SUSTAINABLE FOOD PACKAGING

TOWARDS A GREENER TOMORROW

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Contents

Introduction to Food Packaging

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1. Introduction:

Food packaging encompasses materials and engineering technologies to preserve food products. This research arena not only deals with the traditional roles of protecting food from various spoilage factors like microbial attack, damage during handling, and transportation, but also with the modern features highly vital to the food market at large, e.g., traceability, regulatory compliance, and so forth [1, 2]. In due course of time, there have been a plethora of advancements from the earlier methods like clay pots, etc., with robust integration of technological innovation, especially in the realms of active, intelligent, and sustainable packaging [3-5].

Regarding the evolution of the food packaging domain, the origin traces back to the utilization of natural materials such as plant fibers, skins of animals, etc. [6]. Lately, during the mid-20th century, the imminence of the industrial revolution and scientific progress, witnessed an evolution from the production of tinplate cans to the application of plastics such as polyethylene, thereby enabling lightweight and cost effective solutions [7, 8]. Digitization and technological developments led to the introduction of barcode systems in the 1970s and created a digitalized supply-chain ecosystem [9].

Since then, this field has made significant strides. The overall landscape of packaging technologies has shifted to three major arenas: active entities, intelligent functional features, and sustainable materials [10]. Active packaging involves directly using elements like antimicrobial substances, moisture absorbers and oxygen scavengers in the packaging material, thereby enhancing shelf life and safety parameters.

Although this method is well-established, there is a need for continuous improvement and novel discoveries to meet consumer demands for fewer preservatives [11-14]. Intelligent or smart packaging uses sensors, Radio Frequency Identification/Near Field Communication systems, and so forth, which can monitor the factors causing food spoilage and other important aspects. Despite gaining widespread attention, high production costs and a lack of regulatory protocols impede usage and marketability [15-18]. Parallelly, sustainable packaging has garnered prominence, in which biopolymers (e.g., polylactic acid, polybutylene adipate terephthalate, etc.) and agricultural waste composites have been employed to prepare films. Some of the major benefits include improved barrier properties and alignment with the circular economy goals [19-22]. Another innovation in the food packaging sector lies in the introduction of modified atmosphere packaging (MAP), which encompasses the adjustment of the gaseous environment inside the packaging films, thus allowing real-time regulation of gas and eliminating the limitations of passive oxygen exclusion in the earlier packaging methods [23-26].

Despite the continuous innovation in designing state-of-the-art packaging technologies, there are multitudes of challenges associated with this field, especially in regulatory compliance and the quality of packaging. Specific frameworks of EFSA and USFDA regarding the regulation of recycled plastic polymers in direct contact of the food products for several applications and several other rules of different countries address the need to harmonize protocols with sensor validation, data integrity, and fostering transnational research to identify the gaps and adhere to the guidelines [27, 28]. Furthermore, functional food packaging for specialized nutritional requirements is an emerging research trend that poses distinct safety and labelling limitations, for which extensive trial, testing, and validation are prerequisites.

In this regard, this chapter presents a robust overview of food packaging systems, beginning from foundations, to an in-depth examination of the diverse substances utilized in packaging, classification of various methods, and technological progress pertaining to food packaging. Moreover, this chapter enlists the global regulatory landscapes, and the myriad challenges associated with regulatory compliance. Therefore, this chapter aims to support the creation of harmonized approaches within the framework of food packaging, for research, policy-making, and industrial perspectives.

2. Overview of Food Packaging

Food packaging entails the techniques employed to conserve the functionality of food systems from development, distribution, and finally, dissipation. It revolves around the fulfilment of four major functions: containment, protection, preservation, and communication, to accomplish a holistic objective of delivering safe and effective foods and overseeing environmental sustainability at large (Figure 1) [8, 18, 29, 30]. At first, containment ensures that various food products are secured by the packaging system to promote safe and efficient handling and disposal, thereby mitigating the losses incurred during the transportation and storage phases. Secondly, protection indicates that the food products are shielded from microbial attacks, mechanical damages, chemical and environmental factors, such as moisture, etc. It emphasizes maintaining the food attributes and ensures that the food safety levels are not tampered with. Thirdly, preservation focuses on the prolongation of the storage stability of the food products by leveraging various technologies dedicated to the retardation of microbial contamination and food spoilage, thereby ensuring that the sustainability goals are attained and food wastage is minimized. Lastly, communication deals with the printed and digital labelling of food products to provide detailed information pertaining to nutritional profiles, storage conditions, and safety alerts. This introduces transparency in consumer behavior and helps recall the products that have been spoiled or led to the development of complications after consumption, thus aiding in the nuanced regulation of food items [31, 32]. Collectively, these ensure that food security and structural integrity of the food products are maintained at the highest levels, and swift action can be taken if there is a breach in the safety measures pertaining to food production and marketing.

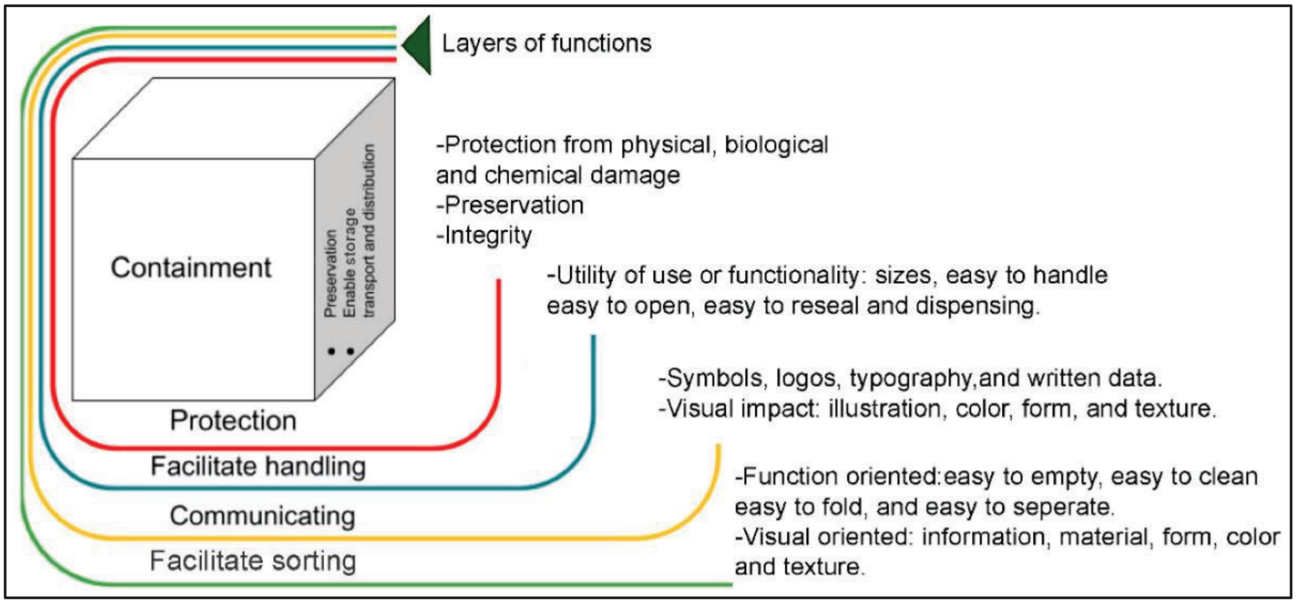

Figure 1:

Schematic representation of the different functions of food packaging
(Taken from [33] under CC BY license).

Transitioning to the global scale of food packaging, it represents about 40% of the total packaging materials generated worldwide, particularly within the plastic domain [34, 35]. This highlights the continued dominance of food grade packaging to meet the growing demands and protect the factors, such as convenience and food safety, which are now some of the top priorities in the markets. Several studies have projected that the market size of the food packaging sector will shoot up to USD 463.65 billion by the year 2027, which demonstrates the necessity and industrial importance of this domain in terms of economy and consumer trends (Figure 2) [2]. However, this has created sustainability issues due to the generation of plastic waste, thus giving rise to myriad challenges like recycling effectiveness, lifecycle emissions, and so forth. Thus, there is a urgent requirement for the development of sustainable practices in food packaging, which has now been a major focus of several government organizations and industries at large [36].

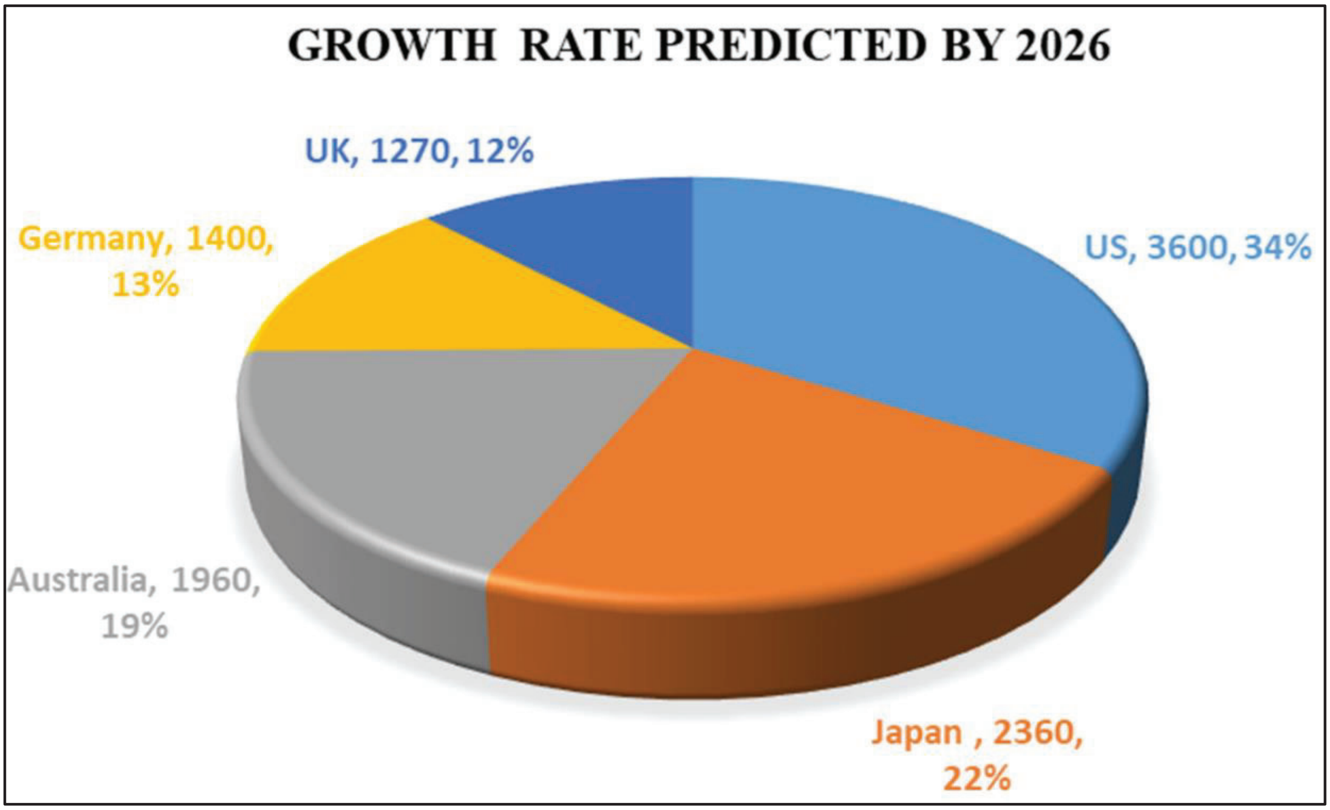

***Figure 2**:*
Pie chart representing the projected market growth of food packaging by 2026
(Taken from [37] under CC BY license).

Another important factor pertaining to food packaging is food waste. Multiple investigations have reported that efficient food packaging has resulted in the drastic reduction of food wastage (Figure 2). This has been confirmed through intensive lifecycle assessments, which have reiterated that the adoption of sustainable ways in packaging food items has not only resulted in mitigating global food insecurity but also in combating greenhouse gas emissions and other detrimental environmental factors. However, these advantages are heavily reliant on the choice of materials, recyclability, and adoption of robust frameworks for promoting sustainable and circular economy [38-40]. Although food packaging has revolutionized the food industry at large, inappropriate handling and disposal mechanisms can give rise to severe environmental issues. Therefore, this necessitates technological advancements and extensive research that can induce functional superiority coupled with environmental sustainability, which have been elucidated in the following sections of this chapter.

3. Structural Hierarchy and Material Selection in Food Packaging

A prerequisite for optimizing food packaging efficacy is a comprehensive analysis of the architectural configurations and the diverse substrates utilized across different food systems is a necessary requirement. In this context, packaging is a multi-layered system that is essential to every step of the food supply chain, from storage and processing to retail and distribution. Additionally, the correct choice of materials in food packaging largely governs the functional performance and the consumer appeal of the packaged food items. Thus, this section discusses a holistic purview of the layered architecture of food packaging and the different components utilized to design robust food packaging models.

3.1 Food Packaging Levels: Primary, Secondary, and Tertiary

Food packaging is a multifaceted system comprising a hierarchical architecture to assure that the food items are protected in compliance with all the regulatory protocols and maintain their safety. In this context, there are primary, secondary, and tertiary levels of food packaging (Figure 3). Primary food packaging encompasses the first and the most critical interface between the food products and the external surroundings. The core function of this level of packaging revolves around the containment and subsequent protection from various contaminating agents. It ensures that the overall quality and safety of the food items are maintained at the highest standards. Furthermore, it holds a pivotal role in preserving the aroma and various flavor components by preventing undesirable chemical or biochemical reactions that can result in the degradation of food attributes, thereby causing a profound impact on the consumer appeal. This aids in reducing food wastage, due to food spoilage and contamination attacks on a larger scale [41, 42]. Another aspect of this packaging level focuses on adhering to the regulatory guidelines delineated by several regulatory authorities (e.g., USFDA, etc.). This emphasizes that the packaging materials remain inert and retard the alterations in nutritional and organoleptic characteristics of the packaged food products. Additionally, it ensures that all the necessary information regarding the packaged product is vividly displayed on the packaging label, encompassing batch numbers, ingredients, allergen declarations, detailed instructions for usage, and so forth, for strict and proper compliance with the labelling and safety requirements and post-market monitoring [43, 44].

Concerning the secondary level of food packaging, it functions as a critical intermediary layer by encasing units of primary-packaged food products, to ensure efficacious handling, confer protection to the products during the storage and transportation phase, improve logistics across the food supply chain, and prolong the storage stability of the packaged items at large. Unlike primary packaging levels, this layer does not involve direct exposure to the food products. Instead, it acts as a mechanical shield by employing materials, like corrugated cardboard boxes, plastic crates, etc., streamlining operational efficiency and the robust palletization of food items for cost-effective transportation and retail distribution [41, 45].

Finally, the tertiary level of food packaging depicts the outermost layer in the hierarchy of food packaging that involves the preservation and effective mobility of the food items during the storage and distribution phase. Some of the major operational benefits revolving around this level encompass organized stacking of the food items, enhancing the efficacy of logistics operations through systematic micromanagement of the distribution of food products, and so forth [44, 45]. In summary, these levels guarantee the packaged food items' safe and economical distribution and transportation by preserving the food product's integrity along the supply chain.

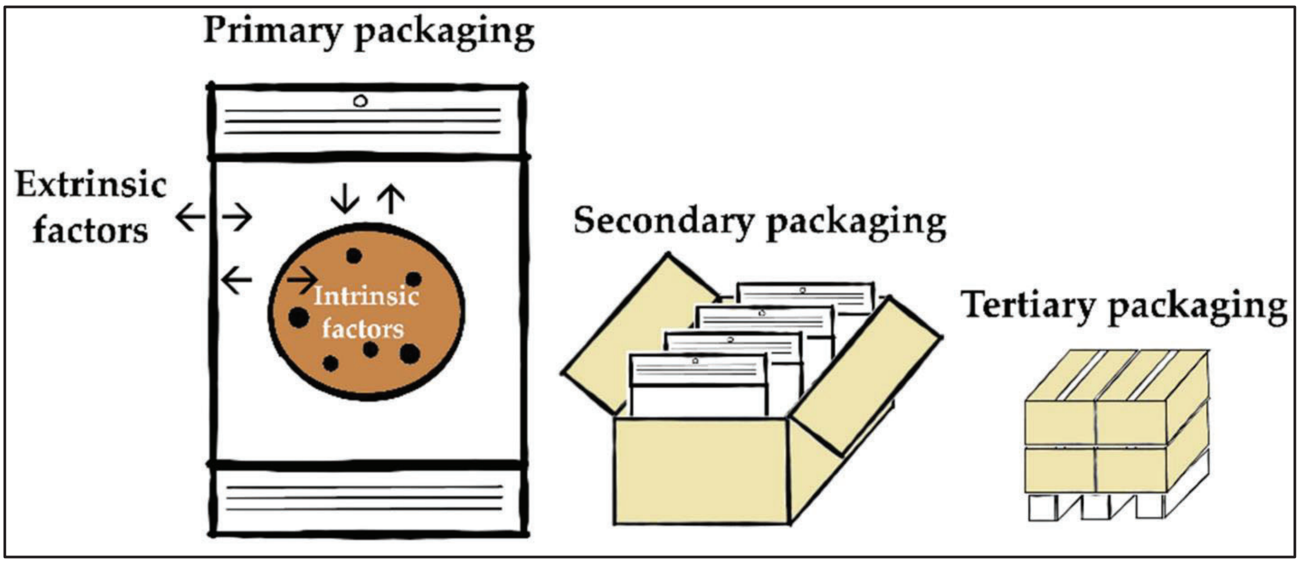

Figure 3:
Schematic representation of the different levels of food packaging
(Taken from [46] under CC BY license).

3.2 Materials utilized for the packaging of food materials

The foundations of food packaging lie in the choice of the correct materials to ensure that the quality and safety of the food items are not compromised at any step along the food supply chain. This part enlightens the various kinds of substances employed in the fabrication of robust food packaging methodologies, ranging from traditional materials (Figure 4) to the new and emerging ones, their advantages and limitations, thus providing comprehensive insights into the foundations of food packaging designs.

3.2.1 Traditional materials

3.2.1.1 Plastic

In food packaging, plastics represent the most predominant class of synthetic materials for several reasons, including versatile behavior, lightweight nature, cost-efficiency, etc. The origin of plastics stems from the petrochemical materials extracted from fossil fuels, like oil, coal and natural gas [47]. Some of the most prevalent composite polymers involved in the formation of plastics from condensation reactions include polyethylene (PE) in varying densities like low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyamide (PA), polyethylene terephthalate (PET), polystyrene (PS), polyvinylidene chloride (PVDC), ethylene-vinyl alcohol (EVOH), etc. Furthermore, polyolefins have been examined to contain improved barrier attributes and are now extensively employed in creating films for food packaging films, beverage packaging, and so forth. Additionally, plastic additives have been employed to fortify the durability of the plastics used to package food items of diverse nature [48, 49]. However, several drawbacks are associated with using plastics in food packaging. The first limitation pertains to the chemical migration of these harmful plastic additives into food products, which can cause serious health issues. Secondly, these plastics are not only causing pollution through the deposition of microplastics and other compounds, but also inflicting a concurrent depletion of fossil fuels, thus contributing to the greater environmental concerns pertaining to plastic-based food packaging [50, 51].

3.2.1.2 Glass

Glass remains among the earliest packaging materials used in the food industry for multiple reasons, including transparency, chemical inertness, robustness, rigidity, etc.

It is prepared from naturally abundant raw materials, such as silica, limestone, etc., thereby rendering it environmental-friendly and perceived as one of the ideal choices for beverage packaging, and so forth. Some of the most significant advantages of glass packaging lie in the fact that its chemically inert nature does not cause impairment of odor or other sensorial characteristics of the packaged food items, it is impervious to moisture, and can be easily recycled. However, some of the major limitations of its use lie in its brittleness, fragility, and high mass, which incur hefty losses during the transportation and storage phases. Nevertheless, due to the properties of reusability, recyclability, and minimal chemical interaction with the packaged food items, it remains one of the best choices in the field of food packaging [41, 52].

3.2.1.3 Metal

Metal-based packaging has become increasingly important in food packaging applications because of several benefits, such as conferring protection against moisture, light, gas, etc., easiness of being molded into various shapes as per requirements (e.g., aluminum foil, drawn and redrawn container, three-piece cans, two-piece cans, aluminum bottles, etc.), potential to sustain high temperatures, robust and rigid architecture, and so forth. The primary metals employed include aluminum, tin plate, and various forms of polymer-coated steel. However, the two disadvantages of metal-based food packaging encompass migration and interaction phenomena. These can promote corrosion of the metals involved in the design of the packaging forms, thereby imparting serious health concerns. Furthermore, studies have highlighted the profound negative environmental impact of metal-based food packaging systems, thus pressing a need to find alternative ways of food packaging design [52, 53].

3.2.1.4 Paper and Cardboard

Alongside plastics, glass, and metals, paper- and cardboard-based materials are commonly used in food packaging applications, owing to several reasons, which include biodegradability, renewability, low cost, printability, and so forth. Despite these advantages, numerous drawbacks revolve around its use, including limited imperviousness to moisture, gas, and other agents, low mechanical robustness, etc. [52, 54]. These limitations have warranted the use of coatings and other methods to alleviate these drawbacks and thereby positioning cellulose-based materials as key contributors to environmental sustainability in modern packaging system for food.

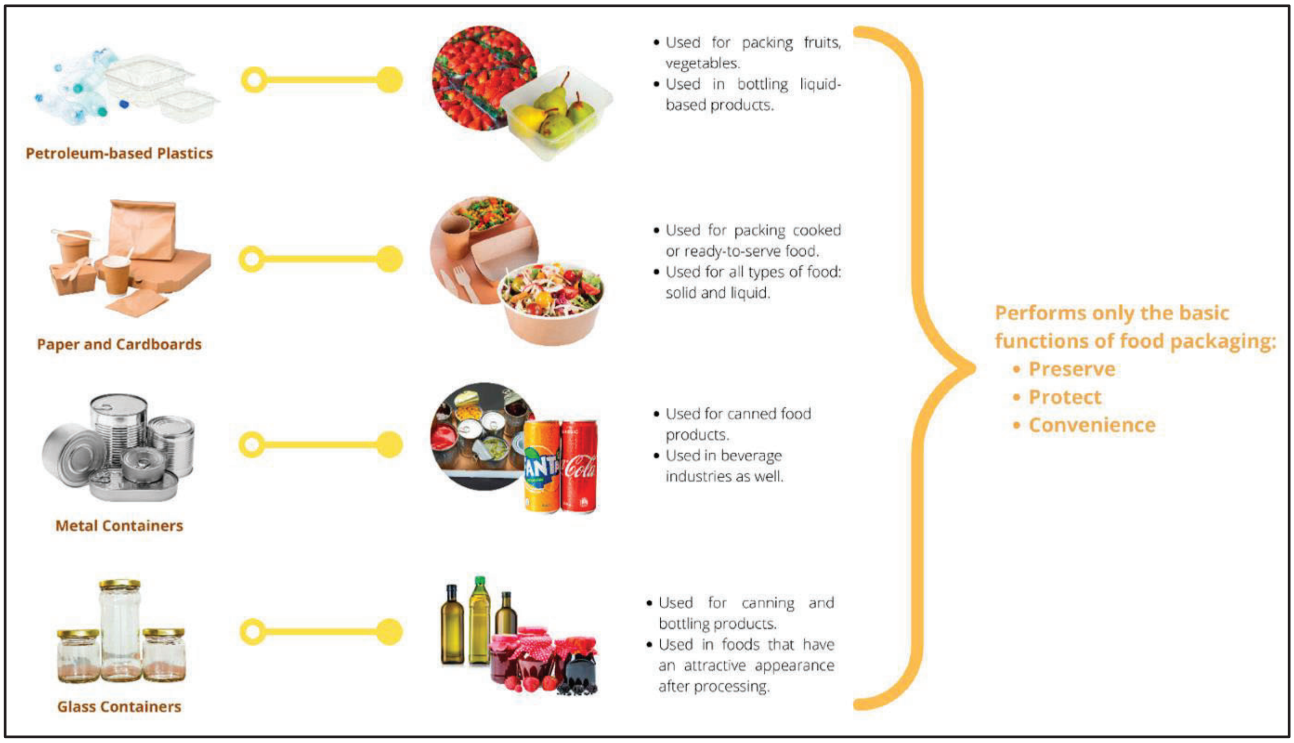

Figure 4:
Different types of conventional food packaging techniques along with their utilities (Reproduced from [55] under CC BY license)

3.2.2 New and Emerging Materials

3.2.2.1 Bio-based materials and bioplastics

Due to the limitations posed by the conventionally sourced materials, the food packaging industry is witnessing a massive transformation in creating packaging designs for food with human wellness and the environment in focus. Bio-based materials and bioplastics have surfaced as potential substitutes to petroleum-based synthetic polymers in food packaging (Figure 5). These include materials primarily sourced from sustainable sources, including plants, fungi, algae, etc., and can be classified broadly into three major types, namely, naturally derived polymers, bio-synthesized polymers, and bio-based chemically identical alternatives to conventional plastics [56, 57]. The first category, naturally derived polymers, represents the materials that are directly extracted or undergo minimal processing from various biological sources (e.g., cellulose, hemicellulose, starch, chitin/chitosan, pectin, soy protein, casein, etc.) [58, 59]. On the contrary, bio-synthesized polymers are sourced from microbial fermentation processes or via metabolic engineering of several microorganisms. One of the most predominant groups in this category is polyhydroxyalkanoates (PHAs), which represent a community of polyesters that are produced intracellularly by different bacterial strains in nutrient-limited environments (e.g., polyhydroxybutyrate (PHB)). Although these materials possess immense importance owing to their environment-friendly nature and functionality, the scalability and cost impede commercial use [60]. Lastly, the third category, bio-based chemically identical substitutes to traditional plastics, also called drop-in bio-based plastics, denote the polymers procured from renewable feedstocks, such as sugarcane, corn starch, and possess a chemical architecture similar to the fossil-derived plastics. These primarily encompass bio-polyethylene terephthalate (bio-PET), bio-polyethylene (bio-PE), and others sourced from corn, sugarcane, etc. Interestingly, these materials are not biodegradable, but can be subjected to rigorous processing and recycling steps, thus acting as agents of initiating the circular economy [61, 62]. Some of the significant advantages presented by these materials include enhancing functional versatility, providing environmental sustainability, contributing to lower life cycle emissions, and so forth. Despite these advantages, several technical limitations exist, including high feedstock and production expenses, reduced mechanical strength and barrier characteristics in comparison to petroleum-derived plastics, etc. [63]. Consequently, additional investigations are needed to overcome these challenges, especially the functional lacunae.

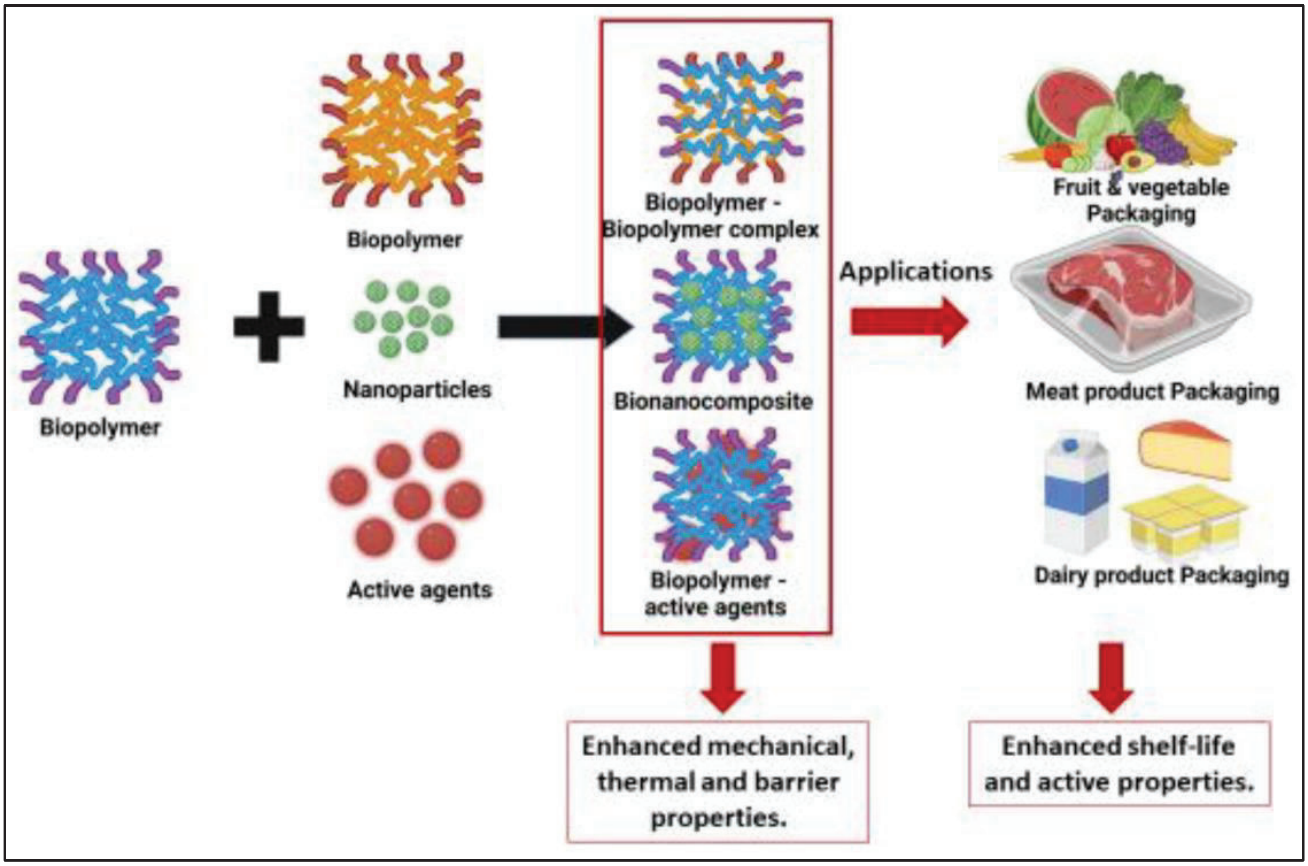

Figure 5: *Diagrammatic representation of the applications of bio-based polymers or biopolymers in food packaging (Taken from [63] under CC BY license).*

3.2.2.2 Edible films and coatings

Edible films and coatings represent the packaging substances employed as wraps and pouches around the food material (Figure 6). Interestingly, these packaging designs form an integral part of the food product, thereby eradicating the need to unpack these packaging materials for the consumers [64, 65]. Some of the materials employed in the fabrication of these packaging architectures encompass polysaccharides (e.g., starch, cellulose, pectin, etc.), proteins (e.g., pea protein, whey protein isolate, collagen protein, etc.), and lipid components (e.g., carnauba wax coating, beeswax coating, etc.) [66]. Several investigations have emphasized the significance of these packaging materials in food commodities, like fruits, vegetables, dairy meat products, etc. [67, 68]. Although these materials are gradually gaining attention in the packaging application in food sector, one principal limitation is the number of active agents leached out into the food products via diffusion. This can cause drastic alterations in the color and aroma of the packaged food items, thereby rendering them toxic and non-edible for consumers [66, 69]. Future research is a requisite to remove these limitations and emphasize it as an efficient approach in creating sustainable food packaging designs.

