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Biodegradable food packaging films – A sustainable packaging material trend in the food industry

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Abstract
In recent years, environmental pollution caused by plastic waste, particularly single-use food packaging materials, has become a serious global issue. Petroleum-based polymers such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) have been widely used due to their low cost and excellent preservation performance; however, their long degradation time and adverse environmental impacts have raised significant concerns. In this context, biodegradable food packaging films have attracted considerable attention as environmentally friendly alternatives that can reduce plastic waste accumulation and support sustainable development in the food packaging industry.

This article presents an overview of biodegradable materials used for food packaging film fabrication, including polysaccharides (chitosan, starch, and cellulose), proteins (gelatin, whey protein, and soy protein), and synthetic biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA). In addition, fabrication methods, mechanical properties, gas barrier performance, water vapor resistance, as well as antimicrobial and antioxidant activities of biodegradable film systems are discussed and analyzed.

Furthermore, the potential applications of biodegradable films in the preservation of fruits, vegetables, meat, seafood, and processed foods are highlighted, particularly for extending shelf life and maintaining product quality. The incorporation of natural bioactive compounds such as essential oils, polyphenols, and nanomaterials has emerged as an effective strategy to enhance preservation efficiency and improve the functional properties of biodegradable films. Nevertheless, limitations related to mechanical strength, moisture sensitivity, production cost, and large-scale commercialization remain major challenges that require further investigation and optimization.

In the future, advances in green material technology, nanotechnology, and circular economy approaches are expected to accelerate the widespread application of biodegradable food packaging films, thereby gradually replacing conventional petroleum-based plastics and minimizing environmental impacts in the food packaging industry.

Keywords: Biodegradable films, food packaging, chitosan, PLA, biopolymers, active packaging, sustainable packaging

Introduction

Food packaging plays a crucial role in the modern food industry by protecting products from physical, chemical, and microbial contamination during storage, transportation, and distribution. In addition to preserving food quality and extending shelf life, packaging materials also contribute to maintaining nutritional value, preventing moisture loss, and improving consumer convenience [1]. Among various packaging materials, petroleum-based plastics such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) have been extensively utilized due to their excellent mechanical strength, flexibility, lightweight nature, and low production cost [2].

Despite these advantages, the widespread use of conventional plastic packaging has generated serious environmental concerns. Most petroleum-based plastics are highly resistant to natural degradation processes and can persist in the environment for hundreds of years after disposal [3]. The accumulation of plastic waste in landfills, rivers, and oceans has become a global environmental challenge, causing adverse impacts on ecosystems, wildlife, and human health. In particular, the fragmentation of plastics into microplastics has raised increasing concerns because these particles can enter the food chain and potentially pose toxicological risks to living organisms [4]. According to recent reports, millions of tons of plastic waste are generated annually worldwide, with food packaging accounting for a significant proportion of single-use plastic consumption [5].

Growing environmental awareness, stricter governmental regulations, and increasing consumer demand for sustainable products have accelerated the development of eco-friendly packaging materials [6]. In this context, biodegradable food packaging films have emerged as promising alternatives to conventional plastics. These materials are designed to undergo decomposition through the action of microorganisms, enzymes, and environmental factors, resulting in the formation of carbon dioxide, water, methane, and biomass under suitable conditions [7]. Unlike traditional plastics, biodegradable polymers can significantly reduce environmental pollution and contribute to the development of sustainable packaging systems.

Biodegradable food packaging films can be produced from a wide range of renewable resources, including polysaccharides, proteins, lipids, and biodegradable synthetic polymers. Natural biopolymers such as chitosan, starch, cellulose, gelatin, and alginate have attracted considerable attention because of their biodegradability, biocompatibility, film-forming ability, and non-toxic nature [8]. In addition, synthetic biodegradable polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) have demonstrated excellent potential for industrial food packaging applications due to their favorable mechanical and barrier properties [9]. Furthermore, recent advances in active and intelligent packaging technologies have enabled the incorporation of natural antimicrobial agents, antioxidants, essential oils, and nanomaterials into biodegradable films to improve food preservation efficiency and enhance functional performance [10].

