barrier properties due to the presence of nanoparticles that create a tortuous path for gas molecules, thereby reducing permeability. Nanoclays, for example, have a layered structure that effectively acts as a barrier, improving the resistance to gas and moisture transmission. Nanocellulose also contributes to reducing water vapor permeability, making the films more suitable for packaging perishable foods. Moreover, the incorporation of metal nanoparticles like silver and ZnO further enhances barrier properties by providing additional antimicrobial benefits, which are critical in maintaining food safety (47,48).

5.3. Antimicrobial and antioxidant properties

The integration of antimicrobial agents, such as silver and ZnONPs, into biodegradable films offers significant benefits for food packaging by inhibiting the growth of bacteria, fungi, and other microorganisms. These nanoparticles release ions that disrupt microbial cell membranes, effectively reducing microbial activity on the surface of the packaging and extending the shelf life of the food product. Additionally, natural antioxidants such as essential oils or polyphenols can be incorporated into the film matrix, providing protection against oxidation processes that cause food degradation. Antioxidant properties are particularly important for preventing lipid oxidation in high-fat foods, thus enhancing the overall quality and shelf life of packaged products (27,33).

5.4. Biodegradability

The integration of antimicrobial agents, such as silver and ZnONPs, into biodegradable films offers significant benefits for food packaging by inhibiting the growth of bacteria, fungi, and other microorganisms. These nanoparticles release ions that disrupt microbial cell membranes, effectively reducing microbial activity on the surface of the packaging and extending the shelf life of the food product. Additionally, natural antioxidants such as essential oils or polyphenols can be incorporated into the film matrix, providing protection against oxidation processes that cause food degradation. Antioxidant properties are particularly important for preventing lipid oxidation in high-fat foods, thus enhancing the overall quality and shelf life of packaged products (31).

6. Applications of nano-biodegradable films in food packaging

6.1. Fresh produce

Nano-biodegradable films are widely applied in the packaging of fresh produce, as they offer enhanced barrier properties that help in reducing the respiration rate of fruits and vegetables. This is essential in extending the shelf life of fresh produce by minimizing moisture loss and gas exchange, which typically accelerates spoilage. Incorporating nanomaterials such as nanocellulose and ZnONPs has been shown to reduce oxygen and water vapor permeability, which helps in maintaining the freshness and nutritional value of fruits and vegetables for longer periods. Additionally, silver and copper nanoparticles incorporated into biodegradable films offer antimicrobial properties that protect fresh produce from microbial contamination during storage. These antimicrobial properties are especially valuable in organic produce packaging, where synthetic preservatives are avoided (29,50).

6.2. Meat and dairy products

Nano-biodegradable films play a crucial role in the packaging of meat and dairy products, which are highly susceptible to spoilage due to microbial growth. The antimicrobial properties of nanoparticles such as silver, ZnO, and chitosan are particularly effective in reducing bacterial contamination, thus extending the shelf life of meat and dairy products. These nanoparticles disrupt microbial cell membranes, preventing the growth of pathogens such as *Escherichia coli* and *Salmonella* on the surface of packaged meat. Additionally, nano-biodegradable films enhance oxygen and moisture barrier properties, preventing the oxidation of fats and the loss of moisture, which are primary factors leading to the degradation of meat and dairy products. For dairy products, particularly cheese, these films are also beneficial as they help in controlling the moisture content, reducing the risk of mold formation, and preserving texture (30,51).

6.3. Dry goods and snack foods

For dry goods and snack foods, nano-biodegradable films are employed to provide protection from moisture, light, and oxygen, which can affect the quality and crispness of the products. Incorporating nanoclays or carbon nanotubes into biodegradable films improves their mechanical strength and barrier properties, thus preventing moisture ingress and maintaining the texture of snack foods over extended periods. Furthermore, these films can be engineered to have active packaging features, such as releasing antioxidants or other compounds that can enhance the shelf life of the packaged dry goods. This application is particularly relevant for snacks that contain oils or other perishable components that are prone to oxidation (26,35).

6.4. Sensory impact of nano-biodegradable films

The interaction between nanomaterials in biodegradable films and food products can significantly influence sensory attributes such as taste, odor, and texture. Sensory properties are critical for consumer acceptance, as even minor changes can affect the perception of food quality.