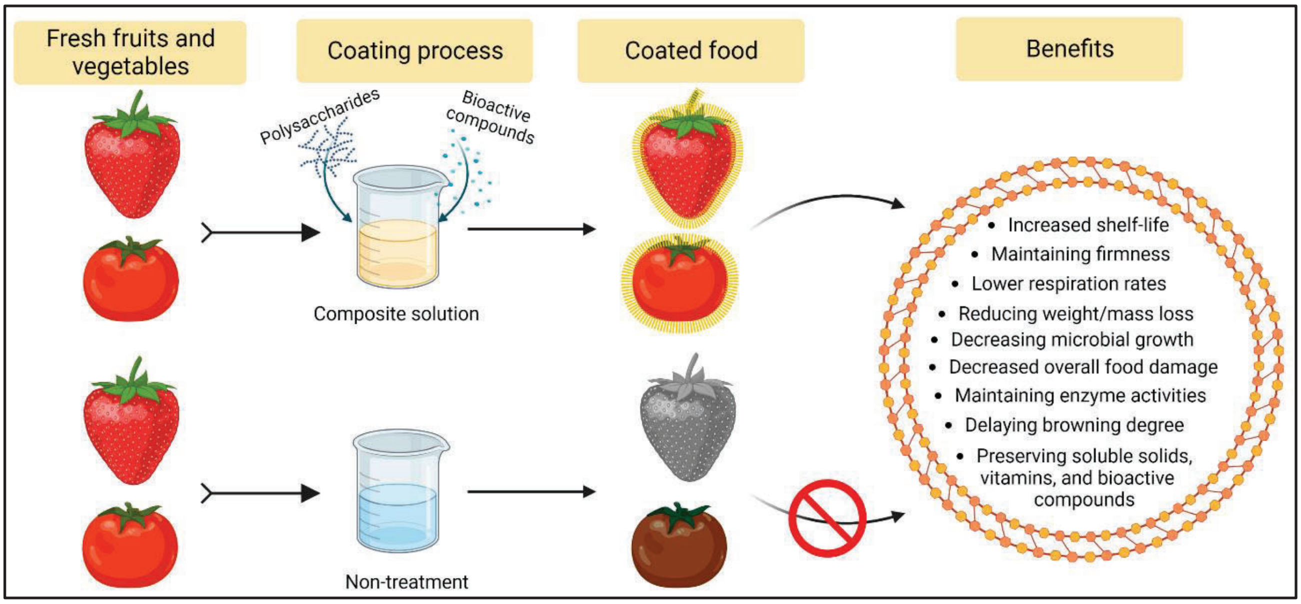

Figure 6: *Schematic representation of the application of polysaccharide-based edible films and coatings in preserving fruits and vegetables (Taken from [70] under CC BY license).*

3.2.2.3 Nanomaterials and nanocomposites

Nanomaterials and nanocomposites represent another diverse class of materials falling under the field of nanotechnology that has recently gained widespread recognition in revolutionizing the food industry. Previous research has demonstrated that using these materials in food packaging enhances the organoleptic characteristics of the packaged food commodities, such as shelf-life, texture, etc. [71, 72]. These materials are generally classified into two major categories, namely inorganic and organic. Inorganic ones typically include transition metals (e.g., copper, gold, etc.), non-metals (e.g., silicates, selenium), metal and their oxides (e.g., silver, zinc oxide, titanium dioxide, etc.), and so forth. On the other hand, the organic ones encompass nanocellulose, starch nanoparticles, etc. These materials have demonstrated excellent barrier properties, antimicrobial activity, improved mechanical attributes, etc. [73-75]. However, one of the major drawbacks associated with using these materials revolves around the phenomenon of migration, in which the materials diffuse inside the packaged food product and alter the physicochemical characteristics of the food items. This makes the food toxic to humans and thereby renders the food product non-consumable [76]. In this context, further investigations are warranted to ensure that the migration is avoided and that these materials can be used in an environmentally friendly way for food packaging. Figure 7 demonstrates the advantages of employing bionanocomposites in food packaging over conventional food packaging techniques.

Figure 7: *Benefits of using bionanocomposites in food packaging compared to traditional food packaging systems (Taken from [77] under CC BY license).*

4. Different types of food packaging methods

Food packaging aims to preserve packaged food commodities from the surrounding environment and several other agents that can destroy the inherent characteristics of food items at large. Although there are multitudes of food packaging methods pertaining to the fabrication of robust food packaging designs, this section presents a thorough insight into the modern and advanced food packaging methods that have emerged as predominant methodologies for food preservation at large.

4.1 Active Packaging Method

Active packaging technique has surfaced as a innovative method in the context of food preservation, transcending from the barrier functionality of traditional food packaging designs to an interactive entity capable of performing multiple roles, including shelf-life extension as well as the maintenance of quality and safety of packaged food products. (Figure 8) [78, 79]. The technique can be broadly categorized into non-migratory active packaging systems (NMAPS) and active release packaging systems (ARPS). NMAPS involve the use of absorbers or scavengers to remove undesirable substances from the package environment without intentional migration. Oxygen scavenging is among the most commonly studied NMAPS approaches, as it regulates headspace oxygen levels to enhance shelf life and product stability. In contrast, active release packaging systems (ARPS) belong to the class of emitting-type packaging systems, in which desired gases are released into the package environment to effectively preserve the quality of the packaged food products [12, 80]. Antimicrobial active packaging systems (AAPS) represent a newer class of active packaging technologies that aim to suppress microbial proliferation in packaged foods, ensuring product stability and preventing unwanted alterations. This is achieved by embedding natural antimicrobial agents within the packaging matrix, allowing their controlled release to the food surface or packaging headspace, thereby suppressing microbial activity [81, 82]. Despite these benefits, there are several limitations related to using active packaging systems. At first, incorporating antimicrobial agents can potentially decrease barrier characteristics, crystallinity, etc., and utilizing oxygen scavengers can promote the proliferation of anaerobic microorganisms. Moreover, the consumer acceptance of active packaging is still not very high, owing to the high production costs involved, compared to other forms of packaging. This necessitates further research to remove the drawbacks and improvise the active packaging designs, in alignment with the current consumer demands, commercial applications, etc. to achieve the goal of sustainable food packaging at large.

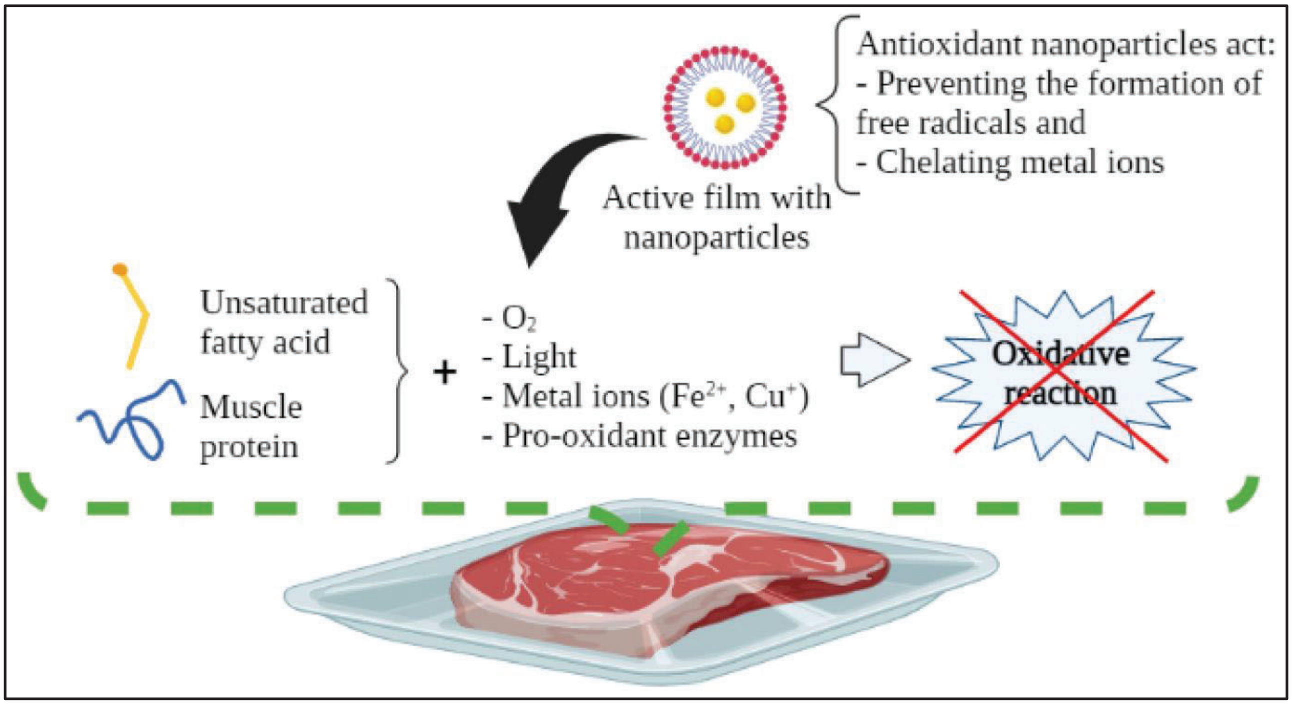

***Figure 8**: Active packaging system reinforced with nanoparticles for antioxidant activity in muscle foods (Taken from [83] under CC BY license).*

4.2 Intelligent Packaging Method

Intelligent packaging (IPK) epitomizes a major upgradation in food packaging by the incorporation of sensor and indicator systems to proactively monitor and provide constant updates pertaining to the state of the food commodities in packet in real time (Figure 9). It offers a holistic advantage over traditional food packaging concepts due to the potential to deliver instantaneous insights on the security and condition of food items. This is achieved via several tools, which include indicators, sensors, data carriers (e.g., RFID, barcodes, etc.), and biosensors in the packaging materials. Subsequently, the systems are created with the ability to detect, record and convey alterations occurring inside the package or in the surroundings [84, 85]. Unlike active packaging, smart packaging doesn't come into close contact with food items but is limited to monitoring their status.[86, 87]. The amalgamation of these two packaging concepts has given rise to innovative packaging methods, which impart more advantages than their counterparts. Concerning the mechanism of action, intelligent packaging involves three major constituents: sensors, indicators, and data carriers. Visual reactions are produced using indicators, such as pH and time-temperature indicators (TTIs) (e.g., changes in color, etc.) when particular thresholds are attained, which can indicate spoilage or other phenomena.

On the other hand, sensors employ chemical and other processes to identify particular analytes, etc., and convert them into signals for quality monitoring applications. Lastly, data carriers (e.g., RFID tags, barcodes, etc.) aid real-time product tracking and traceability throughout the food supply chain [88-90]. Although it offers several benefits and has introduced transparency and live monitoring of the packaged food items at large, several drawbacks need to be addressed meticulously. These are high manufacturing costs, consumer acceptance concerns, and technical challenges associated with them, like the integrity of the sensor under real-life circumstances [16]. Thus, there is a pressing need for more research investigations to create robust IPK designs depending on the market demands, the requirement for cost-effective sustainable solutions, and so forth.

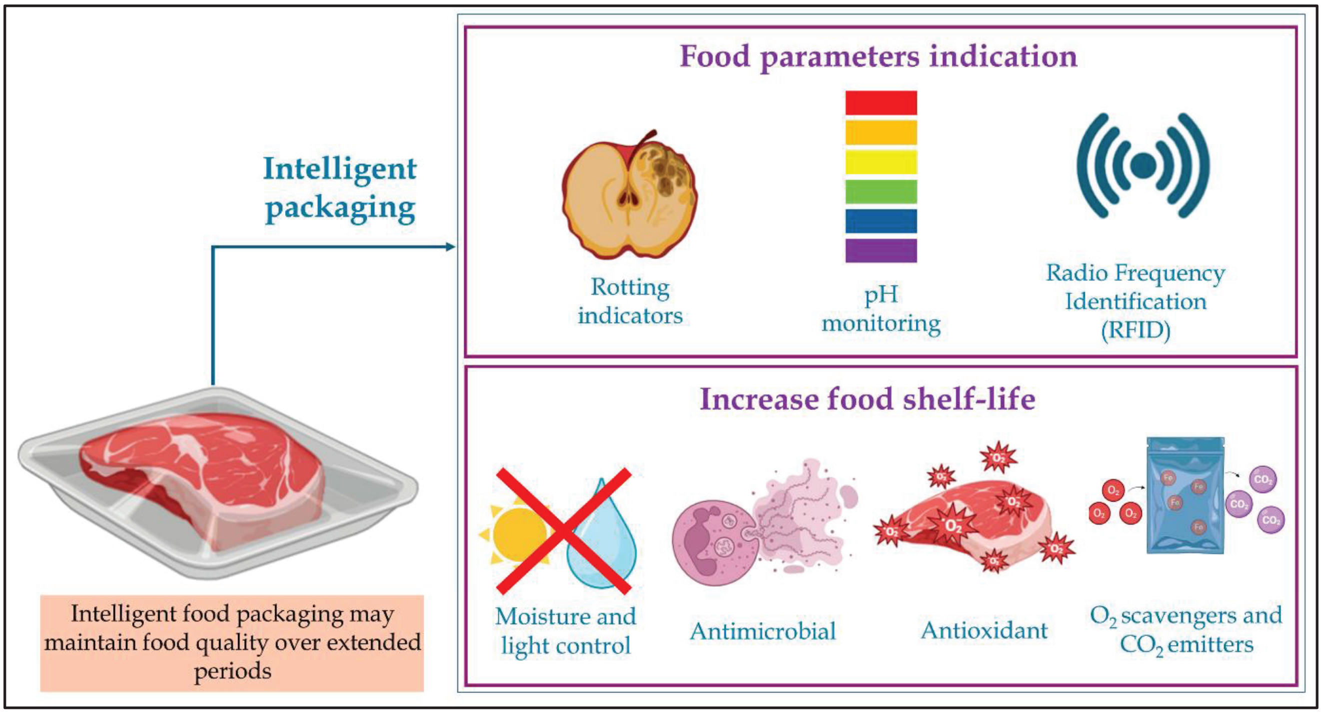

Figure 9: *Schematic representation of the different benefits of intelligent packaging method (Adopted from [91] under CC BY license).*

4.3 Modified atmosphere packaging method

Modified atmosphere packaging (MAPK) represents another form of non-conventional food packaging that deals with the enclosure of different food products within a package in which the atmosphere is modulated to improve the storage stability of the product. The atmosphere inside the package is altered via natural means through respiration processes and gaseous transfer through the packaging material, or by employing gas absorbers or scavengers to achieve a desirable atmosphere within the package [25, 92]. Some commonly used gases in MAPK include nitrogen, oxygen, and carbon dioxide either used as standalone gases or combined with ozone, chlorine, etc, which ensures that the growth and proliferation of various microbes is prevented (Figure 10) [93, 94]. Additionally, it decreases reliance on harmful chemical preservatives, thus helping create clean-label products [95]. Nevertheless, its efficacy is heavily dependent on optimizing gas mixtures, the packaging film properties, respiration and spoilage phenomena, and so on. Therefore, harmonized and systematic research methods need to be adopted to alleviate these drawbacks and fortify MAPK to be integrated into sustainable food packaging technologies for improved packaging attributes, and so forth.

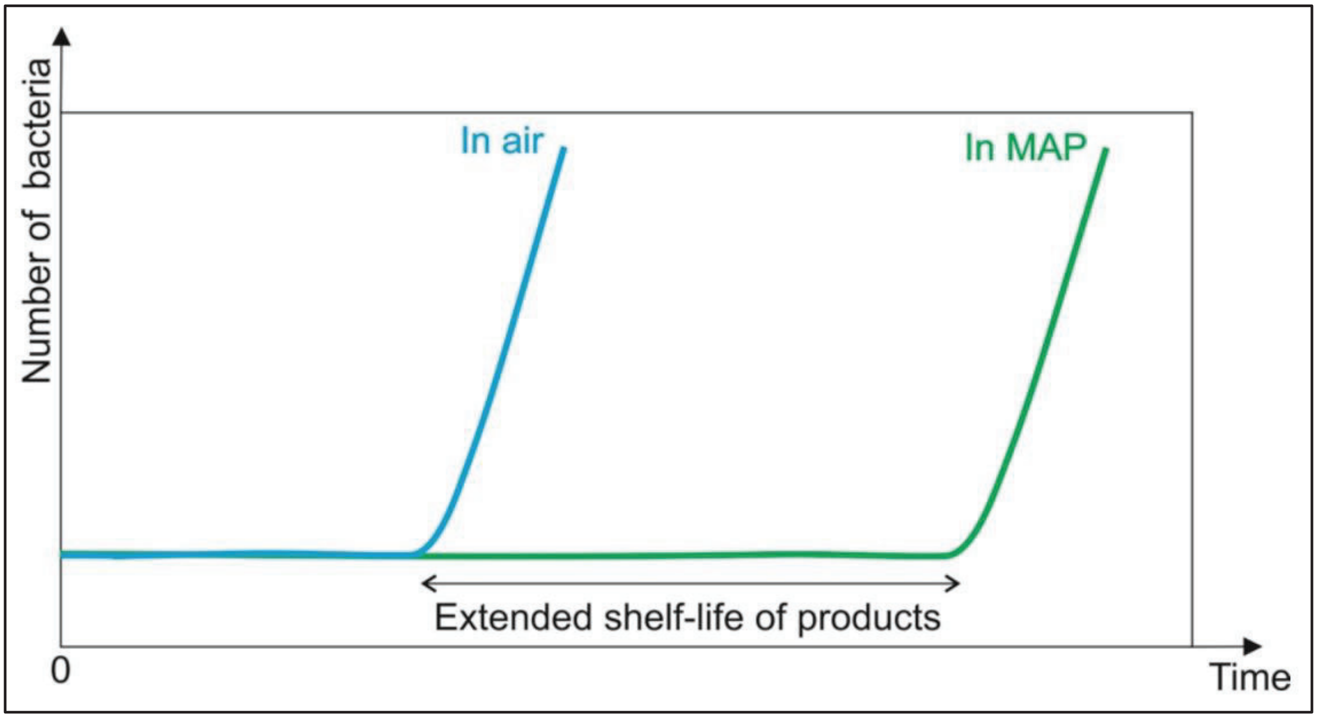

Figure 10: *Graphical representation of the shelf-life of products with and without modified atmospheric food packaging (Adopted from [96] under CC BY license).*

5. Regulatory Landscape and Safety Concerns

The regulatory environment and safety issues surrounding food packaging are dictated by several factors, including national laws, international standards, and emerging sustainability frameworks. These are constantly changing to address the recent environmental concerns and consumer safety, and the primary aim of these regulations is to ensure that the substances employed in food packaging does not produce adverse health hazards or mislead consumers through falsified labelling claims. In this regard, the European Union (EU) has developed robust and comprehensive laws and regulations that mandate clear labelling without any false claims and necessitate scientific evidence for any health or environmental claims declared on packaging. Furthermore, the Packaging and Packaging Waste Directive (PPWD) and the proposed Packaging and Packaging Waste Regulation (PPWR) of the EU are focused on the theme of environmental sustainability, and emphasize the use of reusable materials for packaging purposes [45, 97]. Similarly, there has been constant emphasis on sustainable food packaging among the national laws of various countries, like India, South Korea, the United States, etc. One of the most significant arenas that is gaining increasing attention among the lawmakers is chemical safety [36]. Compounds like phthalates, bisphenol A, and per- and polyfluoroalkyl substances (PFAS) have come under stringent laws owing to their carcinogenic attributes [98]. Although the regulations are constantly changing and being updated to address these threats, a considerable gap exists between the detection and analysis of these compounds and the foundations of these laws. Therefore, rigorous investigations, market surveys, verification of labelling claims, and several other measures need to be integrated to make these laws stricter and more adaptive to the dynamic scenario of the food packaging sector.

6. Conclusion and Future Perspective

The packaged food sector has undergone a dynamic transformation from conventional containment strategies to multifaceted, novels innovations in packaging sector for food to address the persistent issues of food security, safety, quality, functionality, etc. This section addresses detailed insights into the hierarchy of packaging materials for food-primary, secondary, and tertiary levels, followed by an in-depth analysis of both the traditional and emerging packaging materials, and a comprehensive enlightenment on the various methodologies employed in food packaging. Although conventional materials like plastics, glass, etc., predominate the food packaging industry owing to their reliability and affordability, their use has been associated with several environmental and health concerns, prompting the need for alternate, long-lasting solutions. Promising substitutes with improved barrier qualities, antibacterial effectiveness, and real-time monitoring capabilities include bio-based polymers, edible coatings, nanomaterials, and nanocomposites. Additionally, developments in packaging systems including active packaging, intelligent packaging, and modified atmosphere packaging (MAP) have enabled the food industry to prolong storage stability, enhance safety, and mitigate food waste while meeting the demands of modern consumers for transparency and traceability. Notwithstanding these transformations, several limitations persist, such as material migration risks, cost barriers, and scalability challenges. Moreover, these regulatory frameworks are fragmented and unable to adapt to the global changes, with a requirement for constant updation of these laws to vindicate better and improved food packaging designs for sustainability and consumer appeal. future investigations must prioritize enhancing the scale of production, mechanical characteristics, and functional versatility of the materials used in food packaging, and continuous life cycle and risk assessments must be performed to verify the impact of food packaging on the food items.

Food packaging systems from carbohydrates

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1. Introduction

Carbohydrates, especially polysaccharides, form the basis of packaging systems for food preservation. The preponderance of food packaging polymers is typically derived from various types of carbohydrates [99]. Carbohydrates are the preferred material of choice for the synthesis of biopolymers employed in food packaging due to diverse reasons, including superior material strength, optimal barrier properties, and the possibility of extending additional functions including antimicrobial and antioxidant properties, which are essential in specific food packaging systems [100]. Carbohydrates include a diverse array of biomacromolecules. Carbohydrates are generally classified based on their monomeric units, such as monosaccharides (only one monomeric unit), disaccharides (two monomeric units joined together with a glycosidic linkage), oligosaccharides (three to ten monomeric units), and polysaccharides (more than ten monomers to a million) [101]. Out of all these, polysaccharides form the basis of food packaging. Monosaccharides, disaccharides, and oligosaccharides may be used as an additive ingredient, but never used as the film-forming agent [102]. Polysaccharides are generally utilized as film-forming agents in packaged food system. They represent a wide variety of carbohydrate molecules, from simpler homopolymers to more complex heteropolymers. Homopolysaccharides consist of recurrent units of a single type of carbohydrate, like starch, cellulose, glycogen, phytoglycogen, and pectin. On the other hand, heteropolysaccharides, which consist of different types of carbohydrate monomeric unit, consists an even broader range of compounds, such as various gums and hydrocolloids [100, 101, 103].

Out of all these biomolecules discussed above, starch and cellulose have been explored to a greater extent than gums and hydrocolloids [102]. However, in recent times, gums and hydrocolloids have been explored even further for the fabrication of packaging substances for food [103]. Starches are usually isolated from a wide array of foods, such as rice, corn, wheat, sorghum, potatoes, and sago. Apart from these conventional sources, starch can also be isolated from other sources, including the seeds of fruits such as mango, jackfruit, jamun, and litchi [104]. Starch contains two principal macromolecular component: amylose, characterized by linear and exists as a single helical coil, and amylopectin, which exhibits extensively branched and complex in structure [105]. However, since the molecule is formed from one monomeric unit of α-D-glucose, it is categorized as a homopolymer. Nonetheless, the starches differ from one another according to their crystallinity patterns as observed in the x-ray diffractogram. On this basis, starches are grouped into three categories, namely A-type, B-type, and C-type starches, with C-type starches typically comprising a mixture of A-type and B-type crystalline forms [106, 107].

Cellulose, on the other hand, is produced from a specific isomer of glucose referred to as β-D-glucose and is linked by β-glycosidic bonds [108]. Although starch and cellulose are structurally distinct, both materials exhibit excellent film-forming properties [108, 109]. These biopolymers have been extracted from various sources. Apart from conventional sources, starch and cellulose have also been sourced from various non-conventional sources, including agricultural byproducts and waste materials. Subsequently, these biopolymers have been employed in the formulation of packaging films for food [110]. For instance, starch isolated from jackfruit seed, jamun seed, and litchi seed was blended with tamarind kernel hemicelluloses (xyloglucans) for the fabrication of a broad spectrum of composite food packaging materials [111-113]. Furthermore, the performance, functionality, and structural integrity of these starch/hemicellulose composites were strengthened by the incorporation of nanofillers. The first composites consisted of jackfruit seed starch/tamarind seed xyloglucan, which were enhanced by the inclusion of ZnO nanoparticles [111]. Later, jamun seed starch was combined with the same hemicellulose material and chitosan nanoparticles. The antibacterial characteristics of chitosan nanomaterials demonstrated excellent inhibition properties against both

Gram-positive and Gram-negative microorganisms. Also, starch derived from litchi seeds was combined with tamarind kernel xyloglucans and integrated with an organic lignin nanomaterial [113]. However, zinc oxide nanoparticles were selected for their excellent antimicrobial properties and have also received consent from the US FDA for utilization in food-related materials [114]. Chitosan nanoparticles were chosen because they are organic in nature and demonstrate a variety of biological functions, including antimicrobial activity [115]. Lastly, lignin nanoparticles were selected in these studies, as they, like chitosan, are organic in nature and demonstrate powerful antioxidant activities [116].

2. Chemistry of starch and xyloglucan

2.1 Chemistry of xyloglucans

Xyloglucans are a hemicellulose that holds a significant place within the carbohydrate classification. It is derived from diverse dicotyledonous and non-graminaceous monocotyledonous plant cell wall structures [117]. The conformational structure of xyloglucan typically comprises a linear sequence of β-D-glucosyl-linked glucose units, which are intermittently branched with α-1,2-linked xylosyl units [118]. In certain plant species, it has been reported that the xylosyl units are subjected to further branching by the inclusion of galactosyl and fucosyl residues [117, 119]. Xyloglucan has a degree of polymerization between 600 and 700. Among various sources of xyloglucan, tamarind seeds constitute the most prominent source of xyloglucans [119]. Proximate composition analysis shows that tamarind seeds contain more than 50% xyloglucan content. In addition, tamarind kernel xyloglucans demonstrate high stability across a broad array of environmental conditions, including pH variations, temperature fluctuations, and shear stress [120]. It has been recognized for its efficacy as a stabilizer and thickener, finding broad application within the food industry [121]. Xyloglucans are recognized for their capabilities in film formation and are extensively utilized in the formulation of food packaging and coating systems, as well as in encapsulation technologies [122].

2.2 Chemistry of starch

Starch represents one of the most widely available, sustainable, and functionally essential biomacromolecules on Earth. It serves as the principal reserve carbohydrate in higher plants, where it is synthesized and stored primarily in amyloplasts, nonpigmented organelles found in storage tissues such as tubers, seeds, and roots. It is the primary storage carbohydrate in the plant kingdom and provides energy and nutrients for the majority of the animal kingdom, including humans [123]. The biosynthesis of starch involves a complex network of enzymatic reactions, including the actions of branching enzymes, debranching enzymes, and pyrophosphorylase, as well as ADP-glucose starch synthases, which collectively contribute to the formation and organization of starch granules. These granules exhibit considerable morphological diversity, ranging from spherical and oval to lenticular, polyhedral, and flattened shapes relying on the botanical source, developmental stage, and environmental conditions [124]. Structurally, starch comprises of two main polysaccharides: amylose and amylopectin. The linear component, having α-(1→4)-linked D-glucose units and a less branched structure, is termed amylose. While the other component, amylopectin displays a highly branched framework, characterized by frequent α-(1→6) branching points on the α-(1→4)-linked glucose unit backbone. Thus, amylopectin has a much larger and more complex structure in contrast to the linear chain of amylose. The physicochemical characteristics of starch are mostly determined by the relative proportion of amylose to amylopectin, including gelatinization, retrogradation, viscosity, and digestibility. A starch granule primarily consists of amylopectin (70–80%), with amylose making up the remainder of 20-30%. However, these ratios vary significantly between plant species and are influenced by selective breeding or genetic engineering for specific purposes [124, 125]. Interestingly, irrespective of the source and geographical location of starch, they share the same morphology and demonstrate a highly ordered structure. Starch granules exhibit the birefringence feature and take the shape of a "Maltese cross" when seen under a polarizing microscope [126]. Starch granules exhibit a mixture of amorphous and crystalline regions, and when treated with concentrated acids, the amorphous region is generally degraded, leaving the crystalline regions intact [127]. Similar to xyloglucans, starches also exhibit powerful film-forming properties, which are typically employed in the synthesis of packaging films and food coatings. Aside from its biological function as a crucial source of energy, starch has indispensable applications in diverse industrial sectors. In terms of food sector, it is a common gelling agent, thickener, and stabilizer. While, industries outside the food sector, starch is used in paper production, textiles, adhesives, and, more recently, as an environmentally sustainable raw material for the manufacture of biodegradable plastics and biopolymers. Recent developments in starch nanotechnology have made it possible to fabricate starch-based nanoparticles and nanocomposites, thereby improving their functionality for utilization like drug delivery, edible coatings, and active packaging systems. As a biocompatible, biodegradable, and readily available material, starch has remained an important focus of interest as a sustainable material for various applications, extending from agriculture to medicine and materials science.