Although biodegradable packaging materials offer numerous environmental and functional advantages, several limitations still hinder their widespread commercialization. Issues related to high production cost, poor water resistance, limited mechanical strength, and scalability remain significant challenges for industrial implementation [11]. Therefore, continuous research efforts are required to optimize material properties, develop cost-effective fabrication methods, and improve the overall performance of biodegradable films.

The objective of this article is to provide a comprehensive overview of biodegradable food packaging films, including their classification, fabrication methods, physicochemical properties, and practical applications in food preservation. In addition, current challenges and future development trends related to sustainable packaging technologies are discussed. This article aims to highlight the importance of biodegradable packaging materials as environmentally friendly alternatives that can contribute to reducing plastic pollution and promoting sustainability in the food industry.

Overview of Biodegradable Food Packaging Films

1. Definition of Biodegradable Food Packaging Films

Biodegradable food packaging films are polymeric materials capable of undergoing decomposition through the action of naturally occurring microorganisms such as bacteria, fungi, and algae under suitable environmental conditions. During the biodegradation process, the polymer chains are converted into simpler compounds including carbon dioxide (CO_2), water (H_2O), methane (CH_4), mineral salts, and biomass without generating harmful residues in the environment [12]. Unlike conventional petroleum-based plastics, biodegradable films are generally produced from renewable biological resources or biodegradable synthetic polymers, making them environmentally sustainable alternatives for food packaging applications.

Biodegradable films can be classified into several categories based on their origin and chemical composition, including natural biopolymers (polysaccharides, proteins, and lipids) and biodegradable synthetic polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) [13]. These materials possess film-forming ability and can serve as protective barriers against external environmental factors, thereby helping to preserve food quality and extend shelf life.

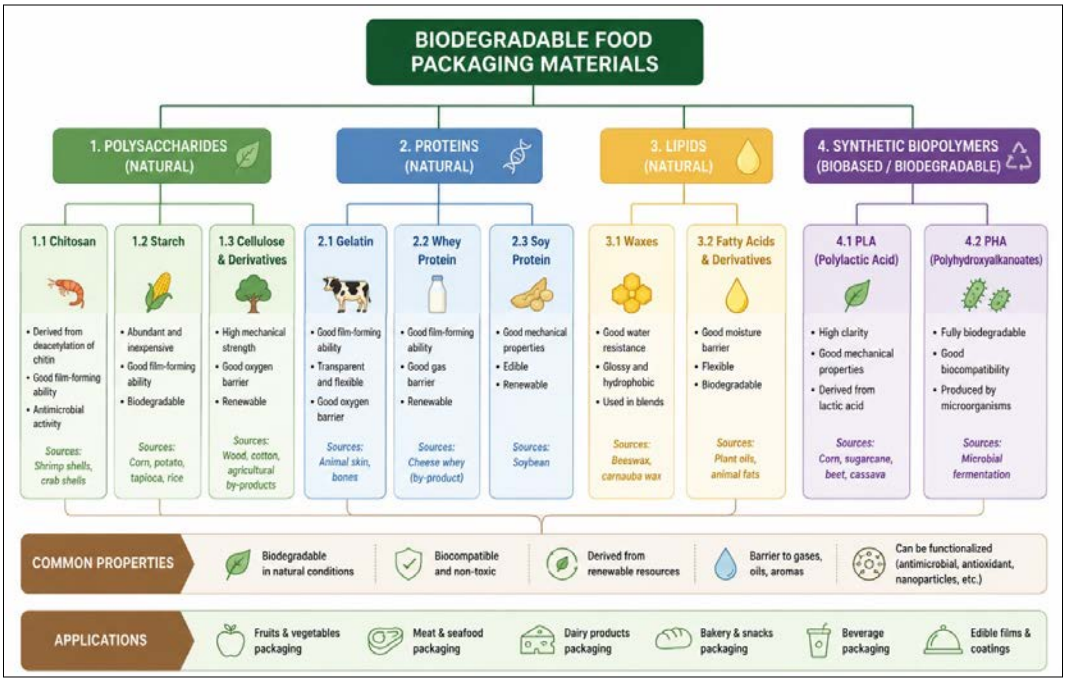

Fig 1: Classification of biodegradable food packaging materials

2. General Characteristics of Biodegradable Films

Biodegradable food packaging films exhibit several important characteristics that make them attractive for sustainable packaging applications. Most biodegradable polymers are derived from renewable agricultural resources, which reduces dependence on fossil fuels and contributes to lowering carbon emissions [14]. In addition, many biodegradable materials possess excellent biocompatibility, non-toxicity, and edibility, making them suitable for direct contact with food products.