6.4.1. Nanomaterial influence on sensory attributes

AgNPs: While widely used for their antimicrobial properties, AgNPs have been reported to impart metallic or bitter tastes to food products under certain conditions. Migration of AgNPs into food can interact with food components, particularly in acidic or high-temperature environments, altering flavor profiles. Studies have shown that optimizing nanoparticle concentration and coating methods can help minimize such effects.

Zinc Oxide (ZnO) Nanoparticles: ZnONPs provide UV protection and antimicrobial functionality; however, their migration into food matrices has been linked to sensory alterations, including subtle changes in taste or smell (22,29,30). Controlled release mechanisms and encapsulation techniques are being explored to mitigate these impacts.

Nanocellulose: Nanocellulose, derived from natural plant sources, has been widely recognized for improving mechanical and barrier properties without significantly affecting food sensory attributes. However, its use in combination with other nanomaterials (e.g., AgNPs or ZnO) may indirectly influence food odor or texture due to synergistic interactions.

To address these concerns, recent studies have focused on developing surface modifications and encapsulation techniques that reduce the migration of nanomaterials into food products. Additionally, sensory evaluation studies are being conducted to identify thresholds at which nanomaterials impact food taste, odor, or texture. Such research is critical for ensuring that nano-enhanced packaging meets both functional and sensory quality standards (27,32).

Figure 1 provides a schematic representation of the progression involved in nano-enhanced biodegradable food packaging. It starts with the selection of biodegradable materials, followed by nanotechnology incorporation to improve mechanical, barrier, and antimicrobial properties. The key challenges such as nanoparticle migration, sensory impacts, and regulatory hurdles are highlighted, leading to various applications in food packaging and their sustainability implications.

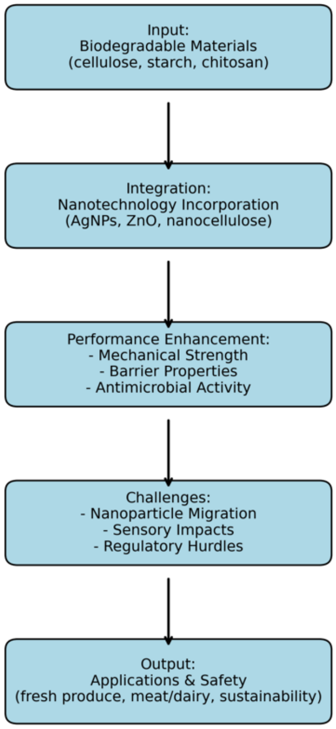

Fig.1. Overview of the development and applications of Nano-Enhanced Biodegradable Food Packaging.

7. Regulatory and safety considerations

7.1. Food safety concerns related to nanomaterials

The use of nanomaterials in food packaging has raised important concerns regarding food safety. Nanoparticles, due to their extremely small size, exhibit unique properties that may pose health risks when they migrate into food products. One of the primary concerns is the potential toxicity of nanoparticles such as silver, ZnO, and titanium dioxide, which are commonly used for their antimicrobial and barrier properties. Studies have shown that nanoparticles can penetrate biological membranes and interact with cells, potentially leading to cytotoxic, genotoxic, and inflammatory responses.

AgNPs, for example, have been extensively studied, with some findings indicating that prolonged exposure can lead to the accumulation of silver ions in tissues, which may cause adverse health effects. However, the risk depends on the concentration and size of the nanoparticles, as well as the duration of exposure (52). Regulatory agencies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) have recommended specific guidelines for the use of nanomaterials in food packaging to mitigate these risks, but further research is required to fully understand the long-term effects. Additionally, there is growing concern about the migration of nanoparticles into food, particularly when packaging materials are exposed to high temperatures or acidic environments, which can accelerate nanoparticle release. This is especially relevant for packaging applications that come into direct contact with food during cooking or heating, such as microwavable trays and containers. To address these concerns, scientists are working to develop more stable nanocomposite materials that minimize the potential for nanoparticle migration, thus improving the safety of nano-enhanced packaging materials (39,53).