3. Food packaging systems from starch and xyloglucans

Starches derived from diverse botanical sources have been extensively explored for the formation of edible coatings and films for use in environmentally friendly food packaging. Their natural abundance, biodegradability, film-forming capability, and generally recognized as safe (GRAS) affiliation renders starches as highly attractive alternatives to synthetic polymers. Two primary techniques are employed for fabricating starch-based films: (a) the solvent-casting method and (b) extrusion processing [127]. The solvent-casting process is commonly used in laboratory-scale and exploratory studies because it is easy, inexpensive, and can create homogeneous films with minimal machinery. In the solvent casting process, first, native starch is stirred along with distilled water to obtain a homogeneous solution. Then the combined solution is heated until temperature reaches 80-90 °C to cause gelatinization of the starch. The semi-crystalline granule structure is disrupted by this heat treatment, releasing amylose and amylopectin into the aqueous phase [128]. Additionally, plasticizers like glycerol or sorbitol are incorporated to the mixture. Plasticizers increase the chain mobility of the matrix, which leads to improved flexibility and handling characteristics of the resultant film [129]. After that, the gelatinized starch solution is thoroughly mixed and poured onto a non-stick, smooth surface, such as a Teflon sheet or glass plate, and spread evenly to ensure uniform thickness. Later, the cast solution is dried for several hours at a temperature between 30 °C and 50 °C in an ambient or controlled environment to allow the solvent to evaporate completely [127]. Following the formation of a thin, transparent, or semi-transparent film, the casting surface is carefully peeled off. Finally, the film is stabilized at a particular temperature and humidity level prior to additional examination and use [130]. Although this film is highly efficient for developing biodegradable films, it presents various challenges, such as longer drying times and susceptibility to moisture in hydrophilic starch [127].

The extrusion is another widely employed and industrially scalable process for fabricating starch-based food packaging films. It delivers significant advantages including continuous processing and reduced drying times [131]. Extrusion processing of films involves mixing starch with other substances, like plasticizers, bioactive component and other functional additives. After that, the mixture is fed into an extruder having a heated barrel and a revolving screw. [132]. The starch granules inside the extruder are mechanically broken by the combined effects of heat, pressure, and shear, which causes partial molecular degradation and gelatinization. A molten, uniform substance produced by this thermomechanical process can be processed through a flat die to fabricate thin films [133]. After that, the extruded sheet is calendared, i.e., passed through a sequence of rollers to achieve the required thickness and surface smoothness. Then the film is rapidly cooled to solidify the material [134]. The extrusion technique is more suitable for commercial production than the solvent-casting method due to its compatibility with various starch sources and functional additives. However, optimization and regulation over processing variables, like temperature, moisture content, screw speed, and die configuration, are required to achieve consistent film quality [131]. Despite the complexity associated with extrusion processing, it is extensively applied in the biodegradable food packaging sector due to its effectiveness, speed, and ability to be integrated into existing manufacturing lines.

4. Case studies of carbohydrate-based food packaging systems:

Polysaccharide biopolymers, like cellulose, hemicellulose, and starch, have garnered considerable attraction within research community as a renewable alternative to synthetic plastics used in food packaging (Figure 11). Cellulose and hemicellulose are associated with improved stability and mechanical strength, while starches offer excellent film-forming qualities and transparency. In recent years, research has primarily emphasized on improving the functional characteristics of carbohydrate polymer-based packaging films by inclusion of antimicrobial agents, nanomaterials, and bioactive components. In a previous study, Wang, Li [135] developed starch-based antimicrobial films incorporated with black tea cellulose nanocrystals (BT-CNCs) (5% w/w) for sustainable food packaging. Their observations indicated that the reinforcement of chitosan (CS), ε-polylysine (ε-PL), and ZnO nanoparticles (ZnONP) to the St/CNC matrix significantly uplifted the mechanical, antibacterial and barrier characteristics of the films. The St/CNCs/CS film exhibited a solubility of 17.74%

and tensile strength of 14.23 MPa, which was highest among all the films. ZnO NP incorporated films exhibited excellent antimicrobial characteristics, particularly against *E. coli*.

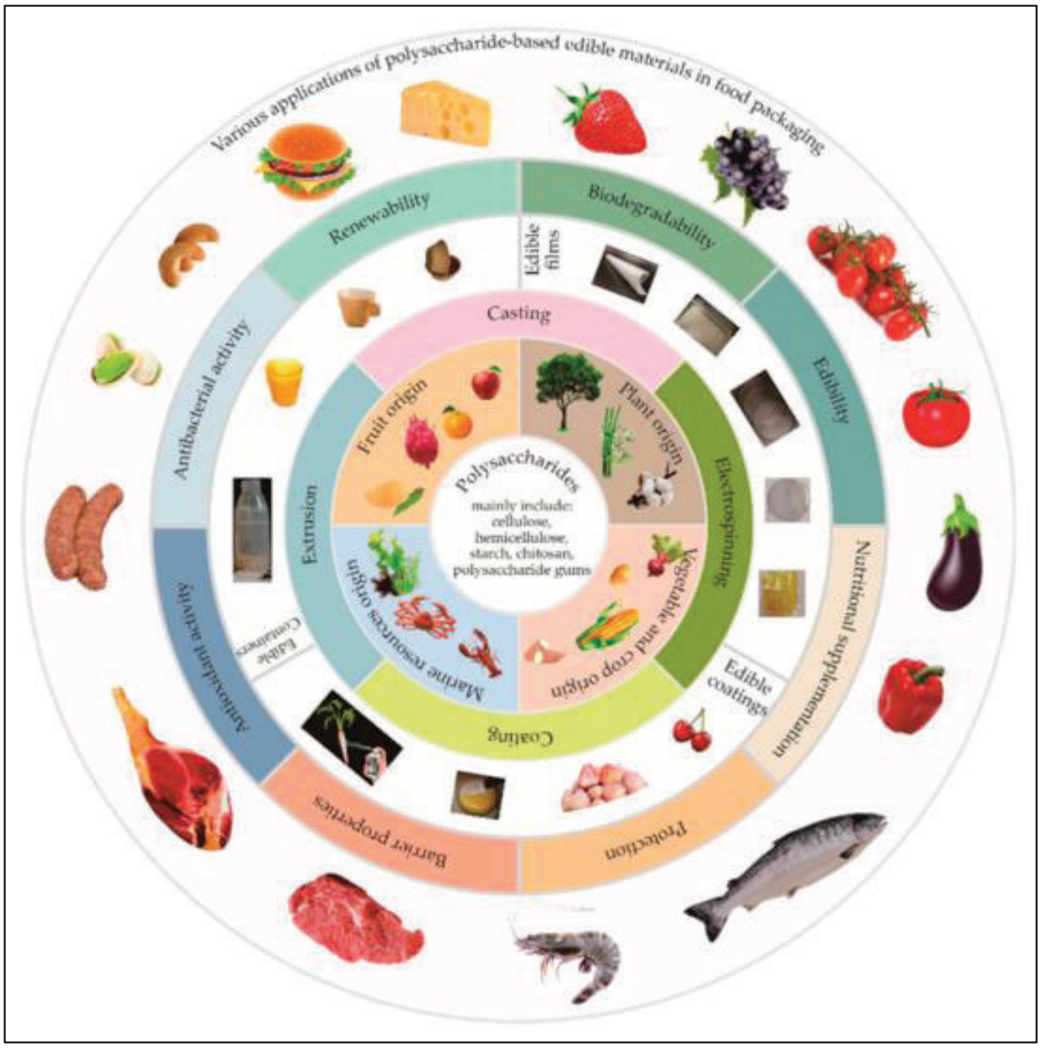

Figure 11: *Application of carbohydrates in food packaging systems (Taken from [136] under CC BY license).*

Similarly, chitosan-starch nanocomposite film integrated with cellulose nanofibers and cinnamon essential oil (CEO) was developed and characterized [137]. The results indicated that the integration of CEO and cellulose nanofibers significantly increased the physico-mechanical and antimicrobial characteristics of the film. FTIR spectra confirmed strong molecular interactions among these film components. A porous and rough surface morphology was observed in SEM results, which indicates well dispersion of the nanofillers. Additionally, the produced films demonstrated improved antibacterial efficacy and antioxidant activity against *S. aureus* and *E. coli*, along with successfully reducing the microbial population during the storage of meat. Another study synthesized carrot derived carbon dots (CDs) and integrated them into starch matrix sourced from corn to formulate an environmentally friendly composite film with excellent freshness-retaining properties [138]. The addition of 512 μg/mL of CDs significantly escalated the antioxidative characteristics of the film, exhibiting an inhibition of DPPH radical scavenging of 92.76%. Moreover, the film, which had 5% CDs, exhibited significant antibacterial efficacy by achieving a 99.9% reduction in both *Escherichia coli* and *Staphylococcus aureus.* The homogeneous distribution of CDs within the starch matrix produced a tightly compact film structure, which enhanced both elasticity and thermal stability. Furthermore, observations indicated the nanocomposite films effectively preserved the characteristic trait of deep-fried meatballs.

Tert-butyl acetoacetate modified starch (m-St) was isolated from avocado seeds, and integrated into a polylactic acid (PLA) matrix by Godoy Zuniga, Ding [139] to develop biocomposites. In comparison to the pure PLA films, the resulting PLA/m-St (1:6) composites demonstrated significantly improved mechanical and barrier characteristics. The UVB-barrier increased from 16.21% to 83.86%, and the Elongation-at-break enhanced from 3.35% to 27.80%. Furthermore, the coatings demonstrated significant improvements in barrier characteristics, reducing water vapor transmission by over 50% and oxygen permeability by 97.53%. This study indicates that starch-based biowaste materials can be valorized into environmentally friendly packaging films with excellent mechanical integrity and performance. Starch-based films are robustly being tailored and blended with other polymers and functional additives to enhance preservation and sensing capabilities for innovative and active packaging. In a recent study, starch was mixed with carboxymethyl cellulose (CMC), anthocyanins, and ZnO nanoparticles (ZnO-NPs) to fabricate multifunctional smart packaging films [140]. The SEM results revealed that the integration of ZnO NPs and anthocyanins led to heterogeneous microstructures, while the crystallinity was slightly reduced, as observed in the XRD analysis. The incorporation of ZnO nanoparticles significantly enhanced the film's ductility, light barrier capacity, and water resistance. However, FTIR results did not show any new peaks, which confirms that there is no interaction between the anthocyanin and ZnO NPs. A hydrophobic shift was observed with the enhancement in ZnO NP percentage, as the water contact angle (surface hydrophobicity) improved from 63° to 114°. The prepared films exhibited significant antibacterial characteristics against *E. coli* and *S. aureus*, even at a concentration of 1% ZnO NPs. Additionally, the films' high pH sensitivity made them appropriate for freshness monitoring. A CMC/starch (80:20) blend containing 3% ZnO nanoparticles, along with 0.1% anthocyanin, was found to be the ideal formulation, with significant promise for use in smart applications in packaging of food.

Antimicrobial food packaging systems

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1. Introduction

A diverse array of synthetic as well as biologically derived polymers have been utilized to fabricate food packaging systems, which have been updated to satisfy the necessity of safe food systems by incorporating various types of additives and fillers [141]. These types of packaging systems for food have been classified as active or bioactive food packaging. This is because these food packaging materials impart additional functions, in addition to their elementary function of containing the food [142]. Among the various category of active food packaging systems, antimicrobial food packaging systems hold a vital position. Antimicrobial food packaging systems are defined as systems that contains an active antimicrobial compound as the active filler [141].

Antimicrobial compounds have been classified based on the sources from which they are derived: (a) plant-derived, (b) animal-derived, and (c) microbial-derived. All these three categories of antimicrobial components have been explored in packaging systems for food in order to create antimicrobial food packaging [143]. Plant-derived antimicrobial compounds are obtained from different plant elements, including the leaf, bark, root, stem, etc. Some of the most essential plant-derived molecules with antimicrobial properties include thymol, carvacrol, eugenol, cinnamaldehyde, limonene, and linalool, among others [144].

2. Essential oils in antimicrobial food packaging

Essential oils (EOs) are increasingly employed packaging system for food owing to their natural antibacterial and antioxidative properties, offering an environmentally sustainable alternative to chemical preservatives (Figure 12). Derived from different aromatic plants i.e., oregano, thyme, clove, cinnamon, lemongrass, and rosemary essential oils, which comprises bioactive components like carvacrol, thymol, eugenol, and cinnamaldehyde, which are known for their strong antimicrobial efficacy against many different kinds of pathogenic foodborne organisms and spoilage microbes, such as fungi, molds and both Gram-positive and Gram-negative bacteria [145, 146].

Essential oils are incorporated into biodegradable polymers such as chitosan, starch, gelatin, sodium alginate, and synthetic biobased polymers like polylactic acid, polyvinyl alcohol etc. [147-151]. The polymer matrix entraps the essential oil, allowing for a slow and controlled release of vapors into the food surface. These volatile components interact with the microorganisms at the surface, inhibiting microbial proliferation and oxidative degradation, and effectively preserving food characteristics and extending the shelf life. These are primarily employed for perishable products, including meats, cheeses, bakery goods, and fruits [146].

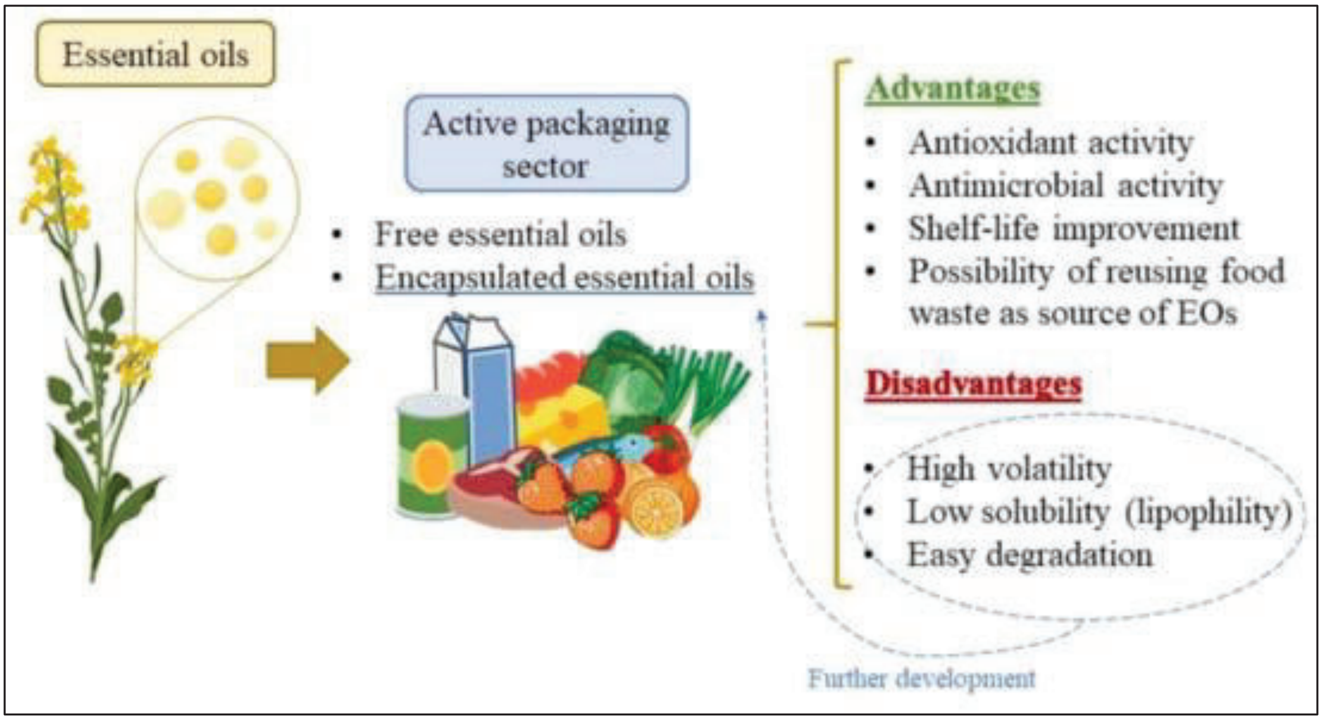

Figure 12: *Essential oils in food packaging system: advantages and disadvantages (Taken from [152] under CC BY license).*

The utilization of essential oils in packaging system for food also aligns with consumer appeal for green-label and organic products. Although, the pungent aroma/flavor of essential oils may affect the sensory properties of the food if not correctly maintained [145]. Furthermore, the instability and degradation of essential oil compounds during storage or processing must be considered when developing active packaging systems [153]. Encapsulation processes, such as nanoemulsions, are utilized in an attempt to enhance stability and regulate the rates of release. Despite these difficulties, essential oils remain a promising ingredient in the fabrication of functional, environment-friendly, and bioactive food packaging technologies [154].

3. Antimicrobial peptides in food packaging

The major microbial-derived antimicrobial compounds include nisin, pediocin, and epsilon polylysine (Figure 13) [155]. The lactic acid bacteria species *Lactococcus lactis* produces the naturally occurring antimicrobial peptide nisin. It is comprised of 34 amino acids and classified as a lantibiotic because it contains uncommon amino acids, such as lanthionine. Nisin exhibits a strong antibacterial action against Gram-positive bacteria [156, 157]. It acts by attaching itself to lipid II, a crucial intermediate in cell wall formation and pore development in the outer membrane of the bacteria. This phenomenon leads to ion leakage through those pores and ultimately leading to the lysis of the cell [158]. However, the presence of the outer membrane of Gram-negative bacteria makes them more resistant to nisin. The incorporation of EDTA and other membrane-disrupting agents significantly enhances the effectiveness of nisin against these bacteria [159].

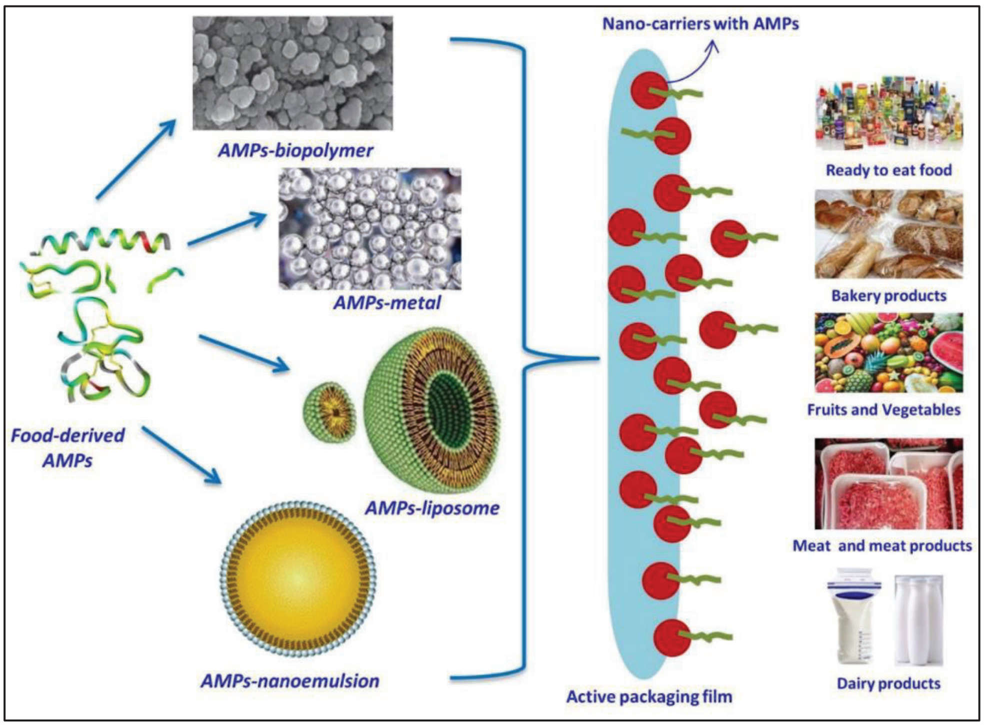

Figure 13: *Antimicrobial peptides in food packaging (Taken from [160] under CC BY license).*

Nisin is generally considered non-toxic and effective. It holds the GRAS (Generally Recognized as Safe) recognition from the U.S. FDA and is approved for application in over 50 countries [161]. In food sector, nisin (E234) is utilized as a preservative in canned foods, dairy products, and processed meats to inhibit spoilage and pathogens, including *Listeria monocytogenes*, *Staphylococcus aureus*, and *Clostridium botulinum* [162]. Apart from that, nisin has also found applications in the biomedical and pharmaceutical sectors. It is being explored as an antimicrobial coating in active packaging materials for medical devices [163]. Nevertheless, the incorporation of nisin is restricted by some drawbacks, including its target of a relatively narrow range of antimicrobial species, mainly Gram-positive bacteria. Moreover, it is highly susceptible to certain proteolytic enzymes and can be easily degraded. The stability of nisin also relies on the pH alterations and composition of the food or delivery matrix [164]. Nevertheless, nisin is recognized as a prominent and well-characterized antimicrobial compound in food safety and biotechnological applications due to its proven effectiveness, natural derivation, and broad regulatory acceptance [162].

Nisin acts as an antimicrobial agent through a two-stage mechanism in which it targets the protective cell membrane of bacteria and inhibits the cell wall formation [158]. Primarily, it binds to lipid II, a critical intermediate substance in the synthesis of peptidoglycan. It is the structural unit of the cell wall of the bacteria [165]. This facilitates the irregular cell wall formation, disruption of cellular integrity, and inclusion of nisin into the cytoplasmic membrane [166]. Nisin aggregates with lipid II and promotes the formation of pores or channels within the cell wall. This helps to disintegrate the cell wall permeability and subsequently allows the essential intracellular ions and molecules, such as potassium, sodium, and magnesium ions, along with other metabolites, to leach out of the cell. Consequently, the membrane potential and cellular energy become depleted, ultimately leading to cell lysis [166, 167]. This dual action mechanism of cell wall disruption and pore formation enhances nisin's effectiveness and reduces the potential risk of resistance development by the microorganisms [165]. However, nisin is more effective against Gram-positive bacteria, due to the absence of a layer outside the cell, which makes lipid II more accessible to nisin. In contrast, Gram-negative bacteria typically exhibit greater resistance owing to the presence of a protective outer membrane. However, the incorporation of membrane-disrupting agents can substantially enhance the antimicrobial efficacy of nisin against these organisms [168]. Overall, nisin's target-oriented and rapid dual-action bactericidal effect makes it a highly effective and widely used natural antimicrobial peptide in food preservation and packaging sectors. Incorporation of nisin into biodegradable films and edible coatings helps retard the proliferation of spoilage and pathogenic Gram-positive bacteria, like *Staphylococcus aureus* and *Listeria monocytogenes*, on the surface of foods where bacterial growth commonly begins [169]. In active packaging systems, nisin can be integrated in biopolymeric materials (e.g., chitosan, starch, gelatin, sodium alginate, and polylactic acid), where it gradually diffuses to the food surface, maintaining microbial control over storage duration [162]. The controlled release functionality improves microbial safety without the need for synthetic chemical preservatives. Nisin-incorporated films have been researched and used for packaging dairy foods, meats, seafood, and ready-to-serve foods, confirming its role in prolonging the shelf life and maintaining the overall product quality [162, 169]. Additionally, nisin functions effectively with many kinds of materials used in edible and biodegradable films. However, several parameters, including pH variations, temperature fluctuations, and the presence of enzymes or food ingredients that can break it down or render it inactive, significantly impact its effectiveness [170]. Despite these challenges, nisin-incorporated food packaging systems continue to be a viable option in the adoption of safe, natural, and functional packaging technologies [162].

ε-Polylysine (ε-PL) is another biologically derived antimicrobial peptide, employed in food preservation and packaging. Structurally, it is a homopolymer constituted of 25-35 L-lysine residues interconnected through α-carboxyl groups and ε-amino. It is produced by bacterial fermentation, primarily using *Streptomyces albulus* [171]. Various countries, including the United States, South Korea, Japan, and China, have approved ε-PL as a food preservative agent and acknowledged GRAS status by the FDA [172]. ε-PL demonstrate antimicrobial properties against a broad range of microbes, including Gram-positive and Gram-negative bacteria, molds and yeasts [173]. It functions by interfering with the outer cell layer of the microbes, resulting in the increased permeability, allowing intracellular components to leak out and eventually causing cell lysis. In contrast to other antimicrobial peptides, ε-PL is heat-resistant and stable over a broad pH range, being effective at acidic to neutral pH. This makes it ideal for thermal food processing. [174].

ε-PL is typically combined with polymers such as polylactic acid, chitosan, gelatin, starch, and alginate targeting antimicrobial edible food packaging. These antimicrobial films are placed in direct contact with the outer surface of food to retard microbial proliferation and prolong shelf life [174]. ε-PL incorporated packaging film has been successfully employed in products such as fresh produce, meats, cheeses, and bakery items, offering protection against spoilage organisms and foodborne pathogenic microbes, including *Aspergillus niger, Escherichia coli*, *Listeria monocytogenes*, and *Salmonella spp.* [175]. Furthermore, ε-polylysine is compatible with other natural antimicrobials and can be employed in combination with organic acids, essential oils, or other biopolymers to enhance its efficacy [173]. ε-Polylysine is a promising agent in the fabrication of clean-label, sustainable technologies for packaged food owing to its non-toxic and biodegradable nature, as well as its functional performance in active packaging systems.

4. Case studies of antimicrobial-based food packaging systems:

Recent studies in packaged food have focused on integrating naturally occurring antibacterial agents like essential oils (EOs) and bioactive peptides to increase food quality, safety, and storage life (Figure 14). Arul Raj, Kasi [176] improved the functional qualities of films for adoption in food packaging by utilizing clove essential oil nanoemulsion (CEON), gelatin obtained from fish processing waste, and cassava starch. The SGCEON3 film, which consists of cassava starch (5%) and a 1:3 ratio of fish gelatin with 10% CEON, exhibited superior antioxidant and antibacterial activity among the formulations, successfully extending the storage stability of fish fillets up to 10 days. The physicochemical analysis showed that the film had a light brown appearance, an improved thickness of 0.19 ± 0.001 mm, a tensile strength of 20.15 MPa, and 270.50% elongation-at-break, that indicated exceptional durability and flexibility. AFM displayed a uniform surface morphology with 39.92 nm of average height deviation and a 54.44 nm of average surface roughness. TGA results revealed a consistent thermal degradation profile across a broad temperature span of 30-600 °C. A symmetrical moderately peaked surface profile was indicated by the skewness and kurtosis values of 0.860 and 1.77, respectively. Furthermore, the molecular compatibility between fish gelatin and CEON was confirmed with FTIR results. A controlled and sustained release of essential oil was observed through migration assays, indicating the potential of SGCEON3 films as efficient packing materials with antibacterial properties for extending food shelf life in a sustainable manner. Shi, Jia

[177] formulated chitosan/CMC composite composites and added *Litsea cubeba* essential oil (LC-EO), revealing significant improvements in their biophysical and functional characteristics. The inclusion of LC-EO increased the mechanical performance, textural integrity, and barrier characteristics of the films, while also imparted hydrophobicity, thermal stability, and biodegradability. Notably, the solubility in water and water content of the films were reduced by 29.68% and 24.37%, respectively, suggesting enhanced resistance to humidity. The acidic food environments are significantly favored by the controlled release behavior of LC-EO from the matrix of the film. Meat samples wrapped in CS/CMC/LCEO films with 4 mg/mL of LC-EO exhibited delayed color changes, texture degradation, and lipid oxidation compared to controls, while maintaining stable pH levels (~6.7) and a lower weight loss rate (15%). In addition, after 10 days of storage, the total viable counts were only 6.35 log CFU/g, indicating that microbial proliferation was inhibited. These findings underscore the potential of CS/CMC/LC-EO films as an effective biodegradable antimicrobial packaging system employed in perishable commodities, specifically meats.