The functional properties of biodegradable films depend largely on the type of polymer used and the interactions between polymer chains. Polysaccharide-based films such as chitosan and starch generally exhibit good oxygen barrier properties due to their dense hydrogen-bonded structures [15]. Protein-based films often demonstrate favorable mechanical properties and transparency, whereas lipid-based materials provide enhanced water resistance [16].

Furthermore, biodegradable films can be designed as active packaging systems by incorporating antimicrobial agents, antioxidants, essential oils, or nanoparticles to improve food preservation performance [17]. Recent advances in material science have also enabled the development of intelligent biodegradable packaging capable of monitoring food freshness and environmental conditions.

Despite these advantages, biodegradable films still face several limitations compared with conventional plastics. Most natural biopolymers are highly hydrophilic, resulting in poor water vapor resistance and reduced mechanical stability under humid conditions [18]. In addition, some biodegradable materials exhibit limited thermal stability and relatively high production costs, which restrict their large-scale industrial application.

3. Advantages and Limitations of Biodegradable Packaging Films

The growing interest in biodegradable food packaging materials is mainly driven by their environmental and functional benefits. One of the most significant advantages is their ability to degrade naturally after disposal, thereby reducing the accumulation of plastic waste in landfills and aquatic ecosystems [19]. Since many biodegradable polymers originate from renewable biomass resources, their production can also contribute to sustainable resource utilization and circular economy development.

Another important advantage is the potential integration of bioactive compounds into biodegradable films. Natural antimicrobial and antioxidant substances such as essential oils, phenolic compounds, and plant extracts can be incorporated into film matrices to inhibit microbial growth and delay lipid oxidation in food products [20]. Such active packaging systems can effectively extend shelf life while reducing the need for synthetic preservatives.

In addition, some biodegradable films are edible and can be consumed together with food products, which further minimizes packaging waste generation [21]. These edible coatings are especially useful for fruits, vegetables, confectionery products, and ready-to-eat foods.

However, biodegradable films also present several disadvantages that limit their commercial competitiveness. Their mechanical strength and flexibility are often lower than those of petroleum-based plastics such as polyethylene and polypropylene [22]. High moisture sensitivity and low water barrier properties remain major concerns, particularly for applications involving foods with high water activity. Moreover, the biodegradation rate may vary depending on environmental conditions such as temperature, humidity, oxygen availability, and microbial activity [23].

Economic factors also represent a major challenge. The production cost of biodegradable polymers is generally higher than that of conventional plastics due to expensive raw materials and complex processing technologies [24]. Therefore, further technological improvements and cost optimization strategies are necessary to promote wider industrial adoption.

4. Biodegradation Mechanism of Biodegradable Polymers

The biodegradation of polymeric materials is a complex process involving physical, chemical, and biological reactions. Generally, biodegradation occurs in two major stages: depolymerization and mineralization [25].

In the first stage, environmental factors such as moisture, heat, ultraviolet radiation, and microbial enzymes initiate the breakdown of long polymer chains into smaller oligomers and monomers through hydrolysis or enzymatic cleavage [26]. The resulting low-molecular-weight compounds are then assimilated by microorganisms and metabolized as carbon and energy sources.

During the second stage, microbial metabolic activities convert these intermediate compounds into final degradation products such as carbon dioxide, water, methane, and biomass [27]. The overall degradation rate depends on multiple factors, including polymer structure, crystallinity, molecular weight, environmental conditions, and microbial population.

Polymers containing hydrolyzable ester, amide, or glycosidic bonds generally exhibit higher biodegradability because these chemical linkages are more susceptible to enzymatic and hydrolytic attack [28]. For example, starch- and chitosan-based materials degrade relatively rapidly in soil and compost environments due to their natural polysaccharide structures.