7.1.1. Nanoparticle migration and its implications

One of the primary concerns surrounding the use of nanomaterials in biodegradable food packaging is the potential migration of nanoparticles into food products. Nanoparticle migration occurs when particles detach from the packaging matrix and transfer into the food, particularly under specific conditions such as high temperature, acidic environments, or prolonged contact. This phenomenon raises significant food safety concerns due to the unique physicochemical properties of nanoparticles, such as their small size, high surface reactivity, and ability to interact with food components. The extent of nanoparticle migration depends on several factors, including:

- **A. Nanoparticle Type and Size**: Smaller particles, such as AgNPs and ZnONPs, are more likely to migrate due to their high mobility and surface area.
- **B. Food Properties**: Acidic and high-fat foods tend to enhance the migration process because they can destabilize the packaging matrix, facilitating nanoparticle release.
- **C. Temperature and Time**: Elevated temperatures, such as those encountered during microwaving or hot storage, accelerate the breakdown of packaging materials, increasing nanoparticle migration rates.
- **D. Packaging Composition**: The interaction between nanoparticles and the polymer matrix (e.g., nanocellulose, chitosan) also determines their retention within the film. Weak bonding or improper dispersion of nanoparticles in the matrix can result in higher migration levels (27,32).

7.1.2. Health and regulatory implications

The migration of nanoparticles poses potential health risks, as studies have shown that certain nanoparticles, such as AgNPs and ZnO, can penetrate biological membranes and accumulate in tissues, leading to cytotoxic or genotoxic effects (39,52). To mitigate these risks, regulatory agencies such as the EFSA and the U.S. FDA have developed guidelines for the safe use of nanomaterials in food packaging. These guidelines emphasize the need for migration testing, risk assessments, and ensuring that nanoparticle concentrations remain within permissible limits. For example, the EFSA requires detailed studies on nanoparticle migration and their potential toxicity before approving nano-enhanced materials for food contact applications (40). Recent efforts to reduce nanoparticle migration include:

A) Developing stronger nanocomposite matrices to improve nanoparticle retention.
B) Employing surface coatings or encapsulation methods to stabilize nanoparticles and prevent their release.
C) Conducting advanced migration studies under simulated food storage and usage conditions to ensure compliance with safety standards.

By addressing the risks of nanoparticle migration and adhering to stringent regulatory requirements, nano-enhanced biodegradable films can provide safer and more sustainable packaging solutions without compromising food safety (54).

7.2. Environmental regulations and standards

Environmental regulations governing the use of nanomaterials in food packaging are evolving as the potential risks and benefits become better understood. Many countries, particularly in the European Union, have implemented strict guidelines on the use of nanotechnology in food-related applications. The European Union's REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) framework is one of the most comprehensive regulatory systems, requiring manufacturers to provide detailed data on the environmental and health impacts of nanomaterials used in food packaging. This regulation ensures that nanomaterials do not pose a risk to human health or the environment before they are approved for use in consumer products. The EFSA also plays a significant role in assessing the risks of nanomaterials and recommending safety measures. In the U.S., the Environmental Protection Agency (EPA) and the FDA have established guidelines to regulate the use of nanomaterials in food packaging, emphasizing the need for manufacturers to conduct safety assessments before introducing new nanotechnologies to the market. These agencies require data on how nanomaterials are produced, their potential environmental impacts, and their behavior during the disposal and degradation of packaging materials. Globally, environmental standards are moving towards encouraging the development of sustainable nanomaterials that are not only safe for food contact but also minimize environmental pollution after disposal. This has led to an increased focus on biodegradable nanocomposites that break down more easily in the environment, thus reducing the ecological footprint of packaging materials (40,55).

8. Future trends and challenges

8.1. Innovations in nanomaterials for food packaging

Nanotechnology continues to drive innovation in the development of food packaging, with the introduction of advanced nanomaterials that enhance the properties of biodegradable films. Recent advancements include the incorporation of metal-organic frameworks (MOFs) and bio-based nanoparticles into packaging materials, which significantly improve gas barrier properties and provide antimicrobial effects. MOFs are highly porous structures that effectively trap gases such as oxygen and carbon dioxide, thereby preventing oxidation and spoilage of food products. Another promising innovation is the use of biopolymer-based nanoparticles, such as cellulose nanofibrils and starch nanoparticles, which enhance the mechanical strength and flexibility of films, making them more durable for packaging applications. Additionally, graphene oxide and other carbon-based nanomaterials have shown potential in providing enhanced moisture resistance, thermal stability, and antimicrobial properties, making them suitable for preserving a wide variety of perishable goods. These innovations are shaping the future of food packaging, as they not only extend shelf life but also reduce the need for synthetic preservatives (56,57).