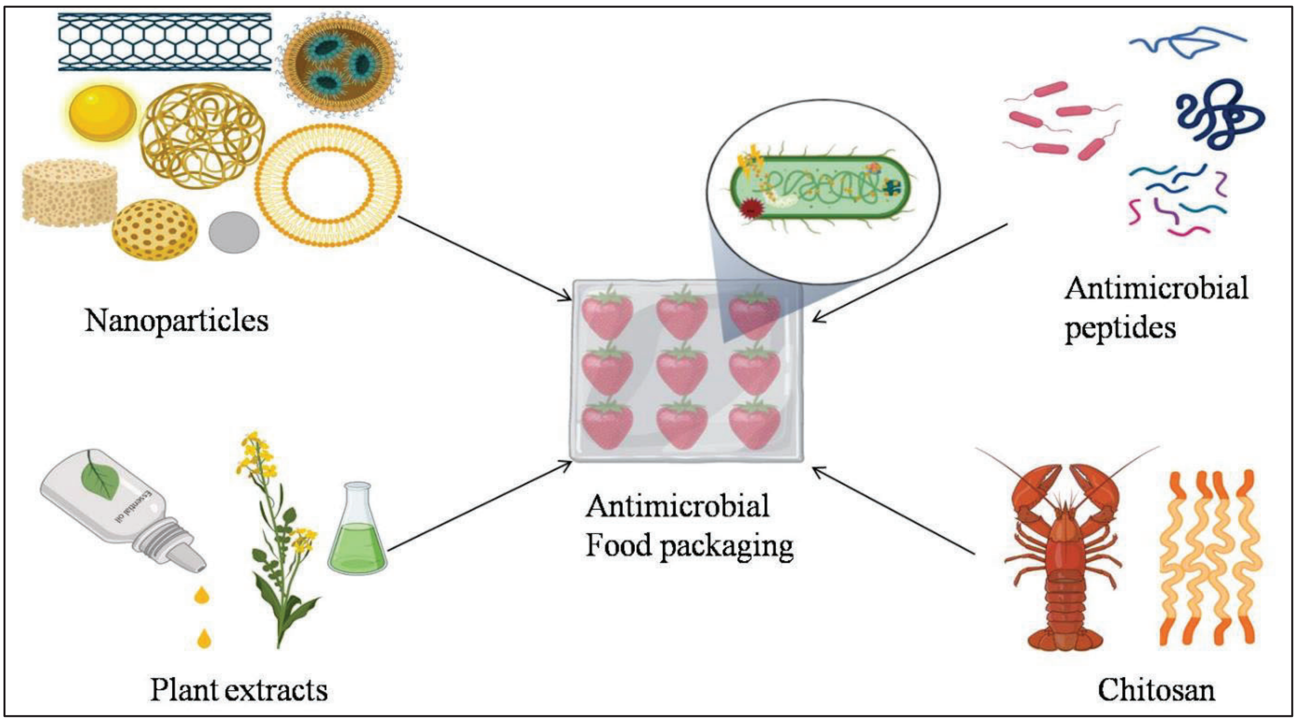

Figure 14: *Antimicrobial food packaging system (Taken from [178] under CC BY license).*

Oregano essential oil (OEO) encapsulated in β-cyclodextrin (β-CD) inclusion complexes (SA/OEO-MP) was integrated in the film matrix based on sodium alginate

(SA) to prolong the storage stability of chilled chicken breast [179]. The OEO-β-CD complex exhibited excellent antioxidant and antibacterial activity, with an encapsulation efficiency of 71.6%, and demonstrated enhanced thermal stability. Lipid oxidation, microbial growth, and spoiling indicators (pH, TBARS, TVB-N, and TVC) were all successfully reduced in treated samples, particularly in the SA/OEO-MP1 group, where the complex enabled a prolonged release of OEO. This study identified SA/OEO-MP coatings as a promising antimicrobial packaging approach for poultry preservation. Similarly, the shelf life of chilled pork was extended using a nano-TiO_2–nisin-modified chitosan composite film as an active packaging material [180]. The addition of 0.7 g/L nano-TiO_2 and nisin prolonged the shelf life of pork from 7 to 20 days at 4 °C when integrated with modified atmospheric packaging (50% CO_2 + 50% N_2). Both elements increased the mechanical performance of the film, whereas nisin improved the compatibility and dispersibility of nano-TiO_2 in the chitosan matrix. By increasing ion leakage and inhibiting membrane-repair enzyme activities and gene expression, the therapy successfully reduced spoilage bacteria, especially *Acinetobacter johnnii* XBB1. This study highlights the promise of nanomaterial-assisted peptide systems, especially nisin, in enabling efficient and preservative-free antimicrobial food packaging. Gui, Zhang [181] created a UV-cured collagen-based film (C-P-H) that contains histidine-modified ε-polylysine. Riboflavin-mediated UV cross-linking was used. The resultant film demonstrated high antibacterial activity against *Salmonella aureus* and *Escherichia coli*, alongside significantly enhanced tensile strength (145.98 MPa), heat stability (76.5 °C), and reduced water vapor permeability. When the C-P-H film was used on pork instead of plastic wrap, the shelf life was increased by around 4 days. This demonstrates the possibility for antibacterial meat packaging using collagen sheets functionalized with peptides.

Protein-based Food Packaging Systems

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1. Introduction

The worldwide food industry is at a pivotal moment, where sustainability, safety, and innovation must converge to create a more secure and responsible food system. The Food and Agriculture Organization (FAO) of the United Nations approximates that each annum, 33% of all food generated for human consumption or sustenance is abandoned or wasted, mainly due to insufficient protection during processing and packaging, storage, transportation, and retail stages [182]. Also, global plastic production has surged to about 367 million metric tons in 2020, with nearly 40% used for single-use packaging, especially in the food sector, and most of these plastics are discarded after brief use, and less than 10% are recycled [183]. The conventional petroleum-derived/based polymers are robustly employed for packaging because of their strength, lightweight, and affordability [184], but they are non-biodegradable and contribute to microplastic pollution. To address this, 15 countries and regions, including New Zealand, Korea, France, India, and the EU, have recently banned single-use plastics to curb environmental and marine pollution [185]. These combined issues have created a pressing need worldwide to reimagine food packaging, focusing on sustainability, resource efficiency, and environmental impact reduction.

Food packaging is essential for preventing contamination and spoilage, keeping food safe and fresh during storage and transport. Common materials used include plastic, paper, metal, and paperboard [186]. Food packaging has evolved from serving as a simple protective layer to becoming a dynamic, sustainable system that is safe and biodegradable. In this changing scenario, the implementation of biological polymers in packaging for food has displayed great promise, particularly as coatings and films. These materials are not only biodegradable but also designed to be safe, durable, and functionally efficient. Under the proper parameters of moisture, temperature, and oxygen, microorganisms can quickly decompose them. Moreover, they are sourced from renewable materials. Although biopolymers traditionally exhibit higher permeability and lower mechanical strength compared to petroleum-based plastics, recent technological innovations have led to the development of protein-, lipid-, and polysaccharide-based biodegradable films that effectively address sustainability and environmental safety challenges [187].

Among natural biopolymers, proteins offer a compelling foundation for next-generation packaging materials owing to their high film-forming properties, affordability, and better permeability in comparison to polysaccharide and lipid-based films. Protein-based films are also considered more attractive because they exhibit higher tensile strength, such as gelatin films (68 MPa), in contrast to films made of polysaccharides like chitosan (41 MPa) [188]. Moreover, their diverse amino acid composition enables strong intermolecular interactions, including hydrogen bonding, disulfide linkages, and hydrophobic associations, allowing them to form cohesive, transparent, and adaptable food packaging material. Additionally, proteins are also an exceptional raw material for edible films because of their intrinsic properties [189]. Covering foods with edible films can preserve moisture and flavor, regulate gas exchange (oxygen, carbon dioxide, and ethylene), deliver active compounds like antimicrobials or antioxidants, and release nitrogen during degradation [190]. Significantly, protein sources are amazingly diverse, extending from animal (gelatin, casein, whey) and plant (soy, zein, pea, hemp) to microalgal, fungal, and industrial by-product proteins, offering pathways to both sustainability and upcycling. Regardless of their promising attributes, protein-based packaging materials still face numerous technological and functional limitations. High sensitivity to moisture, inconsistent film formation, limited strength, and difficulties in scaling up production continue to hinder the large-scale commercial use of these materials.

Protein-based films can be engineered to provide strong mechanical integrity, controlled water-vapor permeability, and excellent gas-barrier properties. Treatments such as crosslinking, plasticization, or incorporation of essential oils improve flexibility, durability, and elongation, while natural antioxidants and antimicrobial agents enhance stability and prevent spoilage [191, 192]. Combining with various biopolymers like chitosan, alginate, or cellulose, and surface modifications with lipids or polysaccharides, further optimizes performance [193]. Although regulatory, cost, and consumer acceptance challenges remain, these protein-based food packaging present significant opportunities for sustainable innovation in food packaging. This chapter provides a comprehensive exploration of food packaging derived from proteins, beginning with the diverse sources of proteins and fundamental material properties that enable them to form functional packaging, processing techniques, modification and improvement of protein-based food packaging, considering the effects of using protein-based materials on the environment and the economy at scale, and how protein-based packaging materials have the potential to reshape future food systems. Ultimately, it highlights the potential of proteins, beyond their nutritional value, to act as key components for the creation of eco-friendly, bioinspired, and sustainable packaging solutions.

2. Sources of proteins for food packaging

Proteins, essential natural polymers formed from amino acid chains, fold into complex structures that provide functional properties like foaming, emulsifying, and gelling. Protein-based food packaging is readily biodegradable because microbes can break its amino acid chains down into simple, natural components. The sources of the most popular proteins used in food packaging are mentioned below and in Figure 15.

2.1 Plant-based

Plant-based proteins such as zein, soy, wheat gluten, pea, and sorghum have gained significant attention. Each exhibit unique physicochemical and functional properties influenced by its molecular composition, extraction method, and film-forming process. Zein, a nontoxic corn endosperm-derived, water-insoluble protein constituting 45–50% of the total corn protein, is rich in hydrophobic amino acids. As it is soluble in alcohol, hydrophobic, and self-assembling, it provides excellent water vapor barrier properties and tensile strength [194]. Zein-based films exhibit great elongation, enhanced toughness, and improved flexibility and are utilized in applications ranging from vitamin retention and fresh produce coatings to controlled drug release [195]. Soy protein (320–350 kDa), the major component of soybeans, contains 12 subunits bound by disulfide and hydrogen linkages. About 70% of total soy protein is abundant in cysteine residues that render disulfide bonds critical for mechanical strength [196]. Soy protein isolates offer good resistance to oxygen and oil under low humidity and are biodegradable. While soy protein isolate (SPI) films are biodegradable, they tend to be brittle. Incorporating 30–40% glycerol by weight improves their mechanical strength and flexibility [197]. Wheat gluten, composed of sulfur-rich and sulfur-poor fractions of gliadin and glutenin, which undergo sulfhydryl–disulfide interchange reactions during thermal processing, creating complex polymeric networks and robust mechanical properties by providing strength and elasticity [198]. As a starch byproduct, it is rich in glutamine and hydrogen bonds, which make it ideal for biofilms. Pea protein, consisting mainly of 70–80% globulin and 10–20% albumin, contains the 11S legumin and 7S vicilin subunits responsible for its film-forming capabilities [199]. Pea protein isolate is hypoallergenic and environmentally sustainable, making it attractive for allergen-free food packaging. Sorghum protein, primarily composed of kafirin, is hydrophobic, like zein, enabling the formation of moisture-resistant films suitable for packaging that requires water-vapor protection [200]. Sorghum protein films exhibit notable tensile strength and flexibility, which can be further enhanced by blending with biodegradable polymers like starch [201]. Potato protein makes up only 1–3% of the fresh tuber. Still, it is a valuable source containing both soluble and insoluble fractions and rich in patatins and protease inhibitors, which provide emulsifying, foaming, and antioxidant properties, making it well-suited for functional food packaging [202].

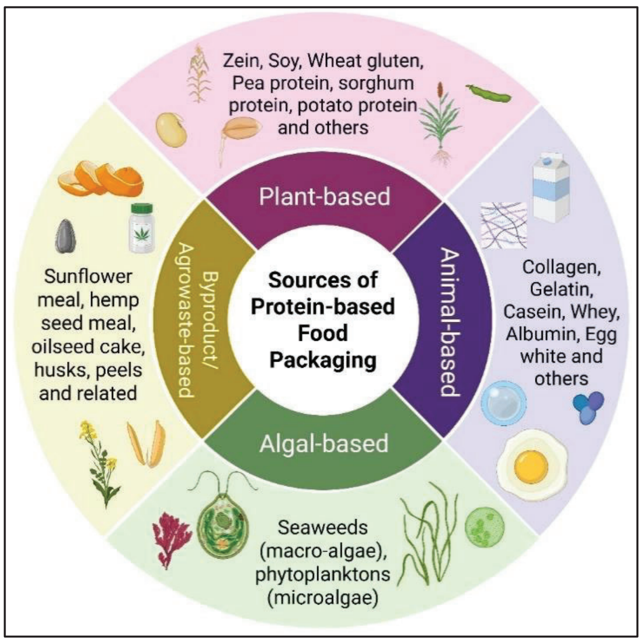

Figure 15: *Sources of proteins for food packaging materials.*

2.2 Animal-based

Animal-derived proteins, including collagen, gelatin, casein, whey, and albumin, are broadly used in food packaging because of their better mechanical, barrier, and biodegradable characteristics. Collagen, the most widely available protein derived from animals, is found in skin, tendons, and connective tissues and forms strong, flexible films suitable for edible coatings in meat products like sausages. Marine sources such as squid, shrimp, and jellyfish also provide high-quality collagen for biodegradable packaging, although fish collagen is limited by its low heat stability [203]. Milk proteins consist mainly of (i) Casein (80% of total), which is composed of α-casein, β-casein, κ-casein, and γ-casein, and exhibits excellent adhesive, gelling and emulsifying characteristics, and can exhibit cohesive and flexible films with good oxygen barrier properties [204] (ii) Whey (20% of total), consisting of α-lactalbumin, β-lactalbumin, and immunoglobulin, having high emulsifying and water-soluble properties and ultimately forms transparent, flexible films with strong mechanical and barrier properties [205]. Gelatin, obtained mainly from pig skin, fish, or bovine sources, is valued for its film-forming and oxygen barrier properties but requires modification with plasticizers or crosslinkers to improve its moisture resistance and mechanical stability [206]. Protein from egg white majorly comprises ovalbumin (54%), ovotransferrin (12%), ovomucin (11%), lysozyme (3.5%), and minor proteins, giving it strong foaming, emulsifying, and gelling properties. These proteins render it an excellent natural polymer for compostable edible packaging, though its films often have high viscosity and weak mechanical strength [207]. Adding plasticizers, organic additives, or modifying the film-forming process can significantly improve their functionality and stability performance.

2.3 Algal-based

Algal proteins have become attractive options for environmentally friendly packaging because of their renewable, biodegradable, and biocompatible nature. Derived from both macroalgae (seaweeds) and microalgae (phytoplankton), these proteins offer nutritional richness and functional versatility [208]. Macroalgae, such as *Porphyra, Ulva*, and *Laminaria*, have long been consumed for their vitamins, minerals, and fibers. In contrast, microalgae, including *Chlorella vulgaris*, *Spirulina maxima*, and *Haematococcus pluvialis,* contain high protein levels (up to 60%) [209] and exhibit remarkable biosynthetic potential. The excellent amino acid profile and bioactive properties of algal proteins enhance their compatibility with biopolymer matrices, enabling the fabrication of coatings and films that improve mechanical strength, antioxidant capacity, and shelf-life stability. Despite increasing studies on plant and silk proteins for packaging, the comprehensive exploration of algal proteins remains limited.

2.4 Industrial byproduct/agro-waste-based

Using agricultural and industrial byproducts as protein sources for packaging represents an eco-friendly strategy to reduce waste and promote circularity. Agro-residues such as bagasse, husks, peels, and oilseed cakes can be converted into valuable biopolymers through chemical, mechanical, or biological treatments [210-213]. These processes enable the extraction of functional compounds like proteins, starch, and cellulose that can be fabricated into biodegradable films and composites. Sunflower protein, extracted from sunflower oil cake, primarily consists of 11S globulin and 2S albumin. Films made from them are renewable and environmentally friendly, utilizing a by-product otherwise regarded as agricultural waste. Importantly, phenolic compounds in sunflower protein remain bound during processing, imparting antioxidant functionality. Antimicrobial sunflower films enriched with grapefruit seed extract effectively inhibit *Listeria monocytogenes* growth in smoked duck meat, while the addition of clove essential oil further improves antibacterial and antioxidant activity, demonstrating strong potential for active packaging applications [123]. Similarly, protein-rich meals from hemp, canola, and other oilseeds also hold strong potential for sustainable packaging due to their excellent film-forming capacity, biodegradability, and functional versatility. For instance. films cast from hemp seed oil cake at alkaline pH with glycerol show good flexibility, while enzymatic crosslinking with microbial transglutaminase (mTGase) produces smoother, stronger, and heat-sealable films with enhanced hydrophobicity and gas barrier properties [214]. These hemp protein films effectively protect foods from contamination and extend shelf life, making them a promising sustainable packaging material.

3. Processing techniques for protein-based food packaging

The fabrication or processing methods critically determine the physicochemical and functional characteristics of protein-based packaging materials for food. Techniques ranging from laboratory-scale casting to industrial-scale extrusion and molding are employed to engineer films and coatings to specific requirements in packaging [215]. This part highlights the key methodologies used in producing packaging materials from protein.

Extrusion is widely used for industrial-scale production of protein-based films and bioplastics, where heated protein blends are forced across a die to form continuous sheets. While plasticizers are often added to aid flow, extrusion offers high efficiency and is well-suited for thermoplastic proteins. Melt extrusion and thermopressing/thermoforming both utilize heat and pressure to process protein-based polymers into films, sheets, or containers, offering high throughput and dimensional stability [216, 217]. Melt extrusion is particularly effective for producing nanostructured composites, encapsulating bioactive compounds, and fabricating multilayered active packaging materials. Thermoforming enables the shaping of trays, pots, and complex geometries from protein–polymer blends, although fossil-based materials remain common, underscoring the need for sustainable biopolymer integration [218]. Injection molding is another technique for large-scale production of rigid, intricately shaped packaging components, such as trays or containers, providing uniform and durable materials for long-lasting applications [219]. Moreover, edible films can also be created by this method and were utilized to create pea isolate films by adding glycerol [220]. Solvent casting is also frequently used because of its easy-to-use, low equipment cost, and adaptability to include functional components like plasticizers, nanoparticles, or essential oils [221]. In this method, protein solutions are cast onto surfaces such as glass or Teflon, followed by controlled drying, resulting in homogeneous, transparent, and flexible films [221]. While solvent-cast films exhibit good optical and barrier properties, their mechanical strength and water vapor resistance are generally lower than those of films produced via extrusion, and solvent recovery and industrial scalability remain challenging. Co-extrusion is a technique for creating multilayered coatings or films by extruding two or more materials simultaneously. It is frequently used to implement edible coatings directly onto foods [222]. For instance, passing minced meat along with calcium alginate across a co-extruding die forms a protective alginate layer on the meat [223]. Applications include packaging sausages with alginate or collagen films, often mixed with polysaccharides and other compounds to improve functioning, barrier properties, and food preservation [224].

Tape Casting, initially developed for ceramics, has been adapted for biopolymers, allowing precise control over film thickness and continuous formation. Biopolymer solutions, such as thermoplastic starch or protein blends, are deposited onto a moving belt and dried under controlled heat or infrared conditions, yielding thin, uniform films [225]. The method enables scalable film production, though parameters such as conveyor speed, nozzle diameter, drying time, and solution rheology critically influence final film quality. Protein-based mixes are pressed under pressure inside a heated mold chamber during the compression molding process, allowing the creation of solid form, including uniform films or complex shapes. This method is particularly suited to active packaging systems, where antioxidant or antimicrobial agents enhance functionality and produce stiffer, thicker components. The other alternative approach is Layer-by-Layer (LBL) assembly, which allows creation of multilayered constructs *via* alternate deposition of polymers with opposing charges, like chitosan and cellulose nanocrystals, producing films with precise thickness control, enhanced mechanical properties, and superior gas barrier performance [226, 227]. This approach allows integration with other fabrication techniques and is compatible with bioactive incorporation for functional coatings. Finally, electrospinning and electrospraying offer unique advantages for producing nanofibrous films or micro/nanoparticles with controlled size and morphology, enabling ultrathin edible coatings and active packaging materials with tunable release of antimicrobials, antioxidants, or probiotics [228, 229]. Electrospinning produces nanometer-scale fibers, whereas electrospraying facilitates particle deposition and addresses thickness uniformity issues seen in casting. However, low throughput, solvent handling, and equipment costs limit industrial scalability [230, 231].

4. Strategies to enhance the performance of protein–based food packaging

Although protein-based packaging materials are sustainable and biodegradable, their broader use in the food sector is restricted by certain performance issues. These materials often show low mechanical strength, brittleness, and poor resistance to moisture because plant proteins are naturally hydrophilic. For example, zein-based films have nearly 200 times higher water vapor permeability than polyethylene, indicating weak barrier properties [232]. To overcome these challenges, several modifications, such as physical, chemical, or enzymatic treatments of proteins, as well as their combination with hydrophobic compounds or other polymers, have been created to improve the flexibility, physical strength, barrier characteristics, and environmental stability of protein-based packaging, including films, coatings, and composite materials. Crosslinking advances the cohesive structure of protein matrices by forming covalent or noncovalent bonds between molecular chains, enhancing their mechanical strength, thermal stability, and water resistance [233]. Exposure to high temperatures causes protein denaturation, disrupting hydrogen bonds and hydrophobic interactions that maintain their three-dimensional structure. This unfolding allows new intermolecular interactions to form between protein chains, leading to crosslinking and network formation. Studies have shown that higher processing temperatures generally promote greater crosslinking, resulting in films with improved mechanical strength [234]. However, identifying the optimal temperature is essential, as excessive heat can lead to protein degradation and reduced film quality. Protein interactions can also be altered by radiation to improve physical and barrier properties. Both ionizing (e.g., γ-irradiation, X-rays) and non-ionizing (e.g., UV) radiations have been employed to induce protein crosslinking, enhancing their structural and functional properties. Exposure to ionizing radiation generates hydroxyl radicals from water within the protein matrix, resulting in structural changes like covalent bond cleavage, free radical creation, aggregation, and ultimately crosslinking of polypeptide branches [233]. Compared to enzymatic methods, irradiation is cost-effective and produces insoluble, sterilizable films. However, controlling these reactions is challenging, and scaling up irradiation for industrial protein film production remains difficult. Chemical crosslinking, in contrast, establishes permanent covalent linkages using enzymatic catalysts or reactive compounds. Agents such as glutaraldehyde, genipin, transglutaminase, and sugars (*via* the Maillard reaction) strengthen the protein network by improving water resistance and durability [235, 236]. Maillard-type crosslinking, which uses natural sugars, is safe and effective under gentle conditions, but excessive reaction can make the material brittle [237]. Schiff base reactions create stronger bonds between aldehyde and amino groups, though they can sometimes cause toxicity or make the film too rigid.

Combining plasticizers, such as glycerol–sorbitol blends, allows fine-tuning of mechanical and barrier properties, making plasticization a key strategy for optimizing protein-based packaging performance [238]. Plasticizers are small, polar molecules that insert between protein chains, depleting intermolecular forces and improving molecular mobility. This enhances flexibility and elongation while reducing brittleness in protein-based materials. Common plasticizers include glycerol, propylene glycol, sorbitol, and polyethylene glycol (PEG) [214, 239]. Glycerol is highly effective at improving flexibility but can increase water sensitivity, whereas sorbitol offers better moisture resistance but less flexibility. Propylene glycol and PEG provide a compromise between ductility and water resistance, though their dispersion may vary with protein type. Enzymatic treatments are also widely employed to enhance the properties of protein-based films. Among these, transglutaminase is one of the most frequently used enzymes, effectively crosslinking proteins such as myofibrillar proteins, wheat gluten, whey, and casein. Through an acyl transfer process, this enzyme facilitates the creation of a covalent connection between the carboxamide group of glutamine and the amino group of lysine. The resulting inter- and intramolecular crosslinks strengthen the protein network, producing films with enhanced mechanical stability and functional performance [240].

Blending proteins with additional bio-based materials, like lipids, polysaccharides, or additional proteins, is an impactful strategy to improve the functionality of protein-based packaging materials [241, 242]. Each component offers specific functional attributes that contribute to improved film performance. For instance, incorporating lipids such as oils, waxes, or fatty acids helps reduce water vapor transmission by their hydrophobic nature, thereby improving the films' moisture-barrier properties [243]. Similarly, blending proteins with polysaccharides such as chitosan, starch, or pectin enables the creation of a well-organized network with hydrogen bonding and electrostatic interactions, resulting in films that have higher tensile strength, flexibility, and barrier properties [244]. Another promising approach involves reinforcing protein films with nanoparticles to create nanocomposite structures. The incorporation of nano-sized fillers like silver, zinc oxide, titanium dioxide, or montmorillonite effectively enhances the mechanical, barrier, and thermal stability of the films by reducing structural defects and increasing cross-link density [245]. Moreover, certain nanoparticles provide additional functionalities, including antimicrobial and UV-shielding properties, which prolong the storage life of packaged foods and offer potential for active packaging systems. Achieving uniform nanoparticle dispersion within the matrix is crucial for maintaining film transparency and ensuring consistent performance. Further improvements can be achieved through surface coating and layer-by-layer assembly, in which thin layers of lipids or polysaccharides are deposited onto the protein film surface [246, 247]. Overall, protein-based food packaging involves a combination of material selection, processing technique, chemical/physical modifications, and incorporation of bioactives to produce packaging solutions that are biodegradable, mechanically robust, and capable of prolonging the storage life and stability of food commodities. Each method offers unique advantages and challenges, and the choice depends on the desired application, scalability, and functional requirements of the packaging material.

5. Smart and active protein-based packaging systems

Active packaging has emerged as a key innovation in the food packaging sector, aiming to prolong product storage life while preserving stability and quality. It functions through direct interaction between the packaging material and the food or its surrounding environment. This approach often involves incorporating bioactive compounds such as antioxidants/antimicrobial agents into packaging materials or surface coatings, commonly known as active coatings. Protein-based films, in particular, serve as effective carriers for such active ingredients, helping to inhibit spoilage, delay oxidation, and enhance sensory characteristics. Additionally, they can be engineered to deliver nutrients or improve the texture and overall quality of food products. Various antimicrobial agents have been successfully implemented in protein-based active packaging to enhance food safety and shelf life. Bacteriocins such as nisin effectively inhibit pathogens such as *Listeria monocytogenes*, *Yarrowia lipolytica, Pseudomonas aeruginosa*, and *Penicillium* species and have been incorporated into protein-based packaging films [248]. EDTA has been utilized in active packaging to boost antibacterial efficiency against *E. coli*, *Salmonella*, and *Listeria*. Enzymatic systems such as lysozyme and the lactoperoxidase system (LPOS) also strengthen antimicrobial activity against *Staphylococcus aureus*, *Bacillus subtilis*, and other spoilage microbes [249]. In addition, essential oils and extracted compounds from plants (e.g., green tea, grape seed, and citric extracts) have gained attention for their natural antimicrobial potential. Commercial formulations such as Artimex 152/NL, Articoat eDLP-02, and Auranta FV have further expanded the scope of active protein films, providing broad-spectrum protection against foodborne and spoilage microorganisms [250]. The addition of antioxidants inside packaging polymers is an effective strategy to delay lipid oxidation, which causes off-flavours, discolouration, nutrient loss, and reduced shelf life. Natural antioxidants like tea polyphenols, extracts from plants, and essential oils have been successfully integrated into protein-based films to enhance food stability [251]. For instance, green tea, *Caesalpinia extracts*, and various essential oils (including marjoram, coriander, clove, orange leaf, and cinnamon) have shown strong antioxidative effects, reducing oxidation in meat, cheese, shrimp, and fish products [252, 253]. These additions not only prolong the storage life but also influence film characteristics like toughness, flexibility, and barrier characteristics, demonstrating their potential to develop multifunctional active packaging systems.

6. Economic Importance and Challenges

The growing global population and rising food demand are intensifying pressure on renewable resources, including energy, water, and land, thereby increasing production costs and environmental impact. Climate change and food waste further threaten sustainability. While large, family-sized packaging offers short-term economic benefits to producers, it often promotes overconsumption and spoilage. Reducing packaging and food waste through eco-efficient, biodegradable packaging can lower greenhouse gas emissions, reduce dependence on petroleum-based plastics, and improve food system resilience. The development of bio-based and nanocomposite materials, along with enhanced recycling strategies and optimized package design, presents a sustainable economic pathway that supports both industry profitability and environmental preservation.

However, several challenges continue to restrict its widespread commercialization. Despite their biodegradability and renewable origin, protein-based films and coatings frequently display less mechanical toughness, greater water sensitivity, and lower heat stability than petroleum-derived polymers. Such limitations reduce their applicability to a narrow range of food systems. In addition, the production cost of edible and biodegradable films remains substantially higher. From an industrial standpoint, the lack of standardized protocols and regulatory frameworks hinders consistent quality assurance and large-scale adoption. Consumer perception also plays a vital role, as it differs markedly from conventional plastics in texture, appearance, and handling; it may face limited acceptance without proper awareness and education. Maintaining the safety and stability of these substances during storage, transportation, and food contact remains another primary concern.

7. Conclusion and Future Prospects

Protein-based packaging polymers offer a sustainable and biodegradable alternative to conventional plastics, combining food protection with the potential for functionalization, such as antimicrobial, antioxidant, and intelligent features. Despite their promise, widespread adoption is limited by technical challenges, including low mechanical strength, water sensitivity, high production costs, and variability in raw materials, as well as regulatory and consumer acceptance barriers. Future research should focus on enhancing film performance through material modification, nanotechnology, and biotechnological integration, thereby enabling antioxidant, antimicrobial, and smart-sensing functionalities for further improvement. With continued progress in processing technologies and cost reduction strategies, large-scale production is expected to become more feasible. Moreover, combining protein-based materials with digital and intelligent systems could lead to personalized, adaptive packaging solutions that monitor food freshness in real time. Overall, the convergence of green materials, advanced biotechnology, and smart packaging innovations will drive the transition toward a more sustainable and resilient food packaging industry.

Nanocomposite-Based Packaging Systems

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1. Introduction

The practice of food packaging is generally related to the history of human civilization. In its earliest forms, packaging was an extension of nature itself, using primitive materials such as gourds, animal skins, and large leaves, which served as rudimentary vessels for carrying, storing, and preserving food and water [254]. The development of early technologies such as basket weaving and pottery represented a significant leap forward, enabling the creation of standardized containers from natural fibers and clay. These innovations were not merely for convenience but were critical enablers of trade, migration, and the formation of settled communities. For instance, clay amphorae of the ancient Mediterranean were instrumental in the long-distance transport of valuable liquids like wine and oil, underpinning the economies of empires [255]. Similarly, the invention of paper from mulberry bark in ancient China during the Han dynasty (202BC–220AD) introduced the concept of a flexible, lightweight packaging material, which was a precursor to the myriad forms of paper and board packaging we see today [256].