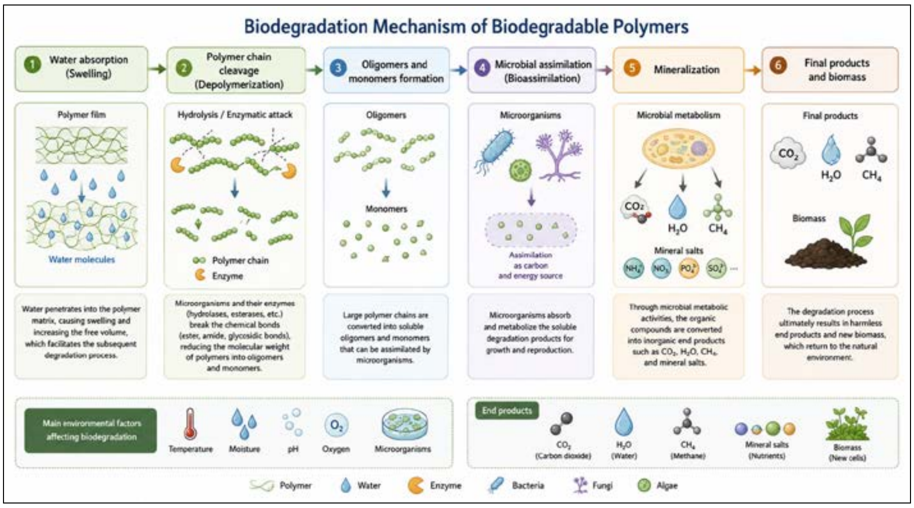

Fig 2: Schematic illustration of the biodegradation mechanism of biodegradable polymers

Types of Materials Used for Biodegradable Food Packaging Films

Biodegradable food packaging films are commonly fabricated from natural and synthetic biodegradable polymers. These materials differ in terms of their origin, physicochemical properties, biodegradability, and industrial applicability. In general, biodegradable film materials can be classified into three major groups: polysaccharide-based materials, protein-based materials, and synthetic biodegradable polymers [46]. Each category possesses unique advantages and limitations for food packaging applications.

1. Polysaccharide-Based Films

Polysaccharides are among the most widely studied materials for biodegradable food packaging because of their abundance, renewability, biodegradability, and excellent film-forming ability [47]. Common polysaccharides used in film fabrication include chitosan, starch, and cellulose.

1.1 Chitosan

Chitosan is a natural polysaccharide obtained from the deacetylation of chitin, which is mainly extracted from crustacean shells such as shrimp and crab shells. Chitosan exhibits excellent film-forming properties and can produce transparent and flexible films with good oxygen barrier performance [48]. One of the most important advantages of chitosan is its intrinsic antimicrobial activity against various foodborne microorganisms, making it highly attractive for active food packaging applications.

However, chitosan films are highly hydrophilic and generally exhibit poor water vapor resistance. Their mechanical stability may also decrease under high-humidity conditions. To overcome these limitations, chitosan is often combined with plasticizers, essential oils, or nanoparticles to improve flexibility and functional performance.

1.2 Starch

Starch is an inexpensive and renewable polymer extracted from agricultural sources such as corn, potato, cassava, and rice. Due to its availability and biodegradability, starch has been extensively investigated for sustainable food packaging applications [49]. Starch-based films generally exhibit high transparency and excellent oxygen barrier properties.

Nevertheless, pure starch films are usually brittle and sensitive to moisture because of their hydrophilic structure. Plasticizers such as glycerol are commonly added to improve flexibility, while blending with other polymers can enhance water resistance and mechanical strength.

1.3 Cellulose

Cellulose is the most abundant natural polymer derived from plant biomass. Cellulose-based films possess excellent mechanical strength, thermal stability, transparency, and oxygen barrier properties [50]. In recent years, nanocellulose materials such as cellulose nanofibers and cellulose nanocrystals have gained increasing attention because they can significantly improve film reinforcement and barrier performance.