8.2. Challenges in commercialization

Despite the technological advancements in nanomaterials for food packaging, commercialization faces several significant challenges. One of the primary issues is the cost of production, as many nanomaterials, such as carbon nanotubes and AgNPs, are expensive to produce at a scale. This high cost makes it difficult for manufacturers to offer cost-competitive products compared to conventional packaging materials. Moreover, the complex regulatory landscape surrounding the use of nanotechnology in food packaging adds further hurdles to commercialization. Regulatory bodies such as the FDA and EFSA require extensive safety assessments and approval processes before nanomaterials can be used in packaging, which can delay product development and increase costs. There are also concerns about consumer acceptance of nanotechnology in food packaging, as many consumers are wary of the potential health risks associated with nanoparticles. Overcoming these challenges will require significant investment in research, clear regulatory pathways, and increased public awareness about the safety and benefits of nanomaterials in food packaging (53,54).

8.3 Sustainability and environmental impact

As the food packaging industry strives toward sustainability, the environmental impact of nanomaterials is a growing concern. While many biodegradable films incorporate nanomaterials to improve their properties, the end-of-life disposal of these films remains a critical issue. Nanoparticles, particularly those derived from metals such as silver and zinc, may pose environmental risks if they accumulate in the ecosystem during disposal. Recent studies have focused on developing bio-based nanomaterials that degrade naturally without harming the environment. For instance, nanocellulose and chitosan nanoparticles have been recognized for their biodegradability and low toxicity, making them suitable alternatives for sustainable packaging solutions. Moreover, the Life Cycle Assessment (LCA) of nano-biodegradable films indicates that their environmental footprint is significantly lower compared to conventional plastics, primarily due to the reduced use of fossil fuels and lower carbon emissions during production. Moving forward, continued research on environmentally safe nanomaterials and the development of recycling technologies for nanocomposite packaging will be essential in minimizing the environmental impact of food packaging (25,58,59).

9. Conclusion

The development and application of nano-biodegradable films represents a significant advancement in the field of sustainable food packaging. These films, enhanced by the incorporation of nanomaterials such as nanocellulose, AgNPs, and ZnO, exhibit improved mechanical properties, barrier functions, and antimicrobial activity, which collectively contribute to extended shelf life and enhanced food safety. Furthermore, the integration of nanotechnology addresses many of the limitations associated with conventional biodegradable polymers, such as poor mechanical strength and moisture sensitivity, making them more suitable for a wide range of food packaging applications. However, the commercialization of these materials remains hindered by high production costs, complex regulatory requirements, and concerns regarding the migration of nanoparticles into food. Despite these challenges, the environmental benefits of using biodegradable nanocomposite films, such as reduced reliance on fossil fuels and decreased plastic waste, underscore their potential to significantly impact the food packaging industry.

Looking forward, continued research into the development of bio-based nanomaterials will be essential in overcoming the current challenges faced by nano-biodegradable films. Innovations such as the use of Metal-Organic Frameworks (MOFs) and green synthesis methods for producing nanoparticles are promising areas for improving both the functionality and sustainability of these films. Additionally, there is a growing emphasis on the development of biodegradable nanocomposites that are not only safe for food contact but also capable of degrading without leaving harmful residues in the environment. Future research should also focus on improving the economic viability of nanotechnology in food packaging, perhaps through the exploration of cost-effective production methods or the use of alternative, abundant nanomaterials. Regulatory frameworks will need to evolve alongside these innovations to ensure the safe and responsible use of nanomaterials in packaging, balancing the benefits of extended food preservation with the need for consumer safety and environmental protection. With sustained advancements in material science and a clear regulatory pathway, nano-biodegradable films hold the potential to become a mainstream solution for sustainable food packaging.

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11. Conflict of interest

The authors claim there is no conflict of interest.

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