The Industrial Revolution, which took place in the mid-18th and 19th centuries, marked a pivotal turning point, transforming the agricultural landscape from subsistence-based farming and manual labor to market-driven industry and machinery [257]. This shift created an unprecedented need for packaging that could support mass production and distribution. Innovations in glass blowing and metalworking led to the widespread availability of jars, bottles, and canisters, while mechanized paper production made cartons and bags ubiquitous. The world wars of the 20th century further accelerated this progress, spurring the development of materials such as cellophane and kraft paper, initially for military applications but quickly adopted for consumer use [258]. These materials offered improved functionality, but it was the dawn of the polymer age that would truly revolutionize the industry and set the stage for the modern packaging landscape.

The invention of synthetic polymers, or plastics, in the mid-20th century was a watershed moment. Polymers, including polypropylene, polyethylene, and polyethylene terephthalate (PET), offered a combination of properties that made them attractive, including being lightweight, durable, flexible, transparent, and remarkably inexpensive to produce [259]. The ability to mold them into virtually any shape, along with their excellent barrier characteristics, made them suitable for preserving a broad variety of foods. This led to the rapid proliferation of single-use plastics, a model that offered unparalleled convenience to consumers and immense logistical advantages to manufacturers. For several decades, the narrative of plastic packaging was one of unmitigated progress, a symbol of modernity that enabled the global food supply chain we rely on today. However, the immense success of plastic packaging has come at a staggering environmental cost [260]. The very properties that make plastics useful, including their durability, have resulted in global pollution crises of monumental proportions, as these materials can sustain in the system for thousands of years. Approximately 79% of the 8.3 billion tons of virgin plastic manufactured since the 1950s have ended up in landfills and the environment [261]. Unlike organic materials, plastics are non-biodegradable and break down over hundreds of years into smaller fragments known as microplastics, which have been found to contaminate every corner of the environment, from the highest mountains to the depths of oceans, infiltrating the entire food web. Recent studies have revealed the alarming extent of this contamination, suggesting that fruits and vegetables alone can contribute significantly to daily microplastic intake, which can reach 99.5% of total consumption, relying on the source of food products and dietary habits [262].

Meanwhile, only a very small amount of garbage is successfully recycled worldwide, with complex multilayered packaging and food contamination posing significant challenges [261]. The EU's Packaging and Packaging Waste Regulation, which attempts to reduce the use of single-use plastics and encourage a more circular economy, is one example of the stricter laws that regulatory bodies are enacting in reaction. Parallel to this environmental crisis is the equally pressing issue of global food loss and waste. The Food and Agriculture Organization projected that approximately one-third of all food produced, up to 1.3 billion tons, is lost or wasted along the supply chain. Inadequate packaging is a major contributor to this problem, particularly in developing countries, where a lack of effective preservation technologies leads to high spoilage rates of perishable goods such as fresh food products [263]. Therefore, replacing plastics is not the sole difficulty, but also to develop new packaging solutions that can preserve food effectively while minimizing environmental impact.

This urgent need for sustainable alternatives has fueled extensive development of biopolymers, which are sourced from renewable biological sources such as polysaccharides and proteins, or produced by microorganisms, like polyhydroxyalkanoates (PHAs), or manufactured from bio-generated monomers, like polylactic acid made from fermented corn starch or sugar cane [264]. The primary purpose why biopolymers are appealing is their potential to be biodegradable and compostable, offering a closed-loop, circular life cycle that contrasts sharply with the linear, disposable model of petroleum-based plastics. However, the transition to biopolymers has been fraught with several challenges. While conceptually appealing, many first-generation biopolymers have failed to match the functional performance of synthetic counterparts, as many biopolymers, particularly polysaccharides, are inherently hydrophilic, resulting in poor barrier properties that compromise the storage stability of the food items [265]. Furthermore, they exhibit poor thermal stability and mechanical properties, such as lower tensile strength, flexibility, and durability, which make them prone to tearing or damage during transport and handling. These deficiencies have limited their use to a narrow range of products and prevented them from serving as a wholesale replacement for petroleum-based plastics. The reality is that a simple substitution of one material for another is not enough, and a true solution must bridge the gap between sustainability and performance.

Therefore, it is at this critical juncture, when the limitations of both conventional and their bio-based alternatives are clear, that nanotechnology offers a transformative path forward. Nanotechnology deals with the engineering of materials at the atomic and molecular level, handling structures that are between 1 and 100 nanometers in at least one dimension, where the materials can exhibit novel properties that are not present at the macroscale [266]. These properties include an incredibly high surface area-to-volume ratio, enhanced chemical reactivity, and unique optical and electrical characteristics. By harnessing these nanoscale phenomena, several studies have engineered materials with precisely tailored functionalities. To overcome the inherent limitations of existing materials, nanocomposites have been developed as hybrid materials created by embedding nanoscale particles or nanofillers within a conventional polymer matrix. This creates dynamic and multifunctional materials that are simultaneously sustainable, high-performing, and intelligent. It represents a move away from the brute-force approach of thick, multilayered plastic films toward a more elegant, scientifically informed model of material design. Despite the immense potential of nanocomposite packaging, the path to widespread adoption is lined with significant challenges that must be addressed through rigorous scientific research and thoughtful policymaking. Its novelty raises important questions about its possible effects on the surroundings and human wellness. Again, issues related to its scalability, cost, consumer perception, and acceptance are critical areas to address to ensure its success in the packaging industry. Clear, transparent communication about the benefits and risks of technology, backed by robust scientific evidence, will be essential to building public trust.

This chapter seeks to give a thorough summary of nanocomposite packaging systems, exploring key areas such as the underlying principles of nanocomposites, fabrication and processing, impact on the functionality of packaging materials, applications, challenges, and future perspectives. By navigating these areas, the chapter seeks to provide a clear understanding of both the transformative promise of nanocomposite packaging and the considerable challenges that must be addressed to realize it on a global scale.

2. Fundamentals of Nanocomposites

2.1 Concept of nanocomposites and nanoscale effects

Nanocomposites represent a novel class of hybrid materials engineered by dispersing a reinforcing phase with a minimum of one nanometre-scale dimension (typically 1-100 nm) within a bulk matrix material [267]. This combination of distinct phases, including a continuous matrix (polymeric, ceramic, or metallic) and a discontinuous nanoscale reinforcement, creates a synergistic system in which the resulting properties can be far superior to those of the individual components or their conventional microscale counterparts [268]. The defining characteristic of a nanocomposite is not merely the small size of the filler but the emergence of new functionalities that arise from the unique physics governing matter at the nanoscale. This allows for significant enhancements in mechanical, thermal, barrier, and functional properties at remarkably low filler concentrations, often below 5% by weight, in contrast to the high loadings (25-40 wt%) required for traditional microcomposites [269]. This efficiency leads to materials that not only perform better but are also lighter and potentially more cost-effective to produce.

The profound impact of nanofillers stems from three fundamental physical principles that manifest at the nanoscale. Firstly, as a particle's size decreases, its surface-area-to-volume ratio increases exponentially. For a spherical particle, this ratio scales inversely with the radius. Consequently, a 10 nm particle possesses 100 times the surface area per unit volume compared to a 1 μm particle if the same material [270]. This explosion in the surface area creates a dramatically expanded interfacial region between the nanofiller and the surrounding polymer matrix. This interface is not a simple boundary but a distinct third phase with its own unique properties, governing stress transfer, charge transport, and molecular mobility while creating abundant sites for chemical bonding, physical adsorption, and molecular interactions between the matrix and the nano filler, which dictate the composite's overall behavior. Moreover, when the dimensions of a material become comparable to characteristic length scales of physical phenomena, such as the de Broglie wavelength of an electron, quantum mechanics begins to dominate [271]. This quantum confinement alters the material's electronic and optical properties. For instance, semiconductor nanoparticles (quantum dots) exhibit size-tunable fluorescence, a property leveraged in advanced sensing and imaging applications [272]. While less dominant in the bulk mechanical and barrier properties of packaging materials, these quantum effects are critical for developing the intelligent functions of next-generation nanocomposites. Furthermore, atoms at the surface of a material have fewer neighboring atoms to bond with compared to atoms in the bulk, leaving them in a higher, unsaturated energy state. This effect is magnified at the nanoscale due to the high surface-to-volume ratio. This elevated surface energy is the driving force behind the strong interfacial interactions that can form between a nanofiller and a polymer matrix. However, it is also a reason why nanoparticles have a strong thermodynamic tendency to agglomerate, or cluster together, to minimize their total surface energy. Overcoming this agglomeration to achieve a uniform dispersion is one of the most critical challenges in nanocomposite fabrication [273].

2.2 Classification of Nanocomposites

Nanocomposites can be classified by the nature of the matrix material (e.g., polymer, ceramic, or meta matrix). However, for understanding their functional properties, a more insightful classification is based on the nanofiller's geometry or dimensionality. The shape and aspect ratio (length-to-diameter ratio) of the reinforcement profoundly influence the final properties of the nanocomposite [274]. Based on this, nanofillers are categorized into three main groups, as summarized in Table 1.

Table 1: *Classification of Nanofillers by Geometry [275].*

Dimensionality	Geometry	Description	Examples	Key Advantages	Key Limitations
0D	Particulate	All dimensions are within the nano scale (equiaxed or spherical)	Metal oxides (ZnO, TiO_2), metal nanoparticles (Ag), quantum dots, nanodiamonds	Highest surface area; idea for optical, catalytic, and antimicrobial functions	Low aspect ratio, inefficient for mechanical reinforcement, high tendency to agglomerate
1D	Fibrous/ Tubular	Two dimensions are in nanoscale, while one is significantly larger (micrometers to millimeters)	Carbon Nanotubes (CNTs), Cellulose nanofibres/ Nanocrystals (CNF/CNC), halloysite nanotubes	The highest aspect ratio (100-10,000) is most efficient for mechanical reinforcement and for creating conductive networks.	Difficult to disperse and align, high cost for some types (e.g., CNTs)
2D	Layered/ Platelet	One dimension is in the nanoscale, while the	Nanoclays (montmorillonite), graphene, MXenes, layered double	High aspect ratio (30-1000), exceptional barrier	Requires exfoliation to separate layers; surface

		other two are significantly larger (tens of nanometers to micrometers)	hydroxides (LDHs)	properties, and reinforcement efficiency at low loadings	chemistry can be complex.

When using 2D layered fillers such as nanoclays, the degree of dispersion within the polymer matrix gives rise to three distinct morphologies. The microcomposite (phase-separated) occurs when the polymer is unable to penetrate the galleries between the tactoid clay layers, which act as conventional fillers. This morphology offers minimal property enhancement. Secondly, the intercalated nanocomposite morphology occurs when polymer chains enter the galleries, expanding the interlayer spacing but maintaining a well-ordered, stacked structure. This offers moderate property improvement. Finally, an exfoliated nanocomposite is one in which the individual clay layers are completely separated and uniformly dispersed throughout the polymer matrix. This state maximizes the filler-matrix interface, unlocking the full potential for property enhancement and representing the ideal morphology for many applications [276].

2.3 Interfacial Interaction Between Polymer Matrices and Nanofillers

The vast interfacial region in a nanocomposite is where the polymer matrix and nanofiller meet, and the nature of the interactions within this region dictates the material's ultimate performance. The strength and efficiency of load transfer, thermal transport, and barrier properties depend on the quality of interfacial adhesion. This adhesion is not a single phenomenon but a complex interplay of several bonding mechanisms, each contributing to varying degrees [277]. Covalent bonding is the strongest form of interaction, involving the formation of direct chemical bonds between the nanofiller and the polymer matrix. It is typically achieved by chemically functionalizing the nanofiller surface with reactive groups (e.g., carboxyl, hydroxyl, or amine groups) that can then form covalent linkages with the polymer chains during processing [278]. While providing superior adhesion and load transfer, this aggressive functionalization can sometimes disrupt the nanofiller's intrinsic structure (e.g., the

sp^2 carbon network in graphene or CNTs), potentially compromising its inherent properties.

Hydrogen bonding provides an intermediate-strength, non-covalent interaction that is crucial in systems where either the polymer or the nanofiller possesses polar functional groups. For example, the hydroxyl groups on the surface of silica nanoparticles can form extensive hydrogen-bond networks with polymers containing carbonyl, hydroxyl, or amine functionalities, such as polyvinyl alcohol or nylons [279]. These bonds are strong enough to ensure good adhesion but are also reversible, allowing for some degree of stress relaxation and energy dissipation, which can enhance toughness. Lastly, the van der Waals forces are weaker, non-specific interactions, including London dispersion forces and dipole-dipole interactions, that are ubiquitous at all interfaces. While individually weak, their cumulative effect over the enormous interfacial area in a nanocomposite can be substantial [280]. They are the primary mechanism of adhesion for non-functionalized, pristine nanofillers and play a key role in non-covalent functionalization strategies, where molecules adsorb onto the nanofiller surface via mechanisms such as π-π stacking on graphene or CNTs.

Mechanical interlocking is a physical mechanism in which polymer chains penetrate the rough surfaces, pores, or entangled networks of nanofiller structures. This creates a physical entanglement that mechanically resists interfacial sliding and pull-out [281]. It is particularly relevant for nanofillers with complex topographies, such as CNT bundles or porous nanoparticles, and is most effective when the polymer has good wetting characteristics and low viscosity during processing. Meanwhile, in nanocomposite systems where the components carry opposite charges, electrostatic attraction can significantly contribute to interfacial adhesion. This is a key principle in clay nanocomposites, where negatively charged silicate layers are often modified with cationic organic surfactants to make them compatible with and attractive to a non-polar polymer matrix [282]. Ultimately, the goal is to engineer an interface that is strong enough to transfer stress from the flexible matrix to the stiff nanofiller without becoming brittle. A weak interface leads to debonding and pull-out under load, failing to fully leverage the nanofiller's strength. Conversely, an excessively strong, rigid interface can prevent energy dissipation, leading to catastrophic failure. Achieving this optimal balance is a central theme in nanocomposite design.

2.4 Mechanisms of Performance Enhancement

The successful integration of nanofillers into a polymer matrix enhances material properties through a combination of synergistic mechanisms that operate at the nanoscale.

2.4.1 Mechanical Properties

The remarkable improvements in modulus (stiffness), strength, and toughness of nanocomposites arise from several concurrent mechanisms. The primary mechanism is efficient stress transfer, where the applied load is transferred from the soft polymer matrix to the much stiffer and stronger nanofillers [283]. For this to occur, the interfacial adhesion must be strong enough to prevent slippage. High-aspect-ratio fillers (1D and 2D) are particularly effective because they can distribute stress over a large area. Lopez-Moreno demonstrated improvements of both the Young's modulus and the tensile strength of up to 200% for polystyrene-nanotube samples with loadings of just 0.01 wt%. Additionally, nanofillers enhance toughness by introducing new energy dissipation mechanisms, such as crack deflection, in which a propagating crack is forced to navigate around nanoparticles, increasing the energy required for fracture. Furthermore, the large surface area of the nanofillers creates an interfacial polymer region where the mobility of polymer chains is restricted. This region, which can extend 5-50nm from the filler surface, acts as a stiffer, reinforcing phase in its own right, further contributing to the overall modulus and strength [285].

2.4.2 Thermal Properties

Nanofillers can significantly enhance the thermal stability and flame-retardant properties of polymers. The primary mechanism for enhancing thermal stability is a barrier effect, in which the dispersed nanofillers hinder the diffusion of volatile decomposition products out of the material and the diffusion of oxygen into it, thereby slowing the degradation process [286]. They also dissipate heat, reducing the formation of localized hot spots. Certain nanofillers, such as metal oxides, can trap free radicals generated during thermal degradation, while others promote the formation of a char layer on the surface during combustion, which insulates the underlying material from the heat source. These effects can increase the decomposition temperature of a polymer by 20-50 °C. Enhancing thermal conductivity, which is important for heat-sealing applications, is more challenging and requires forming a continuous, percolating network of conductive nanofillers, such as CNTs or graphene, to create pathways for efficient phonon transport [274].

2.4.5 Barrier Properties

For food packaging, the most critical enhancement offered by nanocomposites is the dramatic improvement in barrier properties against the permeation of gas (e.g., O_2, CO_2) and water vapor. This is primarily achieved through the tortuous path mechanism [160]. Impermeable, high-aspect-ratio platelet-like nanofillers (e.g., nanoclays, graphene) dispersed within the polymer act as physical obstacles. Gas or vapor molecules attempting to diffuse through the film are forced to navigate a longer, more convoluted path around these platelets. This increased effective diffusion path length significantly reduces the material's overall permeability. The effectiveness of this mechanism depends heavily on the nanofiller aspect ratio, orientation, and degree of exfoliation. Simple models, such as the Nielsen model, predict the permeability as a function of the filler volume (φ) and aspect ratio (α), illustrating that fillers with a higher aspect ratio provide a much greater barrier improvement for the same loading [287]. This mechanism is the key to overcoming the poor barrier performance of many biodegradable polymers, making them viable for demanding packaging applications.

3. Biopolymer Matrices for Nanocomposite Packaging

3.1. Polysaccharide-based polymers

Polysaccharide-based polymers represent the most extensively studied class of biopolymer matrices for packaging applications, owing to their abundance, renewability, and inherent biodegradability.

3.1.1 Starch-Based Systems

Starch, particularly in its thermoplastic form (TPS), has received considerable attention as a packaging matrix due to its low cost, widespread availability, and complete biodegradability [288]. Native starch requires plasticization and thermal processing to disrupt its granular structure and create a thermoplastic material for film formation. Glycerol is the most commonly employed plasticizer, though other polyols and sugars have been investigated [289]. Thermoplastic starch nanocomposites exhibit significant improvements in properties when reinforced with cellulosic nanofillers. Tanpichai et al. demonstrated exceptional property enhancements in TPS films reinforced with chitin nanofibers extracted from shrimp shell waste [290]. The nanocomposite films exhibited a 300% increase in tensile stress and a 603% increase in Young's modulus compared to control TPS films. Water contact angle increased from 86.2º to 98.6º, indicating improved hydrophobicity. Diaz-Cruz et al. reported that tensile strength increased from 3.49 MPa in control corn starch-chitosan blends to 13.61 MPa with 7.5% cellulose nanocrystal (CNC) incorporation, while water vapor permeability minimized at 2.5% CNC loading from 3.01×10^{-10} $g.m^{-1}s^{-1}Pa^{-1}$ to 2.46×10^{-10} $g.m^{-1}s^{-1}Pa^{-1}$ [291]. The films also exhibited antimicrobial activity against *Listeria monocytogenes*, with a maximum inhibition halo of 12.52 mm at 0.5% CNC.

3.1.2 Chitosan-Based Systems

Chitosan, a deacetylated derivative of chitin, offers unique advantages such as a packaging matrix, including inherent antimicrobial properties, film-forming ability, and biodegradability [292]. Its cationic nature enables electrostatic interactions with anionic polymers and nanofillers, facilitating the formation of stable nanocomposite structures. Lavrič et al. characterized chitosan films reinforced with cellulose nanocrystals and found that 3% CNC incorporation increased hydrophobicity, with water contact angles reaching 108 ± 2º [293]. Moisture absorption decreased by 15%, and water vapor transmission rate (WVTR) was reduced by 15-45% while oxygen permeability was reduced by 45%. Indumathi et al. also reported that corn starch-cellulose acetate phthalate-zinc oxide nanocomposite films exhibited optimal oxygen permeability, hydrophobicity, and antimicrobial properties, with biodegradability ranging from 30 to 50% [294].

3.1.3 Cellulose and Cellulose Derivatives

Cellulose and its derivatives represent highly versatile polysaccharide matrices with exceptional mechanical properties and barrier characteristics. The nanoscale structure and high specific surface area of cellulose nanoparticles (533 m^2/g) contribute to their effectiveness as both matrix materials and reinforcing agents [295]. Hydroxypropyl methyl cellulose (HPMC) films reinforced with cellulose micro- and nanofibrils (MFC/NFC) have been extensively characterized. Mascarenhas et al. found that films containing 75-100% MFC/NFC exhibited tensile strength of 50-65 MPa and Young's moduli of 6-10 MPa, though elongation at break decreased to 1-2% [296].

Transparency decreased from 80% to 65% with more than 50% MFC/NFC incorporation. Zhu et al. demonstrated that incorporating 6% nano-SiO_2 increased tensile strength by 41.2% from 54.69 MPa to 77.22 MPa, along with elongation-at-break by 57.86% from 5.9% to 14% [297].

3.2 Protein-based polymers

3.2.1 Whey Protein-Based Systems

Whey protein isolate (WPI) has been extensively investigated as a packaging matrix due to its abundance as a dairy industry byproduct and its excellent film-forming characteristics. Oymaci & Altinkaya demonstrated that incorporating zein nanoparticles into WPI matrices improved both barrier and mechanical properties [298]. The bio-nanocomposite films were prepared via casting/solvent evaporation fabrication, and the study confirmed biodegradability alongside enhanced properties.

3.2.2 Casein-Based Systems

Calcium caseinate has been explored in blend systems with modified starch and polyvinyl alcohol (PVA). Mesa et al. developed nanocomposite films incorporating bentonite nanoclay via solution casting with glycerol as a plasticizer. The nanocomposite films showed that tensile strength can improve by up to 30% when compared to comparable biopolymer formulations, and in comparison to previously published casein-starch compositions, water vapor permeability was considerably decreased [299].

3.2.3 Zein-Based Systems

Zein, a corn-derived protein, exhibits hydrophobic characteristics that complement the hydrophilic nature of many other biopolymers and bioactive compounds, such as essential oils [300]. Its incorporation as nanoparticles into whey protein matrices has been shown to improve barriers and mechanical properties [298]. Furthermore, studies by Huang et al. indicated that eugenol, when combined with zein and PLA, effectively retarded the proliferation of both *S. aureus* and *E. coli* at concentrations below 3% [301].

3.3 Lipid-Based Matrix and Blends

Lipid-based matrices, while less extensively studied than polysaccharide and protein systems, offer unique advantages for moisture barrier applications due to their hydrophobic nature. They can be incorporated as standalone matrices or as components in multilayer and blend systems to enhance water vapor barrier properties. There are limited studies on lipid-based nanocomposite matrices, suggesting this remains an area requiring further research.

3.4 Emerging Biopolymers

Emerging biopolymers, including polylactic acid (PLA), polyhydroxyalkanoates (PHA, PHBV, PHB), and polybutylene succinate (PBS), are synthetic polymers derived from biobased monomers via fermentation or chemical synthesis [302]. There are several advantages, including biodegradability; however, several modifications to improve functionality are required. The use of nanocomposites presents a sustainable solution.

3.4.1 Polylactic Acid

Polylactic acid (PLA), derived from corn, sugarcane, or cassava, has emerged as the most commercially successful biopolymer for packaging applications [303]. The use of nanocomposite technology addresses PLA's limitations, including deterioration under room humidity and at high temperatures, as well as its limited gas barrier properties. Dadashi et al. demonstrated that the inclusion of organoclay in polylactic acid significantly improves the mechanical properties, showing increased tensile strength and elastic modulus, though the elongation percentage decreased [304]. There was a significant improvement in barrier properties, with water permeability decreasing by 12-50% after adding 3-7 wt% of organoclay (Cloisite 20A-C20A) to PLA. Similarly, Hossain et al. found that the addition of 1 wt% cellulose nanowhiskers increased the tensile strength and modulus of polylactic acid by 34% and 31% respectively [305].

3.4.2 Polyhydroxyalkanoates

Polyhydroxyalkanoates represent a family of polyesters produced by bacterial fermentation, offering excellent biodegradability and biocompatibility. Poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) has received particular attention due to its improved processability compared to poly(3-hydroxybutyrate) (PHB). The inclusion of nanocomposites has improved functional performance. For instance, Ojha et al. fabricated PHBV/SiO_2 nanocomposites via solution casting using biogenic silica nanoparticles synthesized from *Wickerhamomyces anomalus* [306]. The nanocomposites showed significant improvements in physical, chemical, and thermos-mechanical properties compared to the controls. Similarly, Zare et al. developed smart, fortified PHBV-chitosan biopolymer films with ZnO-Ag nanocomposites synthesized using Thymus vulgaris leaf extract as a stabilizer and reducing agent [307]. The films demonstrated enhanced mechanical properties, antimicrobial activity, and low migration rates.

3.4.3 Polybutylene Succinate (PBS)

Polybutylene succinate, succinate (PBS), a semisynthetic aliphatic polyester, offers excellent processability and biodegradability. PBS-based bio-nanocomposites for food packaging applications have been extensively studied, with significant improvements in functional performance. Xu et al. demonstrated that PBS-based nanocomposites increased the tensile strength from 23.2-24.9 MPa to 32.9 MPa with NCC and 43.6 MPa with CHW [308]. Barrier properties were improved, with the oxygen transmission rate decreasing from 737.7 to 280 cc/m^2/day with 3% NCC.WVTR was also reduced to 49.4 g/m^2/day from 83.8 g/m^2/day.

3.5 Synthetic-Biopolymer Blends: Role of Compatibilizers

The blending of synthetic polymers with biopolymers represents a strategic approach to balancing performance, cost, and sustainability in packaging applications. However, compatibility and phase behavior are critical determinants of blend performance, influencing mechanical properties, barrier characteristics, and long-term stability. Immiscible polymer blends typically exhibit poor interfacial adhesion, leading to phase separation and compromised properties. The thermodynamic compatibility of polymer blends is governed by the Flory-Huggins interaction parameter, which depends on the chemical structures and polarities of the component polymers [309]. Therefore, compatibilizers play a crucial role in improving interfacial adhesion, reducing domain size, and stabilizing blend morphologies. Both reactive and non-reactive compatibilizers have been employed in biopolymer nanocomposite systems.

Methylene diphenyl diisocyanate (MDI) is a highly effective reactive compatibilizer for biopolymer nanocomposites. Xu et al. showed that adding 4% MDI to PLA/NCC nanocomposites reduced the oxygen and water transmission rates from 180.8 to 109.3 cc/m2/day and from 44.4 to 28.6 g/m2/day, respectively [308]. In addition to the use of compatibilizers, nanofiller surface modification can be performed. Pal et al. employed organically modified montmorillonite clay treated with organic surfactants to enhance compatibility with the PHBV/PBAT matrix [310]. Organic modification reduces the surface energy of the nano clay and improves its dispersion in the hydrophobic polymer matrix.

4. Nanofillers Used in Nanocomposite-based Packaging

4.1 Inorganic Nanofillers

Inorganic nanofillers represent the most extensively studied class of nanomaterials for food packaging applications, offering excellent mechanical reinforcement, barrier enhancement, and antimicrobial properties.

4.1.1 Nano clays

Nano clays, particularly montmorillonite (MMT) and halloysite nanotubes (HNT), are among the most widely used nanofillers in packaging due to their high aspect ratio, natural abundance, low cost, and excellent barrier properties [311]. Montmorillonite is a layered aluminosilicate clay mineral with a platelet structure that, when properly exfoliated or intercalated within polymer matrices, creates tortuous pathways that significantly reduce gas and moisture permeability [312]. Halloysite nanotubes are naturally occurring aluminosilicate clay minerals with a unique tubular structure (inner diameter 10-30 nm, outer diameter 40-70 nm, length 500-1000 nm) that provides excellent mechanical reinforcement and can serve as nanocontainers for the controlled release of active agents [313]. The tubular morphology of HNT offers advantages over platelet-shaped clays, including easier dispersion and the ability to encapsulate and release antimicrobial or antioxidant agents [311]. However, achieving uniform dispersion of nanoclays remains a critical challenge, as agglomeration can compromise their enhanced properties and create defects in the packaging material.

4.1.2 Metal Nanoparticles

Metal nanoparticles, particularly silver, zinc, and copper, are extensively incorporated into food packaging nanocomposites primarily for their potent antimicrobial properties. Silver nanoparticles (AgNPs) are the most widely studied meta nanoparticles for food packaging applications due to their broad-spectrum antimicrobial activity against bacteria, fungi, and viruses [314]. The antimicrobial mechanism of AgNPs involves multiple pathways, including the release of silver ions (Ag+) that disrupt bacterial cell membranes, interfere with DNA replication, and generate reactive oxygen species (ROS) that cause oxidative stress [315]. Accordingly, Madivoli et al. reported that cellulose nanofibrils (CNF) and silver nanoparticles (AgNPs) enhanced the mechanical properties of a polyvinyl alcohol nanocomposite film while proving effective against gram-positive and gram-negative bacteria [316]. The integration of CNF and AgNPs significantly increased tensile strength by twofold, attributed to strong hydrogen-bonding interactions between the hydroxyl groups of PVA and the nanofillers, which restricted polymer chain motion. Importantly, other studies found that AgNPs and TiO_2 nanoparticles released metal ions from packaging into the contents in insufficient amounts to cause harm to human cells. Huang et al. found that TiO_2 migrated into food simulants ranged from 0.0046 mg/kg to 0.61 mg/kg, and microwave treatment increased nanoparticle migration [317]. Similarly, Hari et al. studied the impact of incorporating ZnO nanoparticles into pectin films and found that it increased antibacterial activity against both E. coli and S. aureus by 97.2% and 98.3%, respectively [318].

4.1.3 Metal Oxide Nanoparticles

Metal oxide nanoparticles, including zinc oxide, titanium dioxide (TiO_2), magnesium oxide (MgO), and silicon dioxide (SiO_2), are extensively used in food packaging nanocomposites for their multifunctional properties, including antimicrobial activity, UV-blocking capability, mechanical reinforcement, and barrier enhancement [319]. Zinc oxide nanoparticles, in particular, are valued for their strong antimicrobial activity, UV-blocking properties, and relatively low toxicity compared to other metal oxides. Titanium dioxide nanoparticles also offer excellent UV-blocking properties, photocatalytic antimicrobial activity, and mechanical reinforcement [320]. Vieira et al. also reported that they pose potential health risks, as they produce insufficient meta ions to harm human cells [315]. The selection of metal oxide nanoparticles depends on the specific functional requirements of the packaging application, with considerations for antimicrobial efficacy and UV protection.