Despite these advantages, cellulose-based films also suffer from poor moisture resistance due to their hydrophilic characteristics. Surface modification and polymer blending are therefore often applied to improve their packaging performance.

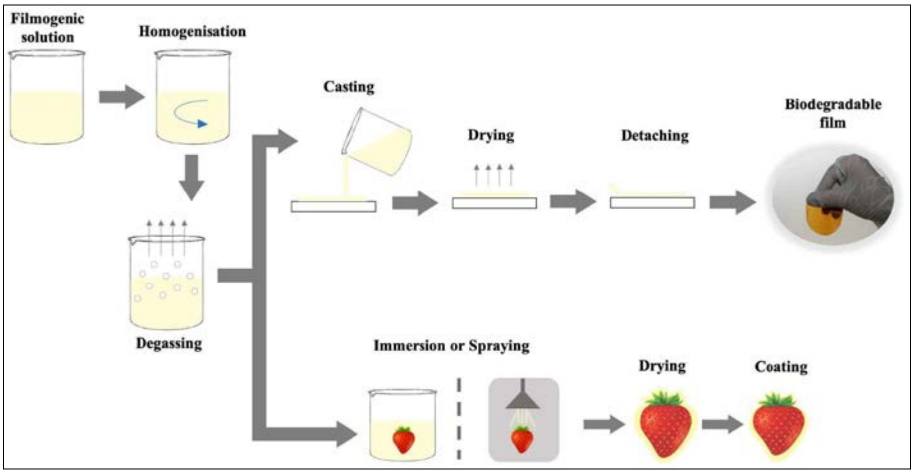

Fig 3: Representative polysaccharide-based biodegradable films used in food packaging applications. Source: created by the authors based on Refs. [46, 50].

2. Protein-Based Films

Protein-based biodegradable films have attracted considerable interest because of their good film-forming ability, flexibility, and excellent gas barrier properties [51]. Common protein materials include gelatin, whey protein, and soy protein.

2.1 Gelatin

Gelatin is produced from the partial hydrolysis of collagen obtained from animal skin and bones. Gelatin films are transparent, flexible, and exhibit favorable oxygen barrier properties. In addition, gelatin-based films are biodegradable and edible, making them suitable for food coating and packaging applications.

However, gelatin films are highly sensitive to moisture and may lose mechanical stability under humid conditions.

2.2 Whey Protein

Whey protein is a byproduct of cheese production and has been widely studied for edible film fabrication. Whey protein films exhibit high transparency and excellent oxygen barrier properties under dry conditions [51]. Their dense protein network contributes to good mechanical strength and flexibility.

Nevertheless, whey protein films still show poor resistance to water vapor because of their hydrophilic nature.

2.3 Soy Protein

Soy protein is an abundant and low-cost material with good film-forming properties. Soy protein films generally possess moderate mechanical strength and good oxygen barrier ability. Due to their biodegradability and edibility, soy protein films have considerable potential for sustainable food packaging applications [52].

However, similar to other protein-based materials, soy protein films are sensitive to moisture and require modification to improve water resistance.

3. Synthetic Biodegradable Polymers

In addition to natural biopolymers, several synthetic biodegradable polymers have been developed for commercial packaging applications. Among them, polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are the most important biodegradable synthetic polymers currently used in the food packaging industry [53].

3.1 Polylactic Acid (PLA)

PLA is a biodegradable thermoplastic polyester produced from renewable resources such as corn starch and sugarcane through lactic acid fermentation. PLA exhibits excellent transparency, good mechanical strength, and high processability using conventional plastic manufacturing technologies including extrusion and thermoforming [54].

Compared with natural biopolymers, PLA has superior moisture resistance and thermal stability. Therefore, PLA has been widely used in disposable cups, trays, containers, and packaging films. However, PLA is relatively brittle and often requires industrial composting conditions for complete degradation.

3.2 Polyhydroxyalkanoates (PHA)

PHA is a family of biodegradable polyesters synthesized naturally by microorganisms. PHA materials possess excellent biodegradability in soil, marine, and compost environments while also exhibiting favorable mechanical and barrier properties [55].

Because of their biodegradability and biocompatibility, PHAs are considered promising alternatives to conventional plastics in food packaging applications. However, their high production cost remains a major limitation for large-scale commercialization.

Applications of Biodegradable Films in Food Preservation

Biodegradable food packaging films have attracted significant attention in recent years due to their potential to enhance food preservation while reducing environmental pollution associated with conventional plastic packaging. Owing to their biodegradability, biocompatibility, and ability to incorporate active compounds such as antimicrobials and antioxidants, biodegradable films have been widely investigated for preserving fruits, vegetables, meat products, seafood, and other perishable foods [56]. In many cases, these films not only act as passive barriers against external contamination but also function as active packaging systems capable of extending shelf life and maintaining food quality.

1. Fruit Preservation

Fresh fruits are highly susceptible to moisture loss, microbial spoilage, and oxidative deterioration during storage. Biodegradable films can help reduce respiration rate, delay ripening, and maintain the physicochemical quality of fruits by controlling gas exchange and moisture transfer [57].

Chitosan-based films have been extensively studied for fruit preservation because of their antimicrobial and antifungal activities. For example, chitosan coatings applied to strawberries significantly reduced fungal growth and delayed fruit spoilage during refrigerated storage [58]. Similarly, edible coatings containing essential oils such as cinnamon oil or thyme oil have demonstrated the ability to inhibit microbial contamination and prolong the shelf life of apples, mangoes, and bananas.

Starch- and cellulose-based films have also shown promising performance in preserving fresh fruits by reducing weight loss and maintaining texture and color stability during storage [59].

2. Vegetable Preservation

Vegetables contain high moisture levels and remain metabolically active after harvest, making them vulnerable to dehydration, discoloration, and microbial contamination. Biodegradable films can create modified microenvironments around vegetables, thereby slowing respiration and reducing quality deterioration [60].

Several studies have reported that chitosan coatings effectively preserve tomatoes, cucumbers, and lettuce by reducing microbial growth and delaying senescence. In addition, biodegradable films incorporated with natural antioxidants can minimize enzymatic browning and maintain nutritional quality during storage [61].

Active packaging films containing plant extracts and essential oils have also demonstrated strong antimicrobial activity against spoilage microorganisms commonly associated with fresh-cut vegetables.

3. Meat Preservation

Meat products are highly perishable because of lipid oxidation, microbial growth, and protein degradation. Biodegradable active packaging films have emerged as effective alternatives for improving meat preservation and food safety [62].

Chitosan films incorporated with essential oils such as oregano oil, clove oil, and tea tree oil have shown strong antimicrobial activity against pathogenic bacteria including *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* [63]. These active films can inhibit microbial growth, reduce oxidation, and extend the shelf life of fresh meat products during refrigerated storage.

PLA- and gelatin-based films containing antioxidants have also demonstrated the ability to retard lipid oxidation and maintain meat color stability. Such packaging systems can significantly improve the sensory quality and microbiological safety of meat products.

4. Seafood Preservation

Seafood products are extremely sensitive to microbial spoilage and oxidative deterioration because of their high protein and unsaturated lipid contents. Biodegradable films have therefore been widely investigated for seafood preservation applications [64].

Edible coatings based on chitosan have demonstrated remarkable effectiveness in preserving fish and shrimp products by inhibiting bacterial growth and reducing lipid oxidation. Several studies reported that chitosan coatings combined with essential oils significantly extended the shelf life of refrigerated shrimp and fish fillets [65].

In addition, biodegradable films containing natural antimicrobial compounds can reduce unpleasant odors, maintain texture quality, and improve the overall storage stability of seafood products.

5. Edible Packaging Applications

Edible films and coatings represent one of the most promising applications of biodegradable packaging materials. Unlike conventional packaging, edible films can be consumed together with food products, thereby minimizing packaging waste generation [66].

Protein- and polysaccharide-based edible films are commonly used for confectionery products, fruits, vegetables, and ready-to-eat foods. These films can serve as carriers for flavors, antioxidants, vitamins, and antimicrobial agents while simultaneously providing protective barrier functions [67].

Recent advances in edible packaging technologies have focused on developing multifunctional films with enhanced mechanical strength, controlled release properties, and smart packaging capabilities. Such innovations are expected to contribute significantly to sustainable food packaging development in the future.