4.2 Organic and Bio-based Nanofillers

Organic and biobased nanofillers have also gained attention as sustainable alternatives to inorganic nanofillers, offering the advantages of biodegradability, biocompatibility, renewability, and a lower environmental impact.

4.2.1 Nanocellulose

Nanocellulose derived from renewable plant sources is among the most promising bio-based nanofillers for sustainable food packaging. Nanocellulose exists in three main forms: Cellulose Nanocrystals (CNC), Cellulose Nanofibrils (CNF), and bacterial nanocellulose (BNC), each with distinct morphologies, properties, and production methods. CNCs are rod-like crystalline structures with diameters of 3-20 nm, produced by acid hydrolysis of cellulose, which offer excellent mechanical reinforcement due to their high crystallinity and aspect ratio [321]. CNFs are long, flexible, and entangled fibers with a diameter of 5-60 nm, produced by mechanical disintegration, and also provide excellent mechanical reinforcement and network-forming properties [322]. Bacterial nanocellulose is produced by bacterial fermentation, forming a highly pure, three-dimensional network structure with exceptional mechanical properties and water-holding capacity. Challenges for nanocellulose-based packaging include moisture sensitivity, limited barrier properties against water vapor, and higher production costs compared to conventional materials [323].

4.2.2 Chitin and Chitosan Nanoparticles

Chitin and chitosan nanoparticles are biobased nanofillers derived from crustacean shells, insect exoskeletons, and fungal cell walls, offering unique advantages of biodegradability, biocompatibility, and inherent antimicrobial properties [315]. Chitosan, the deacetylated derivative of chitin, exhibits strong antimicrobial activity due to its cationic nature, which interacts with negatively charged bacterial cell membranes, causing membrane disruption and cell death. Baishya et al. highlight chitin and chitosan as important organic nanofillers for reinforcing biopolymer composites, improving mechanical, barrier, antimicrobial, and antioxidant properties for sustainable packaging [324]. Challenges for chitin and chitosan nanoparticles include variability in source materials, deacetylation degree, molecular weight, and dispersion in hydrophobic polymer matrices. Therefore, surface modification and compatibilization strategies are essential for achieving uniform dispersion and optimal performance in nanocomposite packaging materials.

4.2.3 Protein-Based Nanoparticles

Protein-based nanoparticles derived from whey protein, soy protein, zein, gelatin, and casein represent emerging bio-based nanofillers for food packaging. Proteins offer several advantages, including their ability to form films and coatings with good mechanical and barrier properties. Protein nanoparticles can be produced via desolvation, coacervation, emulsification, and electrospraying, allowing greater control over particle size and nanoparticle morphology [324]. Challenges include moisture sensitivity, limited thermal stability, potential allergenicity, and higher cost compared to synthetic polymers.

4.3 Carbon-Based Nanofillers

Carbon-based nanofillers, including carbon nanotubes (CNTs), graphene, graphene oxide (GO), and functionalized carbon nanostructures, offer exceptional mechanical, electrical, thermal, and barrier properties, making them attractive for advanced packaging.

CNTs are cylindrical nanostructures composed of rolled graphene sheets, available as single-walled or multi-walled carbon nanotubes, with exceptional mechanical, electrical, and thermal properties. They provide excellent mechanical reinforcement even at low loading levels (typically 0.5-5 wt%), significantly improving tensile strength, modulus, and toughness of polymer matrices [325]. Challenges for CNT-based packaging include high cost, difficulty in achieving uniform dispersion due to strong Van der Waals interactions and tendency to agglomerate, potential toxicity concerns, and regulatory uncertainties. Surface functionalization of CNTs with chemical groups or polymers can improve dispersion and compatibility with polymer matrices, although it adds complexity and cost to the manufacturing process.

Graphene, a two-dimensional single layer of carbon atoms arranged in a hexagonal lattice, and its oxidized derivative, graphene oxide, offer exceptional mechanical, barrier, and electrical properties for packaging. Both graphene and graphene oxide exhibit superior barrier properties compared to other nanofillers, owing to their high aspect ratios and impermeability to gases and vapors [326]. Even at very low incorporation levels (0.1-2 wt%), graphene can dramatically reduce oxygen and water vapor permeability, making it highly effective for extending food shelf life. Graphene oxide offers the advantage of easier dispersion in aqueous and polar solvents due to its oxygen-containing functional groups, and can be reduced to restore some of graphene's electrical conductivity for smart packaging applications [327]. Challenges include high cost, difficulty in large-scale production, and potential toxicity concerns.

5. Processing and Fabrication Techniques

The processing method employed for nanocomposite fabrication critically influences nanofiller dispersion and morphology, and ultimately the properties of the final packaging material. The choice of processing technique depends on the polymer matrix characteristics (thermoplastic vs. water-soluble), target application (flexible film vs. rigid container), production scale, and economic considerations.

5.1 Solution casting

Solution casting is the predominant processing method for water-soluble polymers like PVA and laboratory-scale research on all polymer types. The process involves dissolving the polymer in a suitable solvent, dispersing the nanofiller (via sonication or high shear mixing), casting the solution into a mold or onto a substrate, and evaporating the solvent to form a film. Several studies have used this method due to its suitability for laboratory-scale research and optimization, its low processing temperatures, its ability to avoid thermal degradation, and its excellent nanofiller dispersion achievable through sonication and stirring. For instance, Thomas et al. used solution casting to produce PVA-PEO/halloysite nanotube/nanocellulose films, with careful attention to nanofiller dispersion and interfacial adhesion, resulting in good, homogeneous nanofiller dispersion and avoiding significant aggregation [328]. Zare et al. also used ultrasonication during solution casting to achieve uniform dispersion of ZnO-Ag nanocomposites in PHBV-chitosan matrices without coupling agents, resulting in a homogeneous distribution without the need for surfactants [307]. However, some limitations of the method include environmental and safety concerns due to solvent use, unsuitability for high-volume production as it is a slow, batch process, and limited to thin films as it is difficult to produce thick sections.

5.2 Melt blending and extrusion

Melt blending and extrusion are the most widely used methods for producing PE and PP nanocomposites. It involves feeding polymer pellets and nanofiller into an extruder, where intensive shear forces and elevated temperatures promote nanofiller dispersion and exfoliation. Barros et al. employed blown film extrusion, a variant in which the extruded melt is inflated into a bubble to produce LDPE/nano-clay films with improved barrier properties [329]. Key factors that influence blown film extrusion include the temperature profile, screw speed and configuration, and nanofiller feeding method. For PET nanocomposites, melt compounding followed by compression molding or injection molding is commonly employed. Feng et al. used a melt hot-press procedure to prepare PET/hydrotalcite composite films, in which PET and the nanofiller were uniformly dispersed using a suspended stirrer, dried under vacuum, and then pressed at 280 °C under 20 tons of pressure [330]. Again, Pal et al. used compression molding and cast-film extrusion to produce PHBV/PBAT/nano-clay nanocomposites [310]. The study employed a two-step melt extrusion process: creating a nanoclay masterbatch by blending PBAT with 20% nanoclay, then using this masterbatch to reinforce the PHBV/PBAT blend. This method avoids the use of solvents and enables good nanofiller dispersion through intensive mixing and high pressure. Some challenges of the method include potential thermal degradation of heat-sensitive polymers and bioactive compounds, high energy consumption, and difficulty achieving uniform nanofiller dispersion due to high melt viscosity.

5.3 Electrospinning and electrospraying

Electrospinning and electrospraying are electrostatic processing techniques for creating nanofiber mats or nanoparticle coatings from polymer solutions or melts, offering unique morphologies and high surface area for active packaging applications [322]. It produces continuous nanofibers (diameter 50-500 nm) by applying high voltage to a polymer solution, while electrospraying produces discrete nanoparticles or microparticles [331]. Advantages of electrospinning include a high-area-to-volume ratio for enhanced active-agent release, the ability to incorporate nanofillers and bioactive compounds, and suitability for creating multilayer structures [322]. However, limitations include low production rate and challenges in creating continuous, defect-free films.

Other methods include *in situ* Polymerization, Layer-by-layer assembly, and Coating and Surface Modification Approaches, all of which are applied in creating nanocomposite packaging materials. In particular, layer-by-layer and coating approaches are used in novel technologies such as edible coatings, where the substrate is immersed in the film-forming solution to coat it.

6. Functional Properties of Nanocomposite Packaging

6.1 Mechanical Properties

Mechanical properties are fundamental to packaging performance, determining the material's ability to withstand handling, transportation, and storage stresses. Nanocomposite packaging demonstrates substantial improvements in tensile strength and elastic modulus through nanofiller reinforcement mechanisms, though often at the expense of elongation at break. For instance, El-hadi found that adding poly(3-hydroxybutyrate), cellulose nanocrystal, and a plasticizer (TBC) to polylactic acid led to an up to 205% increase in the elongation break, whereas the strength decreased from 27 MPa to 8 MPa [332]. In contrast, Thakur & Satapathy found that the addition of a 5 wt% clay-loaded nanocomposite film significantly increased tear resistance by more than twofold compared to the control film [333]. Similar findings by Dubey et al. indicated that 4.5 wt% halloysite nanotubes resulted in a consistent increase in tensile strength of about 33.3% in PLA films [334]. Most studies show non-monotonic dose-response curves for mechanical properties. At low loadings (1-3 wt%), tensile strength and modulus increase with nanofiller concentration due to reinforcement mechanisms. At intermediate loadings (3-5 wt%), properties plateau or reach maximum values. At high loadings (>5 wt%), properties often decline due to agglomeration, increased defect density, and poor dispersion. Elongation at break typically decreases monotonically with nanofiller loading due to increased rigidity and reduced polymer chain mobility.

6.2 Barrier Properties

6.2.1 Gas permeability

Oxygen and carbon dioxide barrier properties are critical for food packaging as oxygen promotes oxidative degradation (lipid rancidity, vitamin loss, color fading) and microbial growth, while CO_2 influences respiration rates and microbial activity.

Nanofillers reduce gas permeability by reducing polymer free volume and influencing diffusion pathways. For instance, Abbas et al. found that the incorporation of zinc oxide nanoparticles reduced the permeability of oxygen and carbon dioxide by 66% and 17%, respectively [335]. Similarly, Kim & Cha found that 3 wt% inclusion of nanoclay significantly reduced oxygen permeability by 59% in ethylene-vinyl alcohol copolymer-based nanocomposite films [336]. Sarfraz et al. emphasize that barrier properties of polymers can be significantly improved by incorporating low concentrations of nanofillers, making nanocomposites a potential replacement for complex multilayered polymer structures currently used in food packaging [312]. This simplification of packaging structure can reduce material costs and improve recyclability.

6.2 Water Vapor Transmission

Water vapor barrier properties are critical for controlling moisture exchange between food and the environment, preventing dehydration of fresh foods and moisture uptake by dry foods. However, for fresh produce packaging, moderate water vapor permeability is often desired to prevent condensation and maintain optimal humidity. Most biopolymer matrices, especially polysaccharides, are inherently hydrophilic and have poor water-vapor barrier properties compared to synthetic plastics. Similar to gas permeability, nanofillers can improve water vapor permeability by increasing tortuosity and filling the porous spaces in the polymer matrix, thereby improving barrier properties. Studies by Tang et al. indicated that incorporating closite 30B nanoclay into polylactic acid significantly reduced water vapor permeability by 69% at the highest loading level (5.3 vol%) compared to control PLA films. Naidu & John also found that the inclusion of 5 wt% loading of either bentonite or halloysite nanoclay significantly improved the water vapor permeability by 49% in xylan-alginate films [337]. Van & Lee also indicate that the addition of cellulose nanocrystals into a polyvinyl alcohol matrix led to a 30.3% reduction in the water vapor transmission rate [338]. However, the effectiveness of nanofillers in reducing water vapor permeability depends on their hydrophilicity, with hydrophobic nanofillers, such as graphene and nanoclays, generally more effective than hydrophilic nanofillers (e.g., unmodified nanoclays, nanocellulose).

6.3 Thermal Properties

Thermal stability is important for packaging materials that undergo heat sealing, sterilization, or hot-filling processes and affects shelf life under ambient storage conditions. Nanofillers generally improve thermal stability by acting as heat barriers, promoting char formation, and restricting polymer chain mobility. Wang et al. reported that carboxymethyl chitosan (CMCS)/MgO nanocomposites exhibited significantly higher thermal stability than pure CMCS films, as evidenced by higher thermal decomposition temperatures [339]. Similarly, De Silva et al. found that chitosan/MgO nanocomposites shifted the degradation temperature, with 27% and 37% mass loss at 5% and 10% MgO, respectively, compared to 50% mass loss with the pure chitosan film [340]. One reason for the increasing thermal stability is the effect of increased crystallinity on the polymers, as nanofillers can act as nucleating agents, increasing the crystallization rate and degree of crystallinity.

6.4 Optical and Surface Properties

Optical properties are important in several food packaging applications. Nanofillers can affect transparency depending on their loading, size, refractive index match with the polymer matrix, and dispersion quality. Well-dispersed nanofillers with sizes much smaller than the wavelength of light and refractive indices similar to those of the polymer matrix can maintain transparency, whereas larger nanofillers or agglomerates cause light scattering and reduce transparency [312]. This effect was observed by Alghamdi, who found that Ag/Au nanoparticles in a chitosan/polyacrylamide blend film decreased the direct and indirect bandgap energies with increasing concentration of mixed nanoparticles in the film [341]. Heydari et al. also found that the optical transparency of corn starch films increased with increasing glycerol content but decreased with the presence of nanoparticles (Na-MMT) [342]. In fact, the study demonstrated that the presence of the Na-Montmorillonite nanoparticles in the corn starch caused them to absorb UV light in the range of 216 to 266 nm.

Surface properties, including roughness and wettability (contact angle), influence the packaging material's performance in terms of printability, sealability, adhesion, and interaction with food products. Nanofillers can modify surface properties depending on their distribution; when concentrated at the surface, they increase roughness and alter wettability. Shanmugam et al. investigated how coating nanocellulose films with a pullulan/graphene bio-nanocomposite improves their surface properties for food packaging applications [343]. The study found that increasing the amount of graphene nanoparticles in the pullulan coating boosts the surface hydrophobicity of the coated nanocellulose film.

7. Active and Intelligent Nanocomposite Packaging

Active and intelligent packaging systems offer advanced functionalities beyond passive containment and protection, actively interacting with food and the environment to extend shelf-life, ensuring safety, and providing information on food quality. Nanocomposite materials are particularly well-suited for active and intelligent packaging due to their ability to incorporate functional nanofillers and enable controlled release, sensing, and responsive behaviors.

One key interest in nanocomposite systems is their antimicrobial activity. Several studies have shown that some nanofillers, particularly metal and metal oxide nanoparticles, possess antimicrobial activity by releasing metal ions that disrupt cell membranes and the metabolic activities of microbes. Vieira & Carvalho identify silver nanoparticles as one of the most widely used nanocomposites for antimicrobial packaging due to their effectiveness against a broad spectrum of bacteria, fungi, and yeasts [315]. Studies by Salari et al. confirmed this, as the chitosan/silver nanoparticles nanocomposite film exhibited strong antibacterial activity against food-borne pathogens, making it suitable as an active food packaging material [344].

Another interesting functionality of nanocomposite packaging is the controlled release of active agents. They can provide sustained antimicrobial activity over extended periods, avoiding burst release that can lead to rapid depletion of active agents and potential toxicity concerns [311]. Nanofillers can serve as carriers or reservoirs for antimicrobial agents, enabling controlled release through diffusion, degradation, or responsive mechanisms. Vieira et al. note that controlled-release mechanisms depend on the nanofiller type, loading, dispersion, polymer matrix properties, and environmental conditions [315]. Optimizing these parameters enables tailoring release kinetics to meet specific food preservation requirements. This phenomenon was confirmed in a study by Cui et al., who demonstrated that thymol-loaded mesoporous silica nanoparticles in potato starch films exhibited sustained release of thymol over 10 days, supporting their use in active packaging for prolonged action [345]. Furthermore, some studies have shown synergistic antimicrobial effects of nanofillers and bioactive compounds, such as essential oils and plant extracts. Cinteza et al. also demonstrated the synergistic action between chitosan-stabilized silver nanoparticles and essential oils against common Gram-negative and Gram-positive bacteria [346].

In addition to their antimicrobial action, nanocomposite materials can incorporate oxygen scavengers (e.g., iron oxide nanoparticles) or ethylene scavengers (e.g., metal oxide nanoparticles, activated carbon) to provide active scavenging functionality. Tas et al. observed this effect, where halloysite nanotubes incorporated into a polyethylene matrix had a greater ethylene-scavenging capacity than control PE films, thereby slowing down the ripening of fruits like bananas and tomatoes [347]. Nanocomposites have also been incorporated into intelligent packaging systems, enabling the integration of nanosensors through the incorporation of responsive nanoparticles, conductive nanofillers for electronic sensors, or colorimetric indicators. For instance, Tavassoli et al. formulated a nanocomposite biopolymer material from gelatin and chitosan nanofibers that incorporate plant-based extracts, anthocyanins, and saffron, as colorimetric pH-responsive indicators [348].

8. Challenges and Limitations

Despite significant advances in nanocomposite packaging research, several challenges and limitations must be addressed to enable widespread commercial adoption.

8.1 Health Concerns and Regulatory Frameworks

Toxicological and regulatory hurdles are one of the major limitations to the full exploitation of nanocomposites in the food industry. Toxicological concerns regarding nanoparticles in food packaging include the potential for nanoparticles to migrate into food materials and also to cross biological barriers, including the intestinal and blood-brain barrier, which can accumulate in organs, generate reactive oxygen species, which can cause oxidative stress leading to degenerative diseases [349]. However, evidence suggests that migration levels are typically low and may not pose significant health risks [315]. Banerjee, Bandyopadhyay & Ray highlight that concerns about health and toxicity limit the widespread adoption of polymer nanocomposites for food packaging, emphasizing the need for defined regulation and implementation

[349]. Meanwhile, regulatory frameworks for nanomaterials in food packaging vary across jurisdictions, with major regulatory agencies including the U.S FDA, EFSA, and Health Canada. Regulations, particularly those regarding metal oxide-based nanoparticles in food packaging, are a critical step toward their commercial deployment. Further research is needed to determine safe levels of addition and establish consistent regulatory frameworks to govern the safe use of nanocomposites in food packaging.

8.2 Cost and Scalability

The cost and scalability represent major barriers to the commercial adoption of nanocomposite packaging, with challenges including the high cost of many nanofillers, especially carbon- and bio-based nanofillers, as well as the need for expensive processing equipment and methods, which require a high capital investment. Mulla et al. report that while PLA nanocomposites show promising prospects for industrial acceptance, cost competitiveness with conventional packaging materials remains a challenge [350]. Therefore, laboratory studies demonstrating impressive performance improvements are difficult to translate into commercial products due to the high costs and scalability challenges. The scalability challenges also do not comprise only production capacity but also the maintenance of consistent quality and properties at a large scale. More investment and policies should be implemented to facilitate the adoption of nanocomposites in the food industry, as they offer more sustainable alternatives.

8.3 Sustainability and Environmental Impact

Although sustainability considerations strongly drive the development of nanocomposites, more research is needed on the biodegradability, compostability, and recyclability of the different nanocomposite types. Ros-Lis et al. reported that the superior performance of nanocomposites, such as reduced material weight and prolonged shelf life of fresh products, can compensate for the increased cost associated with incorporating nanoparticles by reducing food loss [351]. Anjos et al. conducted a comprehensive study of the biodegradation behavior of PLA/PHBV/carbonaceous materials hybrid nanocomposites [352]. The study confirmed aerobic biodegradation via aerobic composting, demonstrating that nanocomposite formation does not compromise the biopolymer matrix's inherent biodegradability. However, lifecycle assessment studies on packaging nanocomposites face limitations, such as the absence of functional units that account for the additional functionalities of nanomaterials, the lack of transparent life cycle inventory data for nanoparticle production, and scarce information on nanoparticle release. This may also pose recyclability issues, as different nanocomposite materials and their constituents may require distinct processing strategies. Therefore, major research studies should be conducted in the area to back the sustainability claims of nanocomposite packaging materials.

9. Conclusion

The field of nanocomposite packaging is rapidly evolving, with several promising directions for future research and development that can address current limitations and unlock new functionalities. Several research studies have shown the significant impact of nanocomposites in improving the functional performance of packaging materials and their role in overcoming challenges with conventional packaging materials. However, its full commercialization faces hurdles on both technological and regulatory fronts, and further research into its safety and environmental sustainability can help overcome them. The use of modern technologies, such as Artificial intelligence and machine learning approaches, offers powerful tools for accelerating the design and optimization of nanocomposite packaging materials through the prediction of structure-property relationships, optimization of nanofiller type, loading, and dispersion, design of multifunctional nanocomposites with tailored properties, and analysis of large datasets from literature and experiments. Furthermore, continued interdisciplinary research, industry-academia collaboration, and stakeholder engagement will be essential for realizing the full potential of nanocomposite packaging to create a safer, more sustainable food system.

References:

1. Shlush, E. and M. Davidovich-Pinhas, *Bioplastics for food packaging.* Trends in Food Science & Technology, 2022. **125**: p. 66-80.
2. Salgado, P.R., et al., *Recent Developments in Smart Food Packaging Focused on Biobased and Biodegradable Polymers.* Frontiers in Sustainable Food Systems, 2021. **Volume 5 - 2021**.
3. Versino, F., et al., *Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations.* Foods, 2023. **12**(5): p. 1057.
4. Siciliano, S., C.G. Lopresto, and F. Lamonaca, *From traditional packaging to smart bio-packaging for food safety: a review.* Euro-Mediterranean Journal for Environmental Integration, 2024. **9**(4): p. 1971-1986.
5. Hussain, S., R. Akhter, and S.S. Maktedar, *Advancements in sustainable food packaging: from eco-friendly materials to innovative technologies.* Sustainable Food Technology, 2024. **2**(5): p. 1297-1364.
6. Pulikkalparambil, H., et al., *Recent Advances in Natural Fibre-Based Materials for Food Packaging Applications.* Polymers, 2023. **15**(6): p. 1393.
7. Ada, E., et al., *Challenges for circular food packaging: Circular resources utilization.* Applied Food Research, 2023. **3**(2): p. 100310.
8. Kumari, S., et al., *Recent advances in packaging materials for food products.* Food Bioengineering, 2024. **3**(2): p. 236-249.
9. Abekoon, T., et al., *A comprehensive review to evaluate the synergy of intelligent food packaging with modern food technology and artificial intelligence field.* Discover Sustainability, 2024. **5**(1): p. 160.
10. Young, E., M. Mirosa, and P. Bremer, *A Systematic Review of Consumer Perceptions of Smart Packaging Technologies for Food.* Frontiers in Sustainable Food Systems, 2020. **Volume 4 - 2020**.

11. Kadirvel, V., Y. Palanisamy, and Nandhini D. Ganesan, *Active Packaging System—An Overview of Recent Advances for Enhanced Food Quality and Safety.* Packaging Technology and Science, 2025. **38**(2): p. 145-162.

12. Ahmed, M.W., et al., *A review on active packaging for quality and safety of foods*: *Current trends, applications, prospects and challenges.* Food Packaging and Shelf Life, 2022. **33**: p. 100913.

13. Gil, M. and M. Rudy, *Innovations in the Packaging of Meat and Meat Products—A Review.* Coatings, 2023. **13**(2): p. 333.

14. Rodriguez, O.T., et al., *Performance of Biodegradable Active Packaging in the Preservation of Fresh-Cut Fruits*: *A Systematic Review.* Polymers, 2024. **16**(24): p. 3518.

15. Zuo, J., et al., *RFID-based sensing in smart packaging for food applications*: *A review.* Future Foods, 2022. **6**: p. 100198.

16. Dodero, A., et al., *Intelligent Packaging for Real-Time Monitoring of Food-Quality*: *Current and Future Developments.* Applied Sciences, 2021. **11**(8): p. 3532.

17. Du, L., et al., *Application of Smart Packaging in Fruit and Vegetable Preservation*: *A Review.* Foods, 2025. **14**(3): p. 447.

18. Mkhari, T., J.O. Adeyemi, and O.A. Fawole, *Recent Advances in the Fabrication of Intelligent Packaging for Food Preservation*: *A Review.* Processes, 2025. **13**(2): p. 539.

19. Oliver-Cuenca, V., et al., *Bio-Based and Biodegradable Polymeric Materials for a Circular Economy.* Polymers, 2024. **16**(21): p. 3015.

20. González-López, M.E., et al., *Current trends in biopolymers for food packaging*: *a review.* Frontiers in Sustainable Food Systems, 2023. **Volume 7 - 2023**.

21. Rosenboom, J.-G., R. Langer, and G. Traverso, *Bioplastics for a circular economy.* Nature Reviews Materials, 2022. **7**(2): p. 117-137.

22. Samir, A., et al., *Recent advances in biodegradable polymers for sustainable applications.* npj Materials Degradation, 2022. **6**(1): p. 68.

23. Liu, L., et al., *Application of Modified Atmosphere Preservation Technology in Cherry Storage*: *A Review.* Agriculture, 2025. **15**(5): p. 462.

24. Rashvand, M., et al., *Recent advances in the potential of modeling and simulation to assess the performance of modified atmosphere packaging (MAP) systems for the fresh agricultural product*: *Challenges and development.* Trends in Food Science & Technology, 2023. **136**: p. 48-63.

25. Bhat, S.A., et al., *Advances in apple packaging*: *a review.* Journal of Food Science and Technology, 2023. **60**(7): p. 1847-1859.

26. Herrera, K.Y., et al., *Evaluation of perforation-mediated modified atmosphere packaging for the commercialization of bulk purple passion fruit under refrigeration.* Journal of Food Science, 2024. **89**(12): p. 8673-8688.

27. Sepúlveda-Carter, J., et al., *Regulatory Frameworks and State-of-the-Art Decontamination Technologies for Recycled Polystyrene for Food Contact Applications.* Polymers, 2025. **17**(5): p. 658.

28. De Tandt, E., et al., *A recycler's perspective on the implications of REACH and food contact material (FCM) regulations for the mechanical recycling of FCM plastics.* Waste Management, 2021. **119**: p. 315-329.

29. Farrell, R., et al., *The function and properties of common food packaging materials and their suitability for reusable packaging*: *The transition from a linear to circular economy.* Current Research in Green and Sustainable Chemistry, 2024. **9**: p. 100429.

30. Hu, Y. and T. Li, *Chapter One - Smart food packaging*: *Recent advancement and trends*, in *Advances in Food and Nutrition Research*, X. Lu, Editor. 2024, Academic Press. p. 1-33.

31. Marsh, K. and B. Bugusu, *Food Packaging—Roles, Materials, and Environmental Issues.* Journal of Food Science, 2007. **72**(3): p. R39-R55.

32. Yin, Y. and M.W. Woo, *Transitioning of petroleum-based plastic food packaging to sustainable bio-based alternatives.* Sustainable Food Technology, 2024. **2**(3): p. 548-566.

33. Nemat, B., et al., *Design-Based Approach to Support Sorting Behavior of Food Packaging.* Clean Technologies, 2023. **5**(1): p. 297-328.

34. Ceballos-Santos, S., et al., *Exploring the environmental impacts of plastic packaging: A comprehensive life cycle analysis for seafood distribution crates.* Science of The Total Environment, 2024. **951**: p. 175452.

35. Pavón Losada, J.A., et al., *Food packaging business models as drivers for sustainability in the food packaging industry.* Frontiers in Sustainable Food Systems, 2025. **Volume 9 - 2025**.

36. Thapliyal, D., et al., *Current Status of Sustainable Food Packaging Regulations: Global Perspective.* Sustainability, 2024. **16**(13): p. 5554.

37. Nemes, S.A., K. Szabo, and D.C. Vodnar, *Applicability of Agro-Industrial By-Products in Intelligent Food Packaging.* Coatings, 2020. **10**(6): p. 550.

38. Brennan, L., et al., *The role of packaging in fighting food waste: A systematised review of consumer perceptions of packaging.* Journal of Cleaner Production, 2021. **281**: p. 125276.

39. Ahmed, S., et al., *Research progress on antimicrobial materials for food packaging.* Critical Reviews in Food Science and Nutrition, 2022. **62**(11): p. 3088-3102.

40. Ganeson, K., et al., *Smart packaging - A pragmatic solution to approach sustainable food waste management.* Food Packaging and Shelf Life, 2023. **36**: p. 101044.

41. Alamri, M.S., et al., *Food packaging's materials: A food safety perspective.* Saudi Journal of Biological Sciences, 2021. **28**(8): p. 4490-4499.

42. Uhlig, E., et al., *Food wastage along the global food supply chain and the impact of food packaging.* Journal of Consumer Protection and Food Safety, 2025. **20**(1): p. 5-17.

43. Yuvaraj, D., et al., *Advances in bio food packaging – An overview.* Heliyon, 2021. **7**(9): p. e07998.

44. Ahmad, S., et al., *Packaging design, fill rate and road freight decarbonisation: A literature review and a future research agenda.* Cleaner Logistics and Supply Chain, 2022. **4**: p. 100066.

45. Operato, L., et al., *Food packaging use and post-consumer plastic waste management: a comprehensive review.* Frontiers in Food Science and Technology, 2025. **Volume 5 - 2025**.

46. Bauer, A.-S., et al., *Cereal and Confectionary Packaging: Background, Application and Shelf-Life Extension.* Foods, 2022. **11**(5): p. 697.

47. Singh, N., et al., *Sustainable materials alternative to petrochemical plastics pollution: A review analysis.* Sustainable Horizons, 2022. **2**: p. 100016.

48. Bai, F., et al., *Understanding the effect of plastic food packaging materials on food flavor: A critical review.* Trends in Food Science & Technology, 2024. **148**: p. 104502.

49. Jariyasakoolroj, P., P. Leelaphiwat, and N. Harnkarnsujarit, *Advances in research and development of bioplastic for food packaging.* Journal of the Science of Food and Agriculture, 2020. **100**(14): p. 5032-5045.

50. Ncube, L.K., et al., *An Overview of Plastic Waste Generation and Management in Food Packaging Industries.* Recycling, 2021. **6**(1): p. 12.

51. Kan, M. and S.A. Miller, *Environmental impacts of plastic packaging of food products.* Resources, Conservation and Recycling, 2022. **180**: p. 106156.

52. Verma, M.K., et al., *Trends in packaging material for food products: historical background, current scenario, and future prospects.* Journal of Food Science and Technology, 2021. **58**(11): p. 4069-4082.

53. Deshwal, G.K. and N.R. Panjagari, *Review on metal packaging: materials, forms, food applications, safety and recyclability.* Journal of Food Science and Technology, 2020. **57**(7): p. 2377-2392.

54. Deshwal, G.K., N.R. Panjagari, and T. Alam, *An overview of paper and paper based food packaging materials: health safety and environmental concerns.* Journal of Food Science and Technology, 2019. **56**(10): p. 4391-4403.

55. Iversen, L.J.L., et al., *The Emergence of Edible and Food-Application Coatings for Food Packaging: A Review.* Molecules, 2022. **27**(17): p. 5604.

56. Wang, J., et al., *Biobased materials for food packaging.* Journal of Bioresources and Bioproducts, 2022. **7**(1): p. 1-13.

57. Mangaraj, S., et al., *Application of Biodegradable Polymers in Food Packaging Industry: A Comprehensive Review.* Journal of Packaging Technology and Research, 2019. **3**(1): p. 77-96.

58. Bauer, M.G., et al., *Bio-Based and Degradable Food Packaging Materials: Where Are They?* Advanced Materials Interfaces, 2025. **12**(6): p. 2400645.

59. Asgher, M., et al., *Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials.* Food Research International, 2020. **137**: p. 109625.

60. Shi, X., et al., *Next-Generation Bioplastics for Food Packaging: Sustainable Materials and Applications.* Materials, 2025. **18**(12): p. 2919.

61. Molina-Besch, K. and H. Keszleri, *Exploring the industrial perspective on biobased plastics in food packaging applications – Insights from Sweden.* Sustainable Production and Consumption, 2023. **35**: p. 72-84.

62. Sid, S., et al., *Bio-sourced polymers as alternatives to conventional food packaging materials: A review.* Trends in Food Science & Technology, 2021. **115**: p. 87-104.

63. Perera, K.Y., A.K. Jaiswal, and S. Jaiswal, *Biopolymer-Based Sustainable Food Packaging Materials: Challenges, Solutions, and Applications.* Foods, 2023. **12**(12): p. 2422.

64. Perez-Vazquez, A., et al., *Edible Coatings as a Natural Packaging System to Improve Fruit and Vegetable Shelf Life and Quality.* Foods, 2023. **12**(19): p. 3570.

65. Matloob, A., et al., *A Review on Edible Coatings and Films: Advances, Composition, Production Methods, and Safety Concerns.* ACS Omega, 2023. **8**(32): p. 28932-28944.

66. Kumar, L., et al., *Edible films and coatings for food packaging applications: a review.* Environmental Chemistry Letters, 2022. **20**(1): p. 875-900.

67. Chettri, S., N. Sharma, and A.M. Mohite, *Edible coatings and films for shelf-life extension of fruit and vegetables.* Biomaterials Advances, 2023. **154**: p. 213632.

68. El-Sayed, S.M. and A.M. Youssef, *Emergence of cheese packaging by edible coatings for enhancing its shelf-life.* Journal of Food Measurement and Characterization, 2024. **18**(7): p. 5265-5280.

69. Jahangiri, F., A.K. Mohanty, and M. Misra, *Sustainable biodegradable coatings for food packaging: challenges and opportunities.* Green Chemistry, 2024. **26**(9): p. 4934-4974.

70. Cruz-Monterrosa, R.G., et al., *Application of Polysaccharide-Based Edible Coatings on Fruits and Vegetables: Improvement of Food Quality and Bioactivities.* Polysaccharides, 2023. **4**(2): p. 99-115.

71. Mitura, K., et al., *Active Carbon-Based Nanomaterials in Food Packaging.* Coatings, 2021. **11**(2): p. 161.

72. Herrera-Rivera, M.d.R., et al., *Nanotechnology in food packaging materials: role and application of nanoparticles.* RSC Advances, 2024. **14**(30): p. 21832-21858.

73. Chadha, U., et al., *Current Trends and Future Perspectives of Nanomaterials in Food Packaging Application.* Journal of Nanomaterials, 2022. **2022**(1): p. 2745416.

74. Dash, K.K., et al., *Applications of Inorganic Nanoparticles in Food Packaging: A Comprehensive Review.* Polymers, 2022. **14**(3): p. 521.

75. Liu, G., K. Shi, and H. Sun, *Research Progress in Hemicellulose-Based Nanocomposite Film as Food Packaging.* Polymers, 2023. **15**(4): p. 979.

76. Gupta, R.K., P. Guha, and P.P. Srivastav, *Investigating the toxicological effects of nanomaterials in food packaging associated with human health and the environment.* Journal of Hazardous Materials Letters, 2024. **5**: p. 100125.

77. de Sousa, M.S., et al., *Nanotechnology in Packaging for Food Industry: Past, Present, and Future.* Coatings, 2023. **13**(8): p. 1411.

78. Singh, A.K., et al., *Active packaging technologies for clean label food products: a review.* Journal of Food Measurement and Characterization, 2021. **15**(5): p. 4314-4324.

79. Yildirim, S., et al., *Active Packaging Applications for Food.* Comprehensive Reviews in Food Science and Food Safety, 2018. **17**(1): p. 165-199.

80. Jiang, Y., Y. Zhang, and Y. Deng, *Latest Advances in Active Materials for Food Packaging and Their Application.* Foods, 2023. **12**(22): p. 4055.

81. Fadiji, T., et al., *A Review on Antimicrobial Packaging for Extending the Shelf Life of Food.* Processes, 2023. **11**(2): p. 590.

82. Mousavi Khaneghah, A., S.M.B. Hashemi, and S. Limbo, *Antimicrobial agents and packaging systems in antimicrobial active food packaging: An overview of approaches and interactions.* Food and Bioproducts Processing, 2018. **111**: p. 1-19.

83. Jacinto-Valderrama, R.A., et al., *Recent Trends in Active Packaging Using Nanotechnology to Inhibit Oxidation and Microbiological Growth in Muscle Foods.* Foods, 2023. **12**(19): p. 3662.

84. Abraham, J., *Future of Food Packaging: Intelligent Packaging*, in *Nanotechnology in Intelligent Food Packaging*. 2022. p. 383-417.

85. Cheng, H., et al., *Recent advances in intelligent food packaging materials: Principles, preparation and applications.* Food Chemistry, 2022. **375**: p. 131738.

86. Osmólska, E., M. Stoma, and A. Starek-Wójcicka, *Application of Biosensors, Sensors, and Tags in Intelligent Packaging Used for Food Products—A Review.* Sensors, 2022. **22**(24): p. 9956.

87. Müller, P. and M. Schmid, *Intelligent Packaging in the Food Sector: A Brief Overview.* Foods, 2019. **8**(1): p. 16.

88. Palanisamy, Y., V. Kadirvel, and N.D. Ganesan, *Recent technological advances in food packaging: sensors, automation, and application.* Sustainable Food Technology, 2025. **3**(1): p. 161-180.

89. Kumari, A. and K.K. Gaikwad, *Data carriers for real-time tracking and monitoring in smart, intelligent packaging applications: A technological review.* Next Materials, 2025. **8**: p. 100591.

90. Azeredo, H.M.C. and D.S. Correa, *Smart choices: Mechanisms of intelligent food packaging.* Current Research in Food Science, 2021. **4**: p. 932-936.

91. D'Almeida, A.P. and T.L. de Albuquerque, *Innovations in Food Packaging: From Bio-Based Materials to Smart Packaging Systems.* Processes, 2024. **12**(10): p. 2085.

92. Oliveira, M., et al., *Application of modified atmosphere packaging as a safety approach to fresh-cut fruits and vegetables – A review.* Trends in Food Science & Technology, 2015. **46**(1): p. 13-26.

93. Kandeepan, G. and A. Tahseen, *Modified Atmosphere Packaging (MAP) of Meat and Meat Products: A Review.* Journal of Packaging Technology and Research, 2022. **6**(3): p. 137-148.

94. Caleb, O.J., et al., *Modified Atmosphere Packaging Technology of Fresh and Fresh-cut Produce and the Microbial Consequences—A Review.* Food and Bioprocess Technology, 2013. **6**(2): p. 303-329.

95. Habiba, U., et al., *Advancing sustainability through modified atmosphere packaging (MAP) for fresh food preservation: A critical review.* Journal of Stored Products Research, 2025. **112**: p. 102657.

96. Czerwiński, K., et al., *Towards Impact of Modified Atmosphere Packaging (MAP) on Shelf-Life of Polymer-Film-Packed Food Products: Challenges and Sustainable Developments.* Coatings, 2021. **11**(12): p. 1504.

97. Schifferstein, H.N.J., A. de Boer, and M. Lemke, *Conveying information through food packaging: A literature review comparing legislation with consumer perception.* Journal of Functional Foods, 2021. **86**: p. 104734.

98. Lacourt, C., et al., *Recent and emerging food packaging alternatives: Chemical safety risks, current regulations, and analytical challenges.* Comprehensive Reviews in Food Science and Food Safety, 2024. **23**(6): p. e70059.

99. Cazón, P., et al., *Polysaccharide-based films and coatings for food packaging: A review.* Food Hydrocolloids, 2017. **68**: p. 136-148.

100. Yao, Q.-b., et al., *Polysaccharide-based food packaging and intelligent packaging applications: A comprehensive review.* Trends in Food Science & Technology, 2024. **147**.

101. Guo, J., et al., *Polysaccharide-based high barrier food packaging film: design and application.* Critical Reviews in Food Science and Nutrition, 2025: p. 1-20.

102. Thivya, P., et al., *Recent advances in protein-polysaccharide based biocomposites and their potential applications in food packaging: A review.* International Journal of Biological Macromolecules, 2024. **268**(Pt 2): p. 131757.

103. Ahmed, J., et al., *Thermo-mechanical, rheological, microstructural, and barrier properties of gum-based edible packaging: A review.* Food Packaging and Shelf Life, 2023. **38**.

104. Santhosh, R., D. Nath, and P. Sarkar, *Novel food packaging materials including plant-based byproducts: A review.* Trends in Food Science & Technology, 2021. **118**: p. 471-489.

105. Liu, D., et al., *Recent Advances and Applications in Starch for Intelligent Active Food Packaging: A Review.* Foods, 2022. **11**(18).

106. Taguchi, T., et al., *Evaluation of starch retrogradation by X-ray diffraction using a water-addition method.* Lwt, 2023. **173**.

107. Dominguez-Ayala, J.E., et al., *Crystal structure changes of native and retrograded starches modified by high hydrostatic pressure: Physical dual modification.* Food Hydrocolloids, 2023. **140**.

108. Yekta, R., et al., *Application of cellulose and cellulose derivatives in smart/intelligent bio-based food packaging.* Cellulose, 2023. **30**(16): p. 9925-9953.

109. Liu, Y., et al., *A review of cellulose and its derivatives in biopolymer-based for food packaging application.* Trends in Food Science & Technology, 2021. **112**: p. 532-546.

110. Carvalho, A.C.F., et al., *Valuing agro-industrial waste in the development of sustainable food packaging based on the system of a circular bioeconomy: A review.* Cleaner Waste Systems, 2025. **11**.

111. Santhosh, R. and P. Sarkar, *Jackfruit seed starch/tamarind kernel xyloglucan/zinc oxide nanoparticles-based composite films: Preparation, characterization, and*

application on tomato (Solanum lycopersicum) fruits. Food Hydrocolloids, 2022. **133**.

112. Santhosh, R. and P. Sarkar, *Fabrication of jamun seed starch/tamarind kernel xyloglucan bio-nanocomposite films incorporated with chitosan nanoparticles and their application on sapota (Manilkara zapota) fruits.* International Journal of Biological Macromolecules, 2024. **260**(Pt 2): p. 129625.

113. Santhosh, R., et al., *Active bio-nanocomposites from litchi seed starch, tamarind kernel xyloglucan, and lignin nanoparticles to improve the shelf-life of banana (Musa acuminata).* Food Chem, 2025. **463**(Pt 3): p. 141327.

114. Karuppan Perumal, M.K., et al., *Zinc oxide nanoparticles and their nanocomposites as an imperative coating for smart food packaging.* Applied Food Research, 2025. **5**(1).

115. Mondal, S.K., et al., *Antimicrobial nanoparticles: current landscape and future challenges.* RSC Pharmaceutics, 2024. **1**(3): p. 388-402.

116. Khodadadi, F., M. Nikzad, and S. Hamedi, *Lignin nanoparticles as a promising nanomaterial for encapsulation of Rose damascene essential oil: Physicochemical, structural, antimicrobial and in-vitro release properties.* Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2024. **687**.

117. Chen, S.Q., et al., *Mechanical properties and wound healing potential of bacterial cellulose-xyloglucan-dextran hydrogels.* Carbohydr Polym, 2023. **321**: p. 121268.

118. da Silva, A.C.C., et al., *Xyloglucan-based hybrid nanocomposite with potential for biomedical applications.* Int J Biol Macromol, 2021. **168**: p. 722-732.

119. Freitas, R., et al., *Physico-chemical properties of seed xyloglucans from different sources.* Carbohydrate Polymers, 2005. **60**(4): p. 507-514.

120. Kochumalayil, J., et al., *Tamarind seed xyloglucan – a thermostable high-performance biopolymer from non-food feedstock.* Journal of Materials Chemistry, 2010. **20**(21).

121. Wataoka, I., et al., *Gelation of tamarind seed xyloglucan in sucrose aqueous solution as observed by small-angle X-ray scattering.* Food Hydrocolloids, 2023. **145**.

122. Adair, P., et al., *Preparation, characterization, and antimicrobial activity of xyloglucan-chitosan film from tamarind (tamarind indica L.) seed kernel.* Progress in Organic Coatings, 2023. **179**.

123. Onyeaka, H., et al., *Current Research and Applications of Starch-Based Biodegradable Films for Food Packaging.* Polymers (Basel), 2022. **14**(6).

124. Vianna, T.C., et al., *Essential oils as additives in active starch-based food packaging films: A review.* Int J Biol Macromol, 2021. **182**: p. 1803-1819.

125. García-Guzmán, L., et al., *Progress in Starch-Based Materials for Food Packaging Applications.* Polysaccharides, 2022. **3**(1): p. 136-177.

126. Zhong, C., et al., *Preparation and characterization of rice starch citrates by superheated steam: A new strategy of producing resistant starch.* Lwt, 2022. **154**.

127. Cheng, H., et al., *Starch-based biodegradable packaging materials: A review of their preparation, characterization and diverse applications in the food industry.* Trends in Food Science & Technology, 2021. **114**: p. 70-82.

128. Bangar, S.P., et al., *Functionality and Applicability of Starch-Based Films: An Eco-Friendly Approach.* Foods, 2021. **10**(9).

129. Munoz-Gimena, P.F., et al., *A Review on Reinforcements and Additives in Starch-Based Composites for Food Packaging.* Polymers (Basel), 2023. **15**(13).

130. Cheng, J., et al., *Applications of biodegradable materials in food packaging: A review.* Alexandria Engineering Journal, 2024. **91**: p. 70-83.

131. González-Seligra, P., et al., *Influence of extrusion process conditions on starch film morphology.* Lwt, 2017. **84**: p. 520-528.

132. Gao, W., et al., *Development and characterization of starch films prepared by extrusion blowing: The synergistic plasticizing effect of water and glycerol.* Lwt, 2021. **148**.

133. Pushpadass, H.A., D.B. Marx, and M.A. Hanna, *Effects of Extrusion Temperature and Plasticizers on the Physical and Functional Properties of Starch Films.* Starch - Stärke, 2008. **60**(10): p. 527-538.

134. Wu, H., et al., *Development and characterization of antioxidant composite films based on starch and gelatin incorporating resveratrol fabricated by extrusion compression moulding.* Food Hydrocolloids, 2023. **139**.

135. Wang, L., et al., *Development of starch-cellulose composite films with antimicrobial potential.* Int J Biol Macromol, 2024. **276**(Pt 1): p. 133836.

136. Zhao, Y., et al., *Comprehensive Review of Polysaccharide-Based Materials in Edible Packaging: A Sustainable Approach.* Foods, 2021. **10**(8).

137. Sreekanth, K., et al., *Microbial load reduction in stored raw beef meat using chitosan/starch-based active packaging films incorporated with cellulose nanofibers and cinnamon essential oil.* Meat Science, 2024. **216**: p. 109552.

138. Wu, Y., et al., *Preparation of edible antibacterial films based on corn starch /carbon nanodots for bioactive food packaging.* Food Chemistry, 2024. **444**: p. 138467.

139. Godoy Zuniga, M.M., et al., *Avocado seed starch utilized in eco-friendly, UV-blocking, and high-barrier polylactic acid (PLA) biocomposites for active food packaging applications.* Int J Biol Macromol, 2024. **265**(Pt 1): p. 130837.

140. Li, N., et al., *Development of carboxymethyl cellulose/starch films enriched with ZnO-NPs and anthocyanins for antimicrobial and pH-indicating food packaging.* Int J Biol Macromol, 2024. **282**(Pt 2): p. 136814.

141. Upadhyay, P., et al., *An Overview of Advanced Antimicrobial Food Packaging: Emphasizing Antimicrobial Agents and Polymer-Based Films.* Polymers (Basel), 2024. **16**(14).

142. Fadiji, T., et al., *A Review on Antimicrobial Packaging for Extending the Shelf Life of Food.* Processes, 2023. **11**(2).

143. Gyawali, R. and S.A. Ibrahim, *Natural products as antimicrobial agents.* Food Control, 2014. **46**: p. 412-429.

144. Manzoor, A., et al., *Plant-derived active substances incorporated as antioxidant, antibacterial or antifungal components in coatings/films for food packaging applications.* Food Bioscience, 2023. **53**.

145. Sharma, S., et al., *Essential oils as additives in active food packaging.* Food Chem, 2021. **343**: p. 128403.

146. Ebrahimzadeh, S., et al., *Incorporation of essential oils in edible seaweed-based films: A comprehensive review.* Trends in Food Science & Technology, 2023. **135**: p. 43-56.

147. Kumar, H., et al., *Antioxidant Film Based on Chitosan and Tulsi Essential Oil for Food Packaging.* Food and Bioprocess Technology, 2022. **16**(2): p. 342-355.

148. Lima, R.P., et al., *Development of Gelatin-Based Renewable Packaging with Melaleuca alternifolia Essential Oil for Chicken Breast Preservation.* Polymers (Basel), 2025. **17**(5).

149. Istiqomah, A., et al., *Valorisation of lemongrass essential oils onto chitosan-starch film for sustainable active packaging: Greatly enhanced antibacterial and antioxidant activity.* Int J Biol Macromol, 2022. **210**: p. 669-681.

150. Yang, Z., et al., *Development and characterization of sodium alginate/tea tree essential oil nanoemulsion active film containing TiO(2) nanoparticles for banana packaging.* Int J Biol Macromol, 2022. **213**: p. 145-154.

151. Subbuvel, M. and P. Kavan, *Preparation and characterization of polylactic acid/fenugreek essential oil/curcumin composite films for food packaging applications.* Int J Biol Macromol, 2022. **194**: p. 470-483.

152. Carpena, M., et al., *Essential Oils and Their Application on Active Packaging Systems: A Review.* Resources, 2021. **10**(1).

153. Reis, D.R., A. Ambrosi, and M.D. Luccio, *Encapsulated essential oils: A perspective in food preservation.* Future Foods, 2022. **5**.

154. Hanan, E., et al., *New insights into essential oil nano emulsions loaded natural biopolymers recent development, formulation, characterization and packaging applications: A comprehensive review.* Int J Biol Macromol, 2024. **280**(Pt 2): p. 135751.

155. Liu, Y., et al., *Antimicrobial peptides and their application in food packaging.* Trends in Food Science & Technology, 2021. **112**: p. 471-483.

156. Lopresti, F., et al., *Combining carvacrol and nisin in biodegradable films for antibacterial packaging applications.* Int J Biol Macromol, 2021. **193**(Pt A): p. 117-126.

157. Tavares, T.D., et al., *Combinatory effect of nisin antimicrobial peptide with bioactive molecules: A review.* Journal of Drug Delivery Science and Technology, 2024. **91**.

158. Cleveland, J., et al., *Bacteriocins: safe, natural antimicrobials for food preservation.* Int J Food Microbiol, 2001. **71**(1): p. 1-20.

159. Gao, Y., M.J. van Belkum, and M.E. Stiles, *The outer membrane of gram-negative bacteria inhibits antibacterial activity of brochocin-C.* Appl Environ Microbiol, 1999. **65**(10): p. 4329-33.

160. Singh, B.P., et al., *Nano-Conjugated Food-Derived Antimicrobial Peptides As Natural Biopreservatives: A Review of Technology and Applications.* Antibiotics (Basel), 2023. **12**(2).

161. Radaic, A., M.B. de Jesus, and Y.L. Kapila, *Bacterial anti-microbial peptides and nano-sized drug delivery systems: The state of the art toward improved bacteriocins.* J Control Release, 2020. **321**: p. 100-118.

162. Popa, E.E., et al., *Antimicrobial Active Packaging Containing Nisin for Preservation of Products of Animal Origin: An Overview.* Foods, 2022. **11**(23).

163. Shin, J.M., et al., *Biomedical applications of nisin.* J Appl Microbiol, 2016. **120**(6): p. 1449-65.

164. Guo, L., et al., *Altering Specificity and Enhancing Stability of the Antimicrobial Peptides Nisin and Rombocin through Dehydrated Amino Acid Residue Engineering.* Peptides, 2024. **174**: p. 171152.

165. Prince, A., et al., *Lipid-II Independent Antimicrobial Mechanism of Nisin Depends On Its Crowding And Degree Of Oligomerization.* Sci Rep, 2016. **6**: p. 37908.

166. Scherer, K.M., et al., *The lantibiotic nisin induces lipid II aggregation, causing membrane instability and vesicle budding.* Biophys J, 2015. **108**(5): p. 1114-24.

167. Wiedemann, I., et al., *Specific binding of nisin to the peptidoglycan precursor lipid II combines pore formation and inhibition of cell wall biosynthesis for potent antibiotic activity.* J Biol Chem, 2001. **276**(3): p. 1772-9.

168. Li, Q., M. Montalban-Lopez, and O.P. Kuipers, *Increasing the Antimicrobial Activity of Nisin-Based Lantibiotics against Gram-Negative Pathogens.* Appl Environ Microbiol, 2018. **84**(12).

169. Liang, Q., et al., *Current status and potential of bacteriocin-producing lactic acid bacteria applied in the food industry.* Curr Res Food Sci, 2025. **10**: p. 100997.

170. Elsherif, W.M., et al., *Natural approach of using nisin and its nanoform as food bio-preservatives against methicillin resistant Staphylococcus aureus and E.coli O157:H7 in yoghurt.* BMC Vet Res, 2024. **20**(1): p. 192.

171. Li, S., et al., *Recent advances in microbial epsilon-poly-L-lysine fermentation and its diverse applications.* Biotechnol Biofuels Bioprod, 2022. **15**(1): p. 65.

172. Chen, X.-S., et al., *Preparation, characterization and antimicrobial activity of ε-poly-l-lysine with short chain length produced from glycerol by Streptomyces albulus.* Process Biochemistry, 2018. **68**: p. 22-29.

173. Wang, D., et al., *Preparation and characterization of gelatin/zein nanofiber films loaded with perillaldehyde, thymol, or varepsilon-polylysine and evaluation of their effects on the preservation of chilled chicken breast.* Food Chem, 2022. **373**(Pt A): p. 131439.

174. Zhou, X., et al., *Elaboration and characterization of epsilon-polylysine-sodium alginate nanoparticles for sustained antimicrobial activity.* Int J Biol Macromol, 2023. **251**: p. 126329.

175. Yang, J., et al., *Biopolymer-based packaging films/edible coatings functionalized with epsilon-polylysine: New options for food preservation.* Food Res Int, 2024. **187**: p. 114390.

176. Arul Raj, J.S., et al., *Green Packaging Solutions for Extending the Shelf Life of Fish Fillet: Development and Evaluation of Cinnamon Essential Oil-Infused Cassava Starch and Fish Gelatin Edible Films.* ACS Omega, 2024. **9**(46): p. 45898-45910.

177. Shi, C., et al., *Fortification of cassava starch edible films with Litsea cubeba essential oil for chicken meat preservation.* Int J Biol Macromol, 2024. **276**(Pt 2): p. 133920.

178. Suvarna, V., et al., *Antimicrobial Nanomaterials for Food Packaging.* Antibiotics (Basel), 2022. **11**(6).

179. Yang, X., et al., *Alginate-based edible coating with oregano essential oil/beta-cyclodextrin inclusion complex for chicken breast preservation.* Int J Biol Macromol, 2023. **251**: p. 126126.

180. Yan, R., et al., *Preparation of modified chitosan-based nano-TiO(2)-nisin composite packaging film and preservation mechanism applied to chilled pork.* Int J Biol Macromol, 2024. **269**(Pt 1): p. 131873.

181. Gui, N., et al., *A high-strength collagen-based antimicrobial film grafted with epsilon-polylysine fabrication by riboflavin-mediated ultraviolet irradiation for pork preservation.* Food Chem, 2024. **461**: p. 140889.

182. Dey, S., et al., *Food waste generation and its industrial utilization: An overview.* Environ Sci Pollut Res Int, 2025. **32**(12): p. 7493-7512.

183. Selvam, T., et al., *Agricultural Waste-Derived Biopolymers for Sustainable Food Packaging: Challenges and Future Prospects.* Polymers (Basel), 2025. **17**(14).

184. Yao, Z., H.J. Seong, and Y.S. Jang, *Environmental toxicity and decomposition of polyethylene.* Ecotoxicol Environ Saf, 2022. **242**: p. 113933.

185. Chen, H., et al., *Application of Protein-Based Films and Coatings for Food Packaging: A Review.* Polymers (Basel), 2019. **11**(12).

186. Bhavya, E.P. and M. Raman, *Protein based bio-nanocomposite food packaging and applications: A Review.* Food and Humanity, 2025. **4**.

187. Oliveira, M.A., et al., *Performance evaluation of cashew gum and gelatin blend for food packaging.* Food Packaging and Shelf Life, 2018. **17**: p. 57-64.

188. Khin, M.N., et al., *Investigating next-generation edible packaging: Protein-based films and coatings for delivering active compounds.* Food Hydrocolloids for Health, 2024. **6**.

189. Pérez, L.M., et al., *Effect of different combinations of glycerol and/or trehalose on physical and structural properties of whey protein concentrate-based edible films.* Food Hydrocolloids, 2016. **56**: p. 352-359.

190. Murrieta-Martínez, C.L., et al., *Edible protein films: Sources and behavior.* Packaging Technology and Science, 2018. **31**(3): p. 113-122.

191. Deshmukh, R.K. and K.K. Gaikwad, *Natural antimicrobial and antioxidant compounds for active food packaging applications.* Biomass Conversion and Biorefinery, 2022. **14**(4): p. 4419-4440.

192. Jayachandran, B., et al., *Insights on Chemical Crosslinking Strategies for Proteins.* Molecules, 2022. **27**(23).

193. Maitra, J. and N. Bhardwaj, *Development of bio-based polymeric blends - a comprehensive review.* J Biomater Sci Polym Ed, 2024: p. 1-35.

194. Guo, Y., et al., *Nano-structure and properties of maize zein studied by atomic force microscopy.* Journal of Cereal Science, 2005. **41**(3): p. 277-281.

195. Sudhakar Gomte, S., et al., *Zein-based nanoparticulate systems: a journey through fabrication, targeting strategies and biomedical applications.* J Biomater Sci Polym Ed, 2025. **36**(8): p. 1124-1171.

196. Pandey, N., N. Kumar, and A. Upadhyay, *Soy protein modification strategies, functional interplay and industrial relevance: a review.* Journal of Food Measurement and Characterization, 2024. **19**(2): p. 785-805.

197. Shan, G., et al., *Fabrication and characterization of glycerin-plasticized soy protein amyloid fibril scaffolds by unidirectional freeze casting method.* Food Hydrocolloids, 2024. **147**.

198. Cao, J., G. Fan, and B. Lu, *Exploring the self-assembly mechanisms of wheat gluten polypeptide hydrogels: Synthesis and characterization.* Journal of Food Engineering, 2025. **387**.

199. Gunal-Koroglu, D. and E. Capanoglu, *Plant protein-based edible films and the effect of phenolic additives.* Crit Rev Food Sci Nutr, 2025. **65**(11): p. 2155-2175.

200. Xiao, R., et al., *Comparative Analysis of the Physicochemical Properties of Kafirin-Enriched Proteins Extracted From Various Grain Sorghums and Their Distillers' Grains.* Sustainable Food Proteins, 2025. **3**(2).

201. Kour, M., et al., *Revamping sorghum waste into valuable films: A sustainable bioplastic with tunable properties and agro-suitability.* Sustainable Chemistry and Pharmacy, 2025. **48**.

202. Arik Kibar, A., et al., *Recovery of Proteins and Bioactive Peptides From Potato Peels.* Food Sci Nutr, 2025. **13**(10): p. e71028.

203. Ezati, P., et al., *Recent Advances in Collagen and Collagen-Based Packaging Materials: A Review.* ACS Food Science & Technology, 2025. **5**(5): p. 1767-1784.

204. Souza, A.C.A.d., et al., *Animal-derived proteins as stabilizers of Pickering emulsions: applications and challenges.* Food Science and Technology, 2025. **45**.

205. Garavand, F., et al., *Different strategies to reinforce the milk protein-based packaging composites.* Trends in Food Science & Technology, 2022. **123**: p. 1-14.