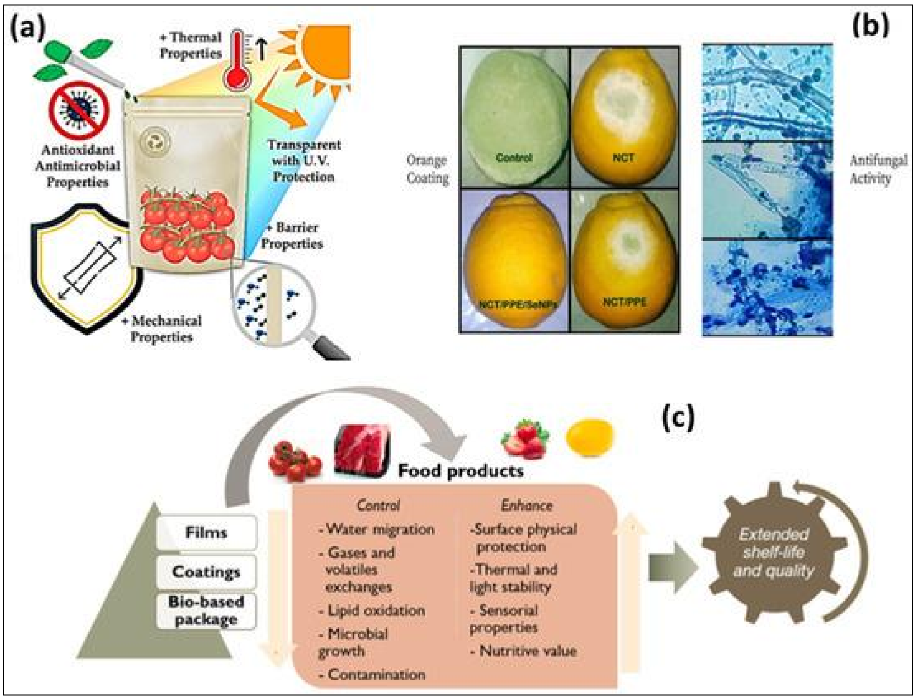

Fig 4: Applications of biodegradable food packaging films in preserving fruits, vegetables, meat, seafood, and edible food products. Source: created by the authors based on Refs. [56, 67].

Future Development Trends of Biodegradable Food Packaging Films

The increasing demand for sustainable food packaging materials has accelerated the development of advanced biodegradable packaging technologies. Future research is expected to focus not only on improving the environmental performance of biodegradable films but also on enhancing their functional, mechanical, and intelligent properties for practical industrial applications. Several emerging trends, including smart packaging, active packaging, nano-enabled packaging systems, agricultural waste valorization, and optimization of biodegradation efficiency, are currently attracting considerable scientific and commercial interest.

1. Smart Packaging Systems

Smart packaging represents one of the most promising directions in modern food packaging technology. Unlike conventional packaging materials, smart biodegradable films are capable of monitoring food quality, freshness, and environmental conditions during storage and distribution [68]. These systems often contain indicators or sensors that respond to changes in pH, temperature, gas composition, or microbial activity.

Colorimetric indicators based on natural pigments such as anthocyanins have been widely investigated for intelligent food packaging applications. These compounds can change color in response to pH variations associated with food spoilage, allowing consumers to visually evaluate product freshness in real time. The integration of smart sensing systems into biodegradable packaging films is expected to improve food safety, reduce food waste, and enhance consumer confidence.

2. Active Packaging Films

Active biodegradable packaging films have received significant attention because they can actively interact with food products to extend shelf life and improve preservation efficiency. Various bioactive compounds such as essential oils, plant extracts, antimicrobial peptides, antioxidants, and organic acids can be incorporated into biodegradable polymer matrices to inhibit microbial growth and retard oxidation processes [69].

Recent studies have focused on developing controlled-release systems capable of gradually releasing active compounds during storage. Such technologies can improve the long-term effectiveness of antimicrobial and antioxidant agents while minimizing sensory alterations in food products. Active packaging systems are therefore considered highly promising for preserving highly perishable foods such as meat, seafood, and fresh produce.