206. Reji, R.E., et al., *A review on gelatin films and coatings for active food packaging: functional properties and applications.* Food Innovation and Advances, 2025. **4**(3): p. 423-436.

207. Liu, J., et al., *Biodegradable composite films based on egg white protein and tea polyphenol: Physicochemical, structural and antibacterial properties.* Food Packaging and Shelf Life, 2023. **38**.

208. Dewan, A., et al., *Recent trends in edible algae functional proteins: Production, bio-functional properties, and sustainable food packaging applications.* Food Chem, 2025. **463**(Pt 4): p. 141483.

209. Kaur, M., et al., *Microalgal bioactive metabolites as promising implements in nutraceuticals and pharmaceuticals: inspiring therapy for health benefits.* Phytochem Rev, 2023: p. 1-31.

210. Ahmed, M.M., et al., *Valorization of plant-based agro-waste into sustainable food packaging materials: Current approaches and functional applications.* Applied Food Research, 2025. **5**(2).

211. Dissanayake, T., et al., *Reinforcing canola protein matrix with chemically tailored nanocrystalline cellulose improves the functionality of canola protein-based packaging materials.* Food Chem, 2022. **383**: p. 132618.

212. Dissanayake, T., et al., *Improving properties of canola protein-based nanocomposite films by hydrophobically modified nanocrystalline cellulose.* Food Packaging and Shelf Life, 2023. **35**.

213. Chairez-Jimenez, C., et al., *Chemically tailored graphite oxide nanoparticles for improving material properties of canola protein-based films.* Food Chem, 2024. **453**: p. 139693.

214. Mena-Prado, I., et al., *Natural Macromolecules Used as Bioplasticizer in Polymer Materials for Food Contact Applications.* Packaging Technology and Science, 2025. **38**(6): p. 511-526.

215. Franca-Oliveira, G., T. Fornari, and B. Hernández-Ledesma, *A Review on the Extraction and Processing of Natural Source-Derived Proteins through Eco-Innovative Approaches.* Processes, 2021. **9**(9).

216. Iñiguez-Moreno, M., et al., *Sustainable Solutions for Postharvest Berry Protection: Natural Edible Coatings.* Food and Bioprocess Technology, 2024. **17**(11): p. 3483-3505.

217. Li, X., et al., *A review of hot melt extrusion technology: Advantages, applications, key factors and future prospects.* Journal of Drug Delivery Science and Technology, 2024. **98**.

218. Genovesi, A., et al., *Extrusion and thermoforming of poly(butylene succinate–co-butylene adipate)/poly(3–hydroxybutyrate–co–3–hydroxyhexanoate) bio-based blends for the fabrication of disposable packaging.* Journal of Applied Polymer Science, 2024. **141**(23).

219. Shen, C., L. Wang, and Q. Li, *Optimization of injection molding process parameters using combination of artificial neural network and genetic algorithm method.* Journal of Materials Processing Technology, 2007. **183**(2-3): p. 412-418.

220. Perez, V., et al., *Characterization of pea protein-based bioplastics processed by injection moulding.* Food and Bioproducts Processing, 2016. **97**: p. 100-108.

221. Othman, S.H., et al., *Properties and Food Packaging Applications of Solvent Casting‐Made Starch‐Based Films Incorporated with Essential Oils: A Review.* Starch - Stärke, 2023. **75**(5-6).

222. Dierickx, L., et al., *Co-extrusion as manufacturing technique for fixed-dose combination mini-matrices.* Eur J Pharm Biopharm, 2012. **81**(3): p. 683-9.

223. Hilbig, J., et al., *Influence of phosphates and pH value on white efflorescence formation on dry fermented sausages.* European Food Research and Technology, 2019. **246**(3): p. 471-484.

224. Marcos, B., et al., *Co-extruded alginate as an alternative to collagen casings in the production of dry-fermented sausages: Impact of coating composition.* Meat Sci, 2020. **169**: p. 108184.

225. Ávila-Martín, L., et al., *Preliminary Modeling Study of a Tape Casting System for Thermoplastic Starch Film Forming.* Biology and Life Sciences Forum, 2023. **28**(1): p. 4.

226. Calva-Estrada, S.J., M. Jiménez-Fernández, and E. Lugo-Cervantes, *Protein-Based Films: Advances in the Development of Biomaterials Applicable to Food Packaging.* Food Engineering Reviews, 2019. **11**(2): p. 78-92.

227. Wong, D.E., J.N. Talbert, and J.M. Goddard, *Layer by layer assembly of a biocatalytic packaging film: lactase covalently bound to low-density polyethylene.* J Food Sci, 2013. **78**(6): p. E853-60.

228. Jiang, L., et al., *A Review of Whey Protein-Based Bioactive Delivery Systems: Design, Fabrication, and Application.* Foods, 2024. **13**(15).

229. Turan, D., G. Gunes, and A. Kilic, *Perspectives of Bio-nanocomposites for Food Packaging Applications*, in *Bionanocomposites for Packaging Applications*. 2018. p. 1-32.

230. Heydari-Majd, M., et al., *Electrospun plant protein-based nanofibers loaded with sakacin as a promising bacteriocin source for active packaging against Listeria monocytogenes in quail breast.* Int J Food Microbiol, 2023. **391–393**: p. 110143.

231. Alehosseini, A., et al., *Electrospun curcumin-loaded protein nanofiber mats as active/bioactive coatings for food packaging applications.* Food Hydrocolloids, 2019. **87**: p. 758-771.

232. Kong, J., et al., *Multi-functional pH-sensitive active and intelligent packaging based on highly cross-linked zein for the monitoring of pork freshness.* Food Chem, 2023. **404**(Pt B): p. 134754.

233. Lim, L.-T., *Plant-Based Protein Films and Coatings*, in *Plant Protein Foods*. 2022. p. 271-311.

234. Perez-Puyana, V., et al., *Physical crosslinking of pea protein-based bioplastics: Effect of heat and UV treatments.* Food Packaging and Shelf Life, 2022. **32**.

235. Benbettaieb, N., et al., *Tuning the Functional Properties of Polysaccharide-Protein Bio-Based Edible Films by Chemical, Enzymatic, and Physical Cross-Linking.* Compr Rev Food Sci Food Saf, 2016. **15**(4): p. 739-752.

236. Jin, C., et al., *Preparation and characterization of wheat gluten nanofiber films based on electrospinning and Maillard crosslinking.* Lwt, 2023. **186**.

237. Zhang, C., et al., *pH-responsive color-indicating film of pea protein isolate cross-linked with dialdehyde carboxylated cellulose nanofibers for pork freshness monitoring.* Int J Biol Macromol, 2024. **257**(Pt 2): p. 128671.

238. Dong, Y., et al., *Effect of polyol plasticizers on properties and microstructure of soluble soybean polysaccharide edible films.* Food Packaging and Shelf Life, 2023. **35**.

239. Rostamzad, H., et al., *Improvement of fish protein film with nanoclay and transglutaminase for food packaging.* Food Packaging and Shelf Life, 2016. **7**: p. 1-7.

240. Schmid, M., et al., *Properties of Transglutaminase Crosslinked Whey Protein Isolate Coatings and Cast Films.* Packaging Technology and Science, 2014. **27**(10): p. 799-817.

241. Campos, C.A., L.N. Gerschenson, and S.K. Flores, *Development of Edible Films and Coatings with Antimicrobial Activity.* Food and Bioprocess Technology, 2010. **4**(6): p. 849-875.

242. Masamba, K., et al., *Evaluation of mechanical and water barrier properties of transglutaminase cross-linked zein films incorporated with oleic acid.* International Journal of Food Science & Technology, 2016. **51**(5): p. 1159-1167.

243. Tongnuanchan, P., et al., *Emulsion film based on fish skin gelatin and palm oil: Physical, structural and thermal properties.* Food Hydrocolloids, 2015. **48**: p. 248-259.

244. Hosseini, S.F., et al., *Development of bioactive fish gelatin/chitosan nanoparticles composite films with antimicrobial properties.* Food Chem, 2016. **194**: p. 1266-74.

245. Arora, A. and G.W. Padua, *Review: nanocomposites in food packaging.* J Food Sci, 2010. **75**(1): p. R43-9.

246. Cai, K., et al., *Polysaccharide-protein surface modification of titanium via a layer-by-layer technique: characterization and cell behaviour aspects.* Biomaterials, 2005. **26**(30): p. 5960-71.

247. Zhang, L., et al., *Applying layer-by-layer deposition to enhance stability and rheological behavior of emulsions: A review.* Food Hydrocolloids, 2025. **158**.

248. Phillips, A. and M. Sen, *Biobased Antimicrobial Food Packaging Coatings*, in *Food Coatings and Preservation Technologies*. 2024. p. 515-549.

249. Yousefi, M., et al., *Antimicrobial Activity of Films and Coatings Containing Lactoperoxidase System: A Review.* Front Nutr, 2022. **9**: p. 828065.

250. Clarke, D., et al., *Incorporation of commercially-derived antimicrobials into gelatin-based films and assessment of their antimicrobial activity and impact on physical film properties.* Food Control, 2016. **64**: p. 202-211.

251. Liu, F., et al., *Preparation of gelatin films incorporated with tea polyphenol nanoparticles for enhancing controlled-release antioxidant properties.* J Agric Food Chem, 2015. **63**(15): p. 3987-95.

252. Gallego, M.G., et al., *Gelatine-Based Antioxidant Packaging Containing Caesalpinia decapetala and Tara as a Coating for Ground Beef Patties.* Antioxidants (Basel), 2016. **5**(2).

253. Wu, J., et al., *Preparation, properties and antioxidant activity of an active film from silver carp (Hypophthalmichthys molitrix) skin gelatin incorporated with green tea extract.* Food Hydrocolloids, 2013. **32**(1): p. 42-51.

254. Gomes, R. and C. Albino. *The Past Packs the Future. Circularity and the Contribution of Pre-disposable Packaging History to Contemporary Reusable Packaging Design*. in *Meeting of Research in Music, Arts and Design*. 2024. Springer.

255. Foley, B.P., et al., *Aspects of ancient Greek trade re-evaluated with amphora DNA evidence.* Journal of Archaeological Science, 2012. **39**(2): p. 389-398.

256. Shi, J.l. and T. Li, *Technical investigation of 15th and 19th century Chinese paper currencies*: *fiber use and pigment identification.* Journal of Raman spectroscopy, 2013. **44**(6): p. 892-898.

257. Constance, D., *The industrialization of agriculture.* Twenty Lessons in the Sociology of Food and Agriculture, 2019: p. 79.

258. Twede, D., *History of packaging*, in *The Routledge companion to marketing history*. 2016, Routledge. p. 115-129.

259. Tajeddin, B. and M. Arabkhedri, *Polymers and food packaging*, in *Polymer science and innovative applications*. 2020, Elsevier. p. 525-543.

260. Stanley, J., et al., *The journey of plastics*: *historical development, environmental challenges, and the emergence of bioplastics for single-use products.* Eng, 2025. **6**(1): p. 17.

261. Geyer, R., J.R. Jambeck, and K.L. Law, *Production, use, and fate of all plastics ever made.* Science advances, 2017. **3**(7): p. e1700782.

262. Espiritu, E.Q., et al., *Microplastics contamination in selected staple consumer food products.* Journal of Food Science and Technology, 2024. **61**(11): p. 2082-2092.

263. Kitinoja, L. and A.A. Kader, *Measuring postharvest losses of fresh fruits and vegetables in developing countries.* PEF white paper, 2015. **15**: p. 26.

264. Panou, A. and I.K. Karabagias, *Biodegradable packaging materials for foods preservation: sources, advantages, limitations, and future perspectives.* Coatings, 2023. **13**(7): p. 1176.

265. Baniasadi, H., et al., *Advances in polysaccharide-based food packaging: Functionalization strategies and sustainability considerations.* Materials Science and Engineering: R: Reports, 2026. **167**: p. 101128.

266. Mihindukulasuriya, S. and L.-T. Lim, *Nanotechnology development in food packaging: A review.* Trends in Food Science & Technology, 2014. **40**(2): p. 149-167.

267. Capek, I., *Nanocomposite structures and dispersions*. Vol. 23. 2019: Elsevier.

268. Ajayan, P.M., L.S. Schadler, and P.V. Braun, *Nanocomposite science and technology*. 2006: John Wiley & Sons.

269. Shelly, D., et al., *Exploring the impact of nanoclay on epoxy nanocomposites: A comprehensive review.* Journal of Composites Science, 2024. **8**(12): p. 506.

270. Camargo, E., et al., *Experimental and numerical study of monodisperse nanoparticles concentration in a nano-differential mobility analyzer.* Brazilian Journal of Chemical Engineering, 2021. **38**(2): p. 389-401.

271. Mimona, M.A., et al., *Quantum Dot nanomaterials: empowering advances in optoelectronic devices.* Chemical Engineering Journal Advances, 2025: p. 100704.

272. Shao, L., Y. Gao, and F. Yan, *Semiconductor quantum dots for biomedicial applications.* Sensors, 2011. **11**(12): p. 11736-11751.

273. Kumar, S.K. and R. Krishnamoorti, *Nanocomposites: structure, phase behavior, and properties.* Annual review of chemical and biomolecular engineering, 2010. **1**(1): p. 37-58.

274. de Oliveira, A.D. and C.A.G. Beatrice, *Polymer nanocomposites with different types of nanofiller*, in *Nanocomposites-recent evolutions*. 2018, IntechOpen.

275. Paras, et al., *A review on low-dimensional nanomaterials: nanofabrication, characterization and applications.* Nanomaterials, 2022. **13**(1): p. 160.

276. Ray, S.S. and M. Okamoto, *Polymer/layered silicate nanocomposites: a review from preparation to processing.* Progress in polymer science, 2003. **28**(11): p. 1539-1641.

277. Idumah, C.I. and C.M. Obele, *Understanding interfacial influence on properties of polymer nanocomposites.* Surfaces and Interfaces, 2021. **22**: p. 100879.

278. Ma, P.-C., et al., *Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review.* Composites Part A: Applied Science and Manufacturing, 2010. **41**(10): p. 1345-1367.

279. Cui, Y., et al., *Metal coordination interfacial enhancement effect: A strategy to fabricate low hygroscopic composite based on ammonium dinitramide (ADN) and polyether with enhanced mechanical properties.* Composites Communications, 2025: p. 102523.

280. Wang, Z., et al., *A roadmap review of thermally conductive polymer composites: critical factors, progress, and prospects.* Advanced functional materials, 2023. **33**(36): p. 2301549.

281. Zhang, S., et al., *Micromechanical interlocking structure at the filler/resin interface for dental composites: a review.* International journal of oral science, 2023. **15**(1): p. 21.

282. Okamoto, M., *Polymer nanocomposites.* Eng, 2023. **4**(1): p. 457-479.

283. Papageorgiou, D.G., et al., *Mechanisms of mechanical reinforcement by graphene and carbon nanotubes in polymer nanocomposites.* Nanoscale, 2020. **12**(4): p. 2228-2267.

284. López-Moreno, A., et al., *Threading through macrocycles enhances the performance of carbon nanotubes as polymer fillers.* ACS nano, 2016. **10**(8): p. 8012-8018.

285. Huang, J., J. Zhou, and M. Liu, *Interphase in polymer nanocomposites.* JACS Au, 2022. **2**(2): p. 280-291.

286. Asadi, N., et al., *Nanocomposite hydrogels for cartilage tissue engineering: a review.* Artificial cells, nanomedicine, and biotechnology, 2018. **46**(3): p. 465-471.

287. Idris, A., A. Muntean, and B. Mesic, *A review on predictive tortuosity models for composite films in gas barrier applications.* Journal of Coatings Technology and Research, 2022. **19**(3): p. 699-716.

288. Rivadeneira-Velasco, K.E., et al., *Green nanocomposites based on thermoplastic starch: A review.* Polymers, 2021. **13**(19): p. 3227.

289. Xu, X., et al., *Effect of different proportions of glycerol and D-mannitol as plasticizer on the properties of extruded corn starch.* Frontiers in Nutrition, 2024. **10**: p. 1335812.

290. Tanpichai, S., K. Thongdonson, and A. Boonmahitthisud, *Enhancement of the mechanical properties and water barrier properties of thermoplastic starch nanocomposite films by chitin nanofibers: Biodegradable coating for extending banana shelf life.* Journal of Materials Research and Technology, 2023. **26**: p. 5617-5625.

291. Díaz-Cruz, C.A., et al., *Evaluation of the antimicrobial, thermal, mechanical, and barrier properties of corn starch–chitosan biodegradable films reinforced with cellulose nanocrystals.* Polymers, 2022. **14**(11): p. 2166.

292. Yan, D., et al., *Antimicrobial properties of chitosan and chitosan derivatives in the treatment of enteric infections.* Molecules, 2021. **26**(23): p. 7136.

293. Lavrič, G., et al., *Functional nanocellulose, alginate and chitosan nanocomposites designed as active film packaging materials.* Polymers, 2021. **13**(15): p. 2523.

294. Indumathi, M., K.S. Sarojini, and G. Rajarajeswari, *Antimicrobial and biodegradable chitosan/cellulose acetate phthalate/ZnO nano composite films with optimal oxygen permeability and hydrophobicity for extending the shelf life of black grape fruits.* International journal of biological macromolecules, 2019. **132**: p. 1112-1120.

295. Qasim, U., et al., *Renewable cellulosic nanocomposites for food packaging to avoid fossil fuel plastic pollution: a review.* Environmental Chemistry Letters, 2021. **19**(1): p. 613-641.

296. Mascarenhas, A.R.P., et al., *Hydroxypropyl methylcellulose films reinforced with cellulose micro/nanofibrils: study of physical, optical, surface, barrier and*

mechanical properties: Valorization cellulosic materials for films production. Nordic Pulp & Paper Research Journal, 2022. **37**(2): p. 366-384.

297. Zhu, Y., et al., *Surface engineering of regenerated cellulose nanocomposite films with high strength, ultraviolet resistance, and a hydrophobic surface.* Polymers, 2023. **15**(6): p. 1427.

298. Oymaci, P. and S.A. Altinkaya, *Improvement of barrier and mechanical properties of whey protein isolate based food packaging films by incorporation of zein nanoparticles as a novel bionanocomposite.* Food hydrocolloids, 2016. **54**: p. 1-9.

299. Gomez Mesa, N.E., A.Y. Pataquiva-Mateus, and Y. Tang, *Exploring Biodegradable Polymeric Nanocomposite Films for Sustainable Food Packaging Application.* Polymers, 2025. **17**(16): p. 2207.

300. Majewska-Smolarek, K. and A. Kowalewska, *Essential Oils as Green Antibacterial Modifiers of Polymeric Materials.* Polymers, 2025. **17**(21): p. 2924.

301. Huang, X., et al., *Eugenol embedded zein and poly (lactic acid) film as active food packaging: Formation, characterization, and antimicrobial effects.* Food Chemistry, 2022. **384**: p. 132482.

302. Dalton, B., et al., *A review on biological synthesis of the biodegradable polymers polyhydroxyalkanoates and the development of multiple applications.* Catalysts, 2022. **12**(3): p. 319.

303. Yusoff, N.H., et al., *Recent trends on bioplastics synthesis and characterizations: Polylactic acid (PLA) incorporated with tapioca starch for packaging applications.* Journal of Molecular Structure, 2021. **1232**: p. 129954.

304. Dadashi, S., et al., *Functional properties of biodegradable nanocomposites from poly lactic acid (PLA).* International Journal of Nanoscience and Nanotechnology, 2014. **10**(4): p. 245-256.

305. Hossain, K.M.Z., et al., *Physico-chemical and mechanical properties of nanocomposites prepared using cellulose nanowhiskers and poly (lactic acid).* Journal of Materials Science, 2012. **47**(6): p. 2675-2686.

306. Ojha, N. and N. Das, *Fabrication and characterization of biodegradable PHBV/SiO2 nanocomposite for thermo‐mechanical and antibacterial applications in food packaging.* IET nanobiotechnology, 2020. **14**(9): p. 785-795.

307. Zare, M., et al., *Smart fortified PHBV-CS biopolymer with ZnO–Ag nanocomposites for enhanced shelf life of food packaging.* ACS applied materials & interfaces, 2019. **11**(51): p. 48309-48320.

308. Xu, J., et al., *Morphological, barrier and mechanical properties of films from poly (butylene succinate) reinforced with nanocrystalline cellulose and chitin whiskers using melt extrusion.* Journal of Polymer Research, 2019. **26**(8): p. 188.

309. Mishra, J., et al., *Fundamental of polymer blends and its thermodynamics*, in *Micro and nano fibrillar composites (MFCs and NFCs) from polymer blends*. 2017, Elsevier. p. 27-55.

310. Pal, A.K., et al., *Reactive extrusion of sustainable PHBV/PBAT-based nanocomposite films with organically modified nanoclay for packaging applications: Compression moulding vs. cast film extrusion.* Composites Part B: Engineering, 2020. **198**: p. 108141.

311. Deshmukh, R.K., et al., *Nano clays and its composites for food packaging applications.* International Nano Letters, 2023. **13**(2): p. 131-153.

312. Sarfraz, J., et al., *Nanocomposites for food packaging applications: An overview.* Nanomaterials, 2020. **11**(1): p. 10.

313. Yuan, P., A. Thill, and F. Bergaya, *Nanosized tubular clay minerals: Halloysite and imogolite*. Vol. 7. 2016: Elsevier.

314. Okur, E.E., et al., *Comprehensive Review of Silver Nanoparticles in Food Packaging Applications.* International Journal of Molecular Sciences, 2025. **26**(20): p. 9842.

315. Vieira, I.R.S., A.P.A.d. de Carvalho, and C.A. Conte-Junior, *Recent advances in biobased and biodegradable polymer nanocomposites, nanoparticles, and natural antioxidants for antibacterial and antioxidant food packaging applications.* Comprehensive Reviews in Food Science and Food Safety, 2022. **21**(4): p. 3673-3716.

316. Madivoli, E.S., et al., *Cellulose nanofibrils and silver nanoparticles enhances the mechanical and antimicrobial properties of polyvinyl alcohol nanocomposite film.* Scientific Reports, 2022. **12**(1): p. 19005.

317. Huang, H., et al., *Migration of Ti and Zn from nanoparticle modified ldpe films into food simulants.* Food Science and Technology Research, 2017. **23**(6): p. 827-834.

318. Hari, K.D., et al., *Improvement of the UV barrier and antibacterial properties of crosslinked pectin/zinc oxide bionanocomposite films.* Polymers, 2021. **13**(15): p. 2403.

319. Nandhini, J., et al., *Advancements in metal oxide bio‐nanocomposites for sustainable food packaging: Fabrication, applications, and future prospectives.* Food Bioengineering, 2024. **3**(4): p. 438-463.

320. Zhang, Y., et al., *A novel two-step modification of TiO2 nanoparticles for PAN fibers with enhanced mechanical strength, UV shielding and antibacterial properties.* Applied Surface Science, 2025. **700**: p. 163156.

321. Rostamabadi, H., et al., *Cellulose nanofibers, nanocrystals, and bacterial nanocellulose: Fabrication, characterization, and their most recent applications.* Future Postharvest and Food, 2024. **1**(1): p. 5-33.

322. Fan, L., et al., *Synergistic enhancement of cement-based materials by an organic-inorganic hybrid of multi-walled carbon nanotubes and cellulose nanofibers.* Construction and Building Materials, 2025. **500**: p. 144144.

323. Amara, C., et al., *Nanocellulose-based composites for packaging applications.* Current Opinion in Green and Sustainable Chemistry, 2021. **31**: p. 100512.

324. Baishya, H., J. Dutta, and S. Kumar, *Nanofillers Reinforcing Biopolymer Composites for Sustainable Food Packaging Applications: A State‐of‐the‐Art Review.* Advanced Functional Materials, 2025: p. 2503819.

325. Upadhyay, G., et al., *Development of carbon nanotube (CNT)-reinforced Mg alloys: fabrication routes and mechanical properties.* Metals, 2022. **12**(8): p. 1392.

326. Ashfaq, J., et al., *Enhancement of thermal and gas barrier properties of graphene-based nanocomposite films.* ACS omega, 2023. **8**(44): p. 41054-41063.

327. Barra, A., et al., *Eco-friendly preparation of electrically conductive chitosan-reduced graphene oxide flexible bionanocomposites for food packaging and biological applications.* Composites Science and Technology, 2019. **173**: p. 53-60.

328. Thomas, J., P.S. Thomas, and R. Stephen, *Improved mechanical, thermal, and barrier properties of halloysite nanotubes and nanocellulose incorporated PVA-PEO films: For food packaging applications.* Food Packaging and Shelf Life, 2024. **46**: p. 101373.

329. Barros, C., et al., *LDPE-Nanoclay films for food packaging with improved barrier properties.* Journal of Plastic Film & Sheeting, 2023. **39**(3): p. 304-320.

330. Feng, X., et al., *A hydrotalcite-based PET composites with enhanced properties for liquid milk packaging applications.* Materials, 2023. **16**(5): p. 1857.

331. Zheng, C., et al., *Advances in biomimetic hydrogel for articular cartilage defect repair: Enabling immunomodulation and chondrogenesis.* Colloids Surf B Biointerfaces, 2025. **253**: p. 114760.

332. El-Hadi, A.M., *Increase the elongation at break of poly (lactic acid) composites for use in food packaging films.* Scientific reports, 2017. **7**(1): p. 46767.

333. Thakur, V. and B.K. Satapathy, *Robust tear-resistant blown nanocomposite films for barrier packaging: role of clay platelet thickness in tear mechanics and barrier performances.* ACS Applied Polymer Materials, 2023. **5**(8): p. 6529-6539.

334. Dubey, K., et al., *Tear‐Mechanics and Barrier Performance Assessment of Melt‐Blown Polylactic Acid/Halloysite Nanocomposite Fruit‐Packaging Films for Shelf‐Life Enhancement.* Polymer Engineering & Science, 2025.

335. Abbas, M., et al., *(Bio) polymer/ZnO nanocomposites for packaging applications: a review of gas barrier and mechanical properties.* Nanomaterials, 2019. **9**(10): p. 1494.

336. Kim, S.W. and S.H. Cha, *Thermal, mechanical, and gas barrier properties of ethylene–vinyl alcohol copolymer‐based nanocomposites for food packaging*

films: Effects of nanoclay loading. Journal of Applied Polymer Science, 2014. **131**(11).

337. Naidu, D.S. and M.J. John, *Effect of clay nanofillers on the mechanical and water vapor permeability properties of xylan–alginate films.* Polymers, 2020. **12**(10): p. 2279.

338. Van Nguyen, S. and B.-K. Lee, *PVA/CNC/TiO2 nanocomposite for food-packaging: Improved mechanical, UV/water vapor barrier, and antimicrobial properties.* Carbohydrate Polymers, 2022. **298**: p. 120064.

339. Wang, Y., et al., *MgO/carboxymethyl chitosan nanocomposite improves thermal stability, waterproof and antibacterial performance for food packaging.* Carbohydrate Polymers, 2020. **236**: p. 116078.

340. De Silva, R., et al., *Nano-MgO reinforced chitosan nanocomposites for high performance packaging applications with improved mechanical, thermal and barrier properties.* Carbohydrate polymers, 2017. **157**: p. 739-747.

341. Alghamdi, A.M., *Enhanced optical, mechanical, thermal, and antibacterial properties in polymer bio‐nanocomposites films via loading Ag/Au nanoparticles for optical devices and food packaging.* Polymer Composites, 2025.

342. Heydari, A., I. Alemzadeh, and M. Vossoughi, *Influence of glycerol and clay contents on biodegradability of corn starch nanocomposites.* International Journal of Engineering Transactions B: Applications, 2014. **27**(2): p. 203-214.

343. Shanmugam, R., et al., *Mechanical, barrier, adhesion and antibacterial properties of pullulan/graphene bio nanocomposite coating on spray coated nanocellulose film for food packaging applications.* Journal of Polymers and the Environment, 2022. **30**(5): p. 1749-1757.

344. Salari, M., et al., *Development and evaluation of chitosan based active nanocomposite films containing bacterial cellulose nanocrystals and silver nanoparticles.* Food hydrocolloids, 2018. **84**: p. 414-423.

345. Cui, Y., et al., *Controlled release mechanism of thymol loaded into mesoporous silica nanoparticles for active packaging films.* Food Bioscience, 2023. **56**: p. 103229.

346. Cinteza, L.O., et al., *Chitosan-stabilized Ag nanoparticles with superior biocompatibility and their synergistic antibacterial effect in mixtures with essential oils.* Nanomaterials, 2018. **8**(10): p. 826.

347. Tas, C.E., et al., *Halloysite nanotubes/polyethylene nanocomposites for active food packaging materials with ethylene scavenging and gas barrier properties.* Food and Bioprocess Technology, 2017. **10**(4): p. 789-798.

348. Tavassoli, M., et al., *Smart biopolymer-based nanocomposite materials containing pH-sensing colorimetric indicators for food freshness monitoring.* Molecules, 2022. **27**(10): p. 3168.

349. Banerjee, R., J. Bandyopadhyay, and S.S. Ray, *Functional Polymers and Their Nanocomposites for Sustainable Packaging Applications.* Macromolecular Materials and Engineering, 2025: p. e00130.

350. Mulla, M.Z., et al., *Poly Lactic Acid (PLA) Nanocomposites: Effect of inorganic nanoparticles reinforcement on its performance and food packaging applications.* Molecules, 2021. **26**(7): p. 1967.

351. Ros-Lis, J.V. and M. Benitez, *Recent advances in life cycle assessment of nanomaterials for packaging applications.* Nanostructured Materials for Food Packaging Applications, 2024: p. 629-649.

352. dos Anjos, E.G.R., et al., *Biodegradation Behavior and Life Cycle Assessment of PLA/PHBV/Carbonaceous Materials Hybrid Nanocomposites for Antimicrobial Multifunctional Packaging.* Journal of Polymers and the Environment, 2024. **32**(10): p. 5098-5114.