3. Nano-Enabled Packaging Technologies

Nanotechnology has emerged as an effective strategy to enhance the functional performance of biodegradable packaging materials. The incorporation of nanoparticles such as nanocellulose, nanoclays, metal nanoparticles, and nanoemulsions into biodegradable films can significantly improve mechanical strength, thermal stability, barrier properties, and antimicrobial activity [70].

Nanomaterials can also facilitate the development of multifunctional packaging systems with smart sensing capabilities and controlled release functions. In particular, nanocellulose has attracted increasing attention because of its biodegradability, renewability, and excellent reinforcement properties. Despite these advantages, safety assessment and regulatory considerations related to nanoparticle migration into food products remain important issues that require further investigation.

4. Utilization of Agricultural Byproducts

The valorization of agricultural and food-processing byproducts is becoming an important strategy for sustainable biodegradable packaging production. Large quantities of agricultural residues such as fruit peels, starch-rich wastes, cellulose fibers, and seafood shells can serve as inexpensive raw materials for biodegradable polymer extraction and film fabrication.

For example, chitin extracted from shrimp shell waste can be converted into chitosan for antimicrobial packaging applications, while fruit-processing residues rich in cellulose and pectin can be utilized for edible coating production. The utilization of agricultural byproducts not only reduces production costs but also contributes to waste management and circular economy development.

5. Optimization of Biodegradation Performance

Although biodegradable films are environmentally friendly alternatives to conventional plastics, optimizing their degradation rate under different environmental conditions remains a major research objective. Future studies are expected to focus on tailoring polymer structures, blending strategies, and processing technologies to achieve balanced mechanical performance and controlled biodegradability.

In addition, the development of standardized biodegradation assessment methods is essential for evaluating the environmental impact and industrial compostability of biodegradable packaging materials. Improving degradation efficiency in soil, marine, and compost environments will play a critical role in promoting the large-scale replacement of petroleum-based plastics in the food packaging industry.

Conclusion

Biodegradable food packaging films have emerged as promising alternatives to conventional petroleum-based plastics due to their environmental compatibility, renewability, and functional properties. The growing concerns regarding plastic pollution and the increasing demand for sustainable packaging solutions have significantly accelerated research and development in this field. Various biodegradable materials, including polysaccharides, proteins, and synthetic biodegradable polymers, have demonstrated considerable potential for food packaging applications.

Among natural biopolymers, chitosan, starch, and cellulose have attracted particular attention because of their biodegradability, film-forming ability, and potential for active packaging development. Protein-based materials such as gelatin, whey protein, and soy protein also exhibit favorable gas barrier properties and flexibility, making them suitable for edible and biodegradable packaging systems. In addition, synthetic biodegradable polymers such as PLA and PHA have shown excellent industrial potential due to their superior mechanical performance, processability, and compatibility with existing plastic manufacturing technologies.

Recent advances in active packaging, smart packaging, and nanotechnology have further expanded the functional capabilities of biodegradable films. The incorporation of antimicrobial agents, antioxidants, essential oils, and nanomaterials has enabled the development of multifunctional packaging systems capable of extending shelf life, improving food safety, and monitoring food freshness. Furthermore, the utilization of agricultural and food-processing byproducts as renewable raw materials represents an important strategy for reducing production costs and supporting circular economy development.

Despite these promising advantages, several challenges still limit the large-scale commercialization of biodegradable food packaging materials. Issues related to moisture sensitivity, mechanical stability, thermal resistance, biodegradation control, and high production costs remain major obstacles compared with conventional petroleum-based plastics. In addition, further studies are required to optimize material formulations, improve processing technologies, and establish standardized regulations for industrial applications and environmental safety assessment.

Overall, biodegradable food packaging films are expected to play a significant role in the future of sustainable food packaging systems. Continued advances in material science, biotechnology, and nanotechnology are likely to accelerate their commercial adoption and contribute to reducing environmental pollution associated with plastic waste. With increasing global emphasis on sustainability and circular economy principles, biodegradable packaging materials are anticipated to become key components of next-generation food packaging technologies.